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THE INDICATOR DEVELOPMENT STRATEGY FOR THE ENVIRONMENTAL MONITORING AND ASSESSMENT PROGRAM

By

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16. ABSTRACT

The overall goal of Environmental Monitoring and Assessment Program (EMAP) is to provide a quantitative assessment of the current status and long-term trends in the condition of the nation's ecological resources on regional and national scales. This document outlines a strategy for indicator selection, development, and evaluation within EMAP. Its objectives are twofold: 1) to present general guidelines, criteria, and procedures for indicator selection and evaluation, and 2) to establish an organizational framework for coordinating and integrating indicator development and use within EMAP. It should serve both to promote internal consistency among EMAP resource groups and to provide a basis for external review of the proposed indicator development process.

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THE ENVIRONMENTAL MONITORING AND ASSESSMENT PROGRAM

The U.S. Environmental Protection Agency (EPA) initiated the Environmental Monitoring and Assessment Program (EMAP) in 1989 to provide improved information on the current status and long-term trends in the condition of the nation's ecological resources. When fully implemented, EMAP will be an inter-agency, multi-resource program designed to quantitatively address six critical questions:

1. What is the current status, extent, and geographic distribution of ecological resources (e.g., forests, agroecosystems, arid lands, wetlands, lakes, streams, and estuaries) in the United States?
2. To what levels of environmental stress and pollutants are these ecological resources exposed and in what regions are the problems most severe?
3. What proportions of these resources are degrading or improving, where, and at what rate?
4. What are the most likely causes of poor or degrading condition?
5. What ecological resources are at greatest current or future risk from environmental stresses and pollutants?
6. Is the overall condition of ecological resources responding as expected to control and mitigation programs?

ECOLOGICAL INDICATORS

EMAP's success will depend, in large part, on its ability to characterize ecological condition, or by human analogy, the *health* of ecological resources on regional and national scales. Because factors such as ecological condition and health often are difficult to measure or cannot be measured directly, EMAP will monitor a set of indicators that collectively describe the overall condition of an ecological resource. The term *indicator* has been adopted within EMAP to refer to the specific environmental attributes to be measured or quantified through field sampling, remote sensing, or compiling of existing data. Achieving EMAP's objectives will require not only indicators of ecological condition (termed *response* indicators), but also indicators of pollutant exposure (*exposure* indicators), habitat quality (*habitat* indicators), and both human and natural sources of stress that might be affecting ecological condition (*stressor* indicators).

There are many indicators of potential value, but only a subset of these environmental attributes can be monitored given the available funding and desired regional scope of EMAP. Identification of the best set of indicators for use in a broad-scale regional status and trends network is, therefore, a major activity within EMAP.

OBJECTIVES OF THIS DOCUMENT

This document outlines a strategy for indicator selection, development, and evaluation within EMAP. Its objectives are twofold: (1) to present general guidelines, criteria, and procedures for indicator selection and evaluation, and (2) to establish an organizational framework for coordinating and integrating indicator development and use within EMAP. It should serve both to promote internal consistency among EMAP resource groups and to provide a basis for external review of the proposed indicator development process.

INDICATOR DEVELOPMENT PROCESS

The proposed process for indicator development within EMAP consists of six phases:

Phase 1: Identifying issues (environmental values and apparent stressors) and assessment endpoints.

Phase 2: Identifying candidate indicators that are linked to the identified endpoints and responsive to stressors.

Phase 3: Screening candidate indicators, based on a set of indicator evaluation criteria and conceptual models, to select as research indicators those that appear most likely to fulfill key requirements.

Phase 4: Quantitatively testing and evaluating the expected performance of research indicators in field pilot studies, or through analysis of existing data sets, to identify the subset of developmental indicators suitable for regional demonstration projects.

Phase 5: Demonstrating developmental indicators on regional scales, using the sampling frame, methods, and data analyses intended for the EMAP network, to identify the subset of core indicators suitable for full-scale implementation.

Phase 6: Periodically reevaluating and refining the core indicators as needed within the national monitoring network.

Monitoring activities in EMAP will be conducted by seven resource groups, each of which will focus on one of seven ecological resource categories: surface waters, the Great Lakes, estuaries, wetlands, forests, agroecosystems, and arid lands. Each EMAP resource group's indicator program will be kept on track through the use of research plans, peer reviews, and an indicator data base. Annual and five-year comprehensive research and monitoring plans will be produced, describing EMAP's results to date, the evidence and rationale for all decisions made within each phase of the indicator development process, future directions and promising new indicators, and specific plans for indicator research and evaluation. The current status of all indicators and the rationale for all decisions regarding indicator selection or rejection also will be documented in an indicator data base.

CONCEPTUAL FRAMEWORK

It is critical to the success of EMAP that the environmental attributes monitored are appropriate to the program's objectives. The first phase of the indicator development process, therefore, is intended to establish a framework for indicator selection and interpretation, by identifying the environmental values, assessment endpoints, and environmental stressors of primary concern and delineating the conceptual models for each ecological resource category or class. EMAP response indicators must correspond to or be predictive of an assessment endpoint, which is a quantitative or quantifiable expression of an environmental value. Changes in response indicators should reflect a corresponding change in an assessment endpoint, and thus in the value of an ecological resource. Exposure, habitat, and stressor indicators, and possibly response indicators, will provide the basis for diagnosing plausible causes of observed poor or changing ecological condition. Conceptual models delineate the linkages between environmental values (assessment endpoints), major ecological resource components and processes, and the external stressors and factors that influence ecological resource condition. These models serve three primary purposes:

1. To explicitly define the framework for indicator interpretation (e.g., relationships between the selected indicators and the assessment endpoints of interest).
2. To identify any "gaps" within the proposed suite of indicators (i.e., missing indicators or links for which additional or new indicators are needed.
3. To guide the data analysis strategy for diagnosing plausible causes of poor or degrading ecological condition.

Therefore, in Phase 1 of the indicator development process, three major activities will be initiated:

1. Listing environmental values associated with each ecological resource category.
2. Listing major problems and external stressors currently impacting or threatening each resource category.
3. Developing conceptual models that link assessment endpoints and stressors to the major ecological resource components and processes, and subsequently to EMAP indicators.

INDICATOR SELECTION AND EVALUATION

In Phase 2, based on literature reviews and interactions with scientists conducting relevant research, all potentially useful measures of ecological resource status and the natural and anthropogenic factors that influence status will be identified as candidate indicators for EMAP. The identification of candidate indicators is a continual process. Each ecological resource group must continually reassess its proposed suite of indicators for completeness, consider new candidate indicators that may arise as a result of advances in ecological research and monitoring technologies, and revisit potential indicators previously rejected or postponed as new information or technologies alter the context of indicator evaluation.

During Phases 3 through 5, candidate indicators will be critically evaluated and iteratively filtered to identify the best possible suite of core indicators for implementation in the EMAP network. The process of indicator testing and prioritization will be guided by specific criteria for indicator selection and peer reviews of decisions made at each phase. The use of clearly defined criteria will increase the objectivity, consistency, and depth of indicator evaluations. The amount, quantification, and quality of data necessary to satisfy each of the critical criteria will increase at each phase in the indicator development process.

Phase 3 (selecting research indicators) will rely on literature reviews and expert knowledge (e.g., workshops with outside scientists) to qualitatively evaluate the likelihood that each candidate indicator will be able to satisfy the indicator selection criteria and thus be worthy of additional attention. Enough information will be needed to determine which indicators merit further research, but such investigations will not actually be carried out. Expert judgement, therefore, plays a particularly important role in the selection of research indicators.

In Phase 4 (selecting probationary core indicators), the selection criteria are applied more stringently to quantitatively address questions concerning spatial and temporal indicator variability, optimal sampling protocols, and data interpretability. Indicator performance will be assessed by analyzing existing data sets and/or by conducting field pilot studies. The ecological resources sampled for field pilots will encompass the full range of environmental conditions expected in EMAP, but will not necessarily be sites on the EMAP sampling grid. Issues to be addressed in field pilot studies include the following:

- Characterizing ecological resource units to identify the optimal sampling period and to quantify the most probable temporal variability of each indicator within that sampling period.
- Conducting extensive spatial sampling within an ecological resource unit to quantify indicator spatial variability and select the optimal sampling protocol.

- Sampling along gradients, from "polluted" to "unpolluted" or "impacted" to "natural" sites to evaluate (1) the responsiveness of the indicator to stress, (2) the specificity of the indicator to particular types of stress or change, and (3) the repeatability of the indicator response in different regions or ecological resource classes.

Phase 5 (identifying core indicators) is a demonstration, not a research effort. Thus, by the time Phase 5 is implemented, there must be a high degree of confidence that the selected developmental indicators will indeed ultimately be accepted as core indicators. Phase 5 addresses issues that can only be answered by testing the developmental indicators using the EMAP sampling frame, methods, and data analyses. Important functions of Phase 5 include: (1) confirming the pilot study results on a regional scale, (2) developing the EMAP infrastructure for conducting regional monitoring efforts, (3) confirming the utility and interpretability of the EMAP outputs for assessing the regional status of ecological resources, and (4) determining whether the proposed EMAP sampling grid density is sufficient to assess regional patterns and associations between indicators of ecological condition and anthropogenic stressors.

Scientific advances and technological improvements will occur throughout the duration of EMAP. This may necessitate modifying certain indicators and replacing some indicators with others that provide improved information or equivalent information at reduced cost, as well as adding indicators that address emerging issues of importance. Phase 6 (reevaluating and modifying the suite of core indicators), therefore, will be a continual process. EMAP must balance the need for continuity of methods (to maximize trend detection capability) with the benefits of refining or replacing indicators that fail to perform optimally. The core suite of indicators will be revised only after a thorough assessment indicates that it is clearly necessary. The advantages of the new indicator or method must be significant and well documented. Field pilot studies and demonstration projects will be conducted to calibrate the relationship between the old and new indicators (or measurement techniques), and both the old and new (or modified) indicators will be monitored long enough to ensure data comparability before phasing out the original indicator.

INTEGRATION ACROSS EMAP RESOURCE GROUPS

At present, individual EMAP resource groups have the primary responsibility for selecting and evaluating indicators within each of the seven major ecological resource categories (agroecosystems, arid lands, forests, wetlands, inland surface waters, the Great Lakes, and estuaries). Integration and coordination of the indicator development process across EMAP resource groups is necessary, however, to fully achieve the program goals. The primary approach for achieving an integrated set of indicators is through a coordinated effort of communication and information exchange. Within EMAP, the Indicator Coordinator, working closely with the EMAP Integration and Assessment task group, has the responsibility for facilitating and encouraging these activities as they relate to the selection and evaluation of EMAP indicators. Five major tasks are planned:

1. Compile and cross reference lists of assessment endpoints, environmental values, stressors, and indicators proposed by each group, to identify areas of similarity, commonality, or inconsistency in approach.

2. Conduct one or more workshops involving looking-outward (interaction) matrix exercises to identify gaps or important linking and stressor indicators that have been overlooked.

3. Develop conceptual models that identify cross-linkages and relationships among ecological resource categories. Development of integrated conceptual models will (1) help to formalize expected relationships among indicators in different resource categories, (2) ensure consistency in indicator definitions, (3) encourage the identification and use of linking, common, and migratory indicators, (4) identify commonalities in approach and indicator use among EMAP resource groups, and (5) ensure that all important processes and linkages are considered within the EMAP monitoring network.

4. As appropriate, propose alternative assessment endpoints and indicators that would provide similar information, but would be common or improve comparability with endpoints and indicators being monitored by other EMAP resource groups.

5. For indicators selected by more than one group, examine and compare the proposed field sampling and measurement methods and suggest modifications as needed to improve comparability among groups.

Communication among groups will be ensured through regular meetings and workshops, and through the exchange of written materials and research plans. The lists, matrices, and models related to each of the above tasks will be continually updated, as needed, as the indicator development process within each EMAP resource group advances and evolves.

Indicators monitored by different resource groups may not be measured during the same sampling period or be co-located in the same sampling unit. This could result in both temporal and spatial displacement of indicators and could hinder diagnostic analyses examining linkages that cross resource boundaries. Data analysis techniques must be developed, therefore, to deal with non-co-located and/or spatially displaced data that rely primarily on regional-scale data aggregations and associations.

THE INDICATOR COORDINATOR

As noted earlier, the responsibility for coordinating the indicator development process among ecological resource groups has been assigned to the Indicator Coordinator. The Indicator Coordinator will play a pro-active role in facilitating communication and the flow of information among groups and promoting the implementation of the indicator development strategy. Four primary functions for the Indicator Coordinator have been identified:

1. Centralized information point/communication: The Indicator Coordinator will ensure that all relevant information is continually exchanged among the EMAP resource groups and task groups. The Indicator Coordinator will review all documents relating to indicators, and pass on relevant information to the respective EMAP resource groups. Also, the Indicator Coordinator will serve as the centralized contact point and source of information on EMAP indicators for the external scientific community.

2. Strategy implementation: The Indicator Coordinator will be responsible for ensuring that the steps and procedures for inter-group integration, outlined earlier, are completed. The Indicator Coordinator will work with the EMAP resource groups and the Integration and Assessment task group to (1) develop integrative conceptual models to assist with indicator selection and evaluation, (2) identify linking indicators, and (3) encourage the use of compatible sampling and measurement methods.

3. Indicator data base: The Indicator Coordinator will be responsible for technical oversight of the content, accuracy, and completeness of the indicator data base as a record of the indicator development process.

4. Research review: Research to identify new indicators or evaluate existing indicators within EMAP will be initiated and directed primarily by the EMAP resource groups. However, the Indicator Coordinator will play an active role in reviewing research proposals as well as final project reports. In addition, the Indicator Coordinator will maintain an updated, integrated listing of priority research needs relating to EMAP indicators. The Indicator Coordinator will also monitor ongoing and planned research on indicators outside EMAP by maintaining regular contact with appropriate research agencies and programs.

1. INTRODUCTION

The Environmental Monitoring and Assessment Program (EMAP) has been initiated by the U.S. Environmental Protection Agency's (EPA) Office of Research and Development. EMAP is intended to be an umbrella program under which EPA can work as part of an interagency effort to monitor and periodically assess the condition of the ecological resources of the United States. When fully implemented, EMAP will be an integrated, multi-resource program that can be used to quantitatively determine the status of ecological resources at various geographic scales and over long periods of time, and to detect changes in the status of these resources on a regional and national basis.

EMAP's success depends on its ability to characterize ecological condition (or health), and to identify likely causes of adverse changes. Because concepts such as ecological "condition" or "health" are often difficult to measure directly, EMAP will monitor a set of environmental indicators that, acting as surrogates for less easily measured ecosystem characteristics, will collectively describe the overall condition of an ecological resource. An indicator is defined as an environmental attribute that, when measured or quantified over appropriate temporal and spatial scales through field sampling, remote sensing, or compilation of existing data, quantifies the magnitude of a stress, the status of a habitat characteristic, the degree of exposure of a resource to a stressor, or the degree of response of an ecological resource to an exposure. Because of the importance of indicators in interpreting ecosystem condition, the selection, development, and evaluation of these indicators for use in a broad-scale regional status and trends network are major EMAP activities.

This document provides an overview of EMAP, discusses the role of indicators in EMAP, and outlines a strategy for indicator development and evaluation within EMAP. Its objectives are twofold: (1) to present general guidelines, criteria, and procedures for indicator selection and evaluation, and (2) to establish an organizational framework for coordinating and integrating indicator development and use within EMAP. It should serve both to promote internal consistency among EMAP resource groups and to provide a basis for internal and external review of proposed EMAP indicators.

This document focuses on indicator development and its use within EMAP, but the issues discussed and the guidelines developed may have broader applications. Detailed, process-oriented research on indicators will be conducted within other related research programs (e.g., EPA's Core Research Program). Since these efforts can be expected to develop information that can complement or supplement the capabilities of the EMAP indicators, EMAP's objectives will be best served through a close linking of the EMAP indicator development process to these ongoing and planned research programs.

Conceptually, indicator development is a process of sequential hypothesis testing to determine whether or not proposed indicators can be used to estimate ecological conditions on a wide spatial scale and over a long time period, using synoptic survey monitoring methods. When applied to a wide array of potential indicators, this process of testing potential indicators is intended to develop an integrated suite of indicators for monitoring the fundamental elements and processes of ecosystems in different categories of ecological resources (e.g., forests, wetlands). The procedures described in this document are intended to guide this testing process from the identification of potentially useful indicators (candidate indicators) through adoption of acceptable indicators for use in the monitoring program (core indicators). Implementation of this strategy, and the timing of the development of indicators within each of the EMAP ecological resource groups, is the responsibility of the resource groups, with the assistance of the EMAP Indicator Coordinator.

In addition to developing indicators for routine monitoring, EMAP resource groups will need to track fundamentally catastrophic stressors (e.g., hurricanes, wildfires, El Niño, volcanic eruptions) that could affect either the resource condition or the underlying structure and function of the ecosystems being monitored by the groups. Although catastrophes may or may not have influenced current conditions, their incidence may obviate the relationships on which indicators have been developed by the resource groups. Tracking such events will allow the resource groups to explain radical changes in resource condition, and to evaluate the adequacy of their indicator suite, as necessary. Procedures for tracking these catastrophic events are not addressed by the Indicator Development Strategy.

Because EMAP was initiated in 1989, it is still in the early stages of program design and planning. As the program matures, the indicator development process is also likely to evolve and improve. This document and the guidelines presented are not intended to be rigid; they will be revised and updated as needed. The document is formatted as follows:

- Section 2 provides background on EMAP and the role of indicators in ecological monitoring.
- Section 3 presents an overview of the indicator development strategy.
- Section 4 provides detailed procedures for selecting and evaluating indicators and documenting decisions made during these evaluations.
- Section 5 discusses procedures for inter-group coordination and integration.
- Section 6 defines the role of the EMAP indicator development coordinator.
- Section 7 outlines procedures for initiating indicator research to support the EMAP monitoring network.
- Section 8 lists the references cited.

Some of the background material presented in this report relies heavily on Hunsaker and Carpenter (1990). In some cases, text from this source has been modified only slightly to reflect recent changes in EMAP or to alter its emphasis to address indicator development issues. For additional information regarding the use of indicators in the various EMAP activities, readers should refer to that document and to the research plans for each of the ecological resource groups.

In the process of writing this document, we received many comments, ideas, and expressions of concern about issues that were either beyond the scope of the indicator strategy or impossible to address fully, given our limited resources and time. We expect that EMAP participants will consider these issues and take necessary actions, and that new developments will be reflected in revised versions of this strategy. Some of the issues of greatest concern that require further attention are:

- EMAP indicator concepts and terminology
- Roles and responsibilities of the Indicator Coordinator
- Uses and development of conceptual models for selecting, explaining, and interpreting indicators (they need to be more specific and better adapted to spatial and temporal scales relevant to EMAP)
- Ways to express ecosystem condition in terms of "health"
- Coordination and integration of the use of indicators among EMAP groups, one goal of which is to provide a stronger ecosystem perspective

2. BACKGROUND

2.1 EMAP OVERVIEW

In 1988, EPA's Science Advisory Board recommended implementing a program within the Agency to monitor ecological status and trends, as well as to develop innovative methods for anticipating emerging problems before they reach crisis proportions. More recently, the Administrator of EPA established an agency priority for the 1990s of measuring for results; that is, confirming that the nation's annual expenditure on environmental issues is producing significant results in maintaining and improving environmental quality (Reilly, 1989). In an effort to identify emerging problems before they become widespread or irreversible, and to foster evaluation of the success of policies and regulatory programs, EPA's Office of Research and Development began planning the Environmental Monitoring and Assessment Program (EMAP). Initiated in 1989, EMAP was created in response to the need for better assessments of the condition of the nation's ecological resources.

2.1.1 Perspective

EMAP is intended to be an umbrella program, under which EPA participates in an interagency effort (i.e., federal, state, local and private agencies) to monitor and report on the condition of the nation's ecological resources. When fully implemented, EMAP is intended to answer six critical questions:

- What is the current status, extent, and geographic distribution of our ecological resources (e.g., forests, agroecosystems, arid lands, wetlands, lakes, streams, and estuaries)?
- To what levels of environmental stress and pollutants are these ecological resources exposed and in what regions are the problems most severe?
- What proportions of these resources are degrading or improving, where and at what rate?
- What are the possible reasons for adverse or beneficial conditions?
- What ecological resources are at current and future risk from environmental stresses and pollutants?
- Are adversely effected ecological resources improving overall in response to control and mitigation programs?

2.1.2 EMAP Objectives

To answer the questions in Section 2.1.1, EMAP has adopted an interdisciplinary approach to design and implement an integrated resource monitoring program with the following objectives:

- Estimate current status, extent, changes, and trends in indicators of the condition of the nation's ecological resources on a regional basis with known confidence.
- Monitor indicators of pollutant exposure and habitat condition and seek associations between human-induced stresses and ecological condition that identify possible causes of adverse effects.
- Provide periodic statistical summaries and interpretive reports on status and trends of the environment to the EPA Administrator and the public.

Meeting the first two of these objectives requires identifying indicators of the condition of ecological resources, pollutant exposure, habitat loss or degradation, and both human and natural sources of stress (e.g., climate change, introductions of exotics) that might be associated with degraded or changing ecological condition. This report addresses the strategy that will guide the development of potential indicators and the procedures that will be used to develop a comprehensive set of indicators for implementation in EMAP.

2.1.3 EMAP Approach

EMAP has been designed to provide information needed to conduct a 'top-down' or effects-driven approach to risk assessment (Messer, 1990). In 'top-down' risk assessments, the observation of an effect stimulates efforts to identify plausible hazards or stressors that may have caused the effect, by focusing on changes in system status and associations among various indicators of stress exposure and response. This approach enhances the likelihood of detecting cumulative impacts of natural and anthropogenic influences on ecological resources.

2.1.4 Design Attributes

EMAP is intended to provide reliable and unbiased estimates of the status and trends in the condition of our nation's ecological resources by monitoring indicators of these ecological resources and assessing the relationships among these indicators. To accomplish this goal requires the availability of indicator data of known precision and quantifiable confidence limits at regional scales of resolution. In addition, these data must cover temporal periods of years to decades. EMAP has been designed to provide a probability-based sample of ecological resource condition that can yield the necessary data quality. The following paragraphs summarize the major attributes of the design in the context of indicator development activities. For additional detail on the EMAP design, see Overton et al. (1990).

The EMAP design is hierarchical, and has four distinct tiers (Figure 2-1). Tier 1 is the broadest level and has the greatest spatial coverage among the tiers. This tier describes the extent of ecological resources

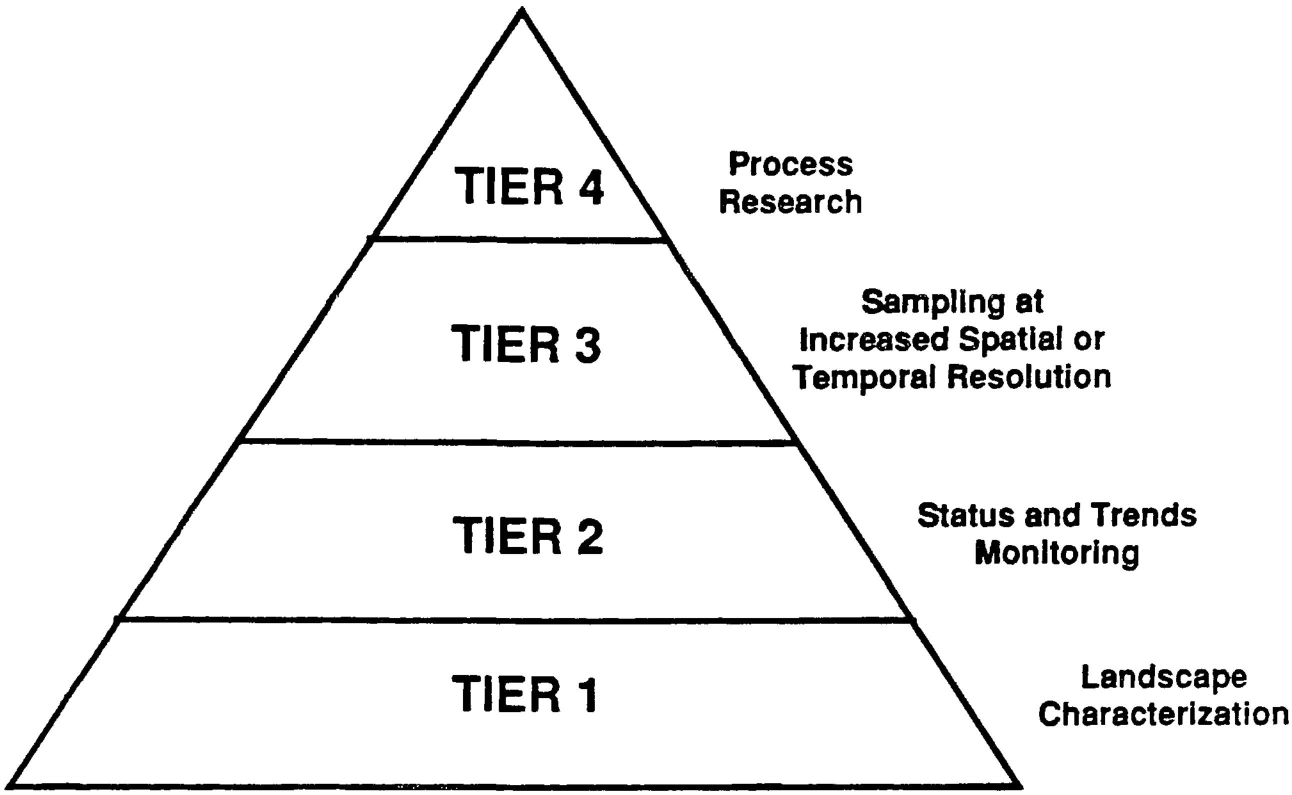

Figure 2-1. Four-tier structure of EMAP and the major activities associated with each of the tiers (after Paulsen et al., 1990).

available for sampling and monitoring in the other tiers. The landscape and ecological resources within 40-km^2 hexagons surrounding approximately 12,600 gridpoints in the conterminous United States will be characterized, based largely on remote sensing and existing maps. Similar sampling grids will eventually be developed for Alaska and Hawaii. Tier 2 uses probability methods to select a subset of the ecological resource units contained within these 40-km^2 hexagons, in proportion to their occurrence and a subjective assessment of their importance. The Tier 2 subset will be used for field sampling and monitoring of indicators of ecological condition. Tier 3 activities provide for increased sampling intensity, either temporally or spatially, to ensure adequate information about status and trends for subpopulations of interest (e.g., redwood forests, low alkalinity lakes) or to provide diagnostic information beyond that available from Tier 2 efforts. Tier 4 includes process-level research that may be conducted at specific, nonrandomly selected sites to develop new methods or to pilot test potential indicators.

Tier 2 activities rely heavily on the specific indicators implemented in each of the components of the program. The proposed Tier 2 sampling design involves periodic visitation to selected points in the nationwide grid to collect samples and data on ambient conditions. The nominal density of these grid points is one point per 640 km^2, which can be increased or decreased to meet specific needs. Selection of specific sites for monitoring will strongly depend on the location of the ecological resources within the grid. The grid used in Tier 2 activities can be extended to provide global as well as national coverage and can be enhanced for state coverage.

Other agencies, including the U.S. Departments of Agriculture, Commerce, Energy, and Interior, have active, ongoing monitoring programs that address some of EMAP's needs for certain data. EMAP will develop procedures for directly integrating data and components from these monitoring programs into the EMAP grid, where the form and nature of the data are appropriate. In cooperation with other agencies, EMAP will supplement existing networks to fill critical data gaps. The spatial and temporal constraints of the sampling design are discussed in Overton et al. (1990).

2.1.5 EMAP Activities

The development of ecological indicators is one of eight primary activities under EMAP, as shown in Figure 2-2. In addition to the strategic development, evaluation, and testing of indicators (Ecological Indicators), these activities include:

- Design and evaluation of integrated statistical monitoring frameworks and protocols for collecting data (Monitoring Systems Design).
- Nationwide characterization of the extent and location of ecological resources (Landscape Characterization).
- Demonstration studies and implementation of an integrated sampling network (Operational Monitoring).
- Development of quality assurance and quality control procedures, and new methods (Methods Development).
- Data storage, retrieval, management, and dissemination (Information Management).
- Statistical analytical procedures (Environmental Statistics).
- Periodic statistical reports and interpretive assessments on the status and trends in condition of the nation's ecological resources (Integrated Assessments).

The arrows in Figure 2-2 depict direct information linkages or dependencies that require interaction among these activities. Ecological indicators are clearly linked to all other activities in EMAP, which denotes the fundamental importance of the indicator development process to the overall success of EMAP.

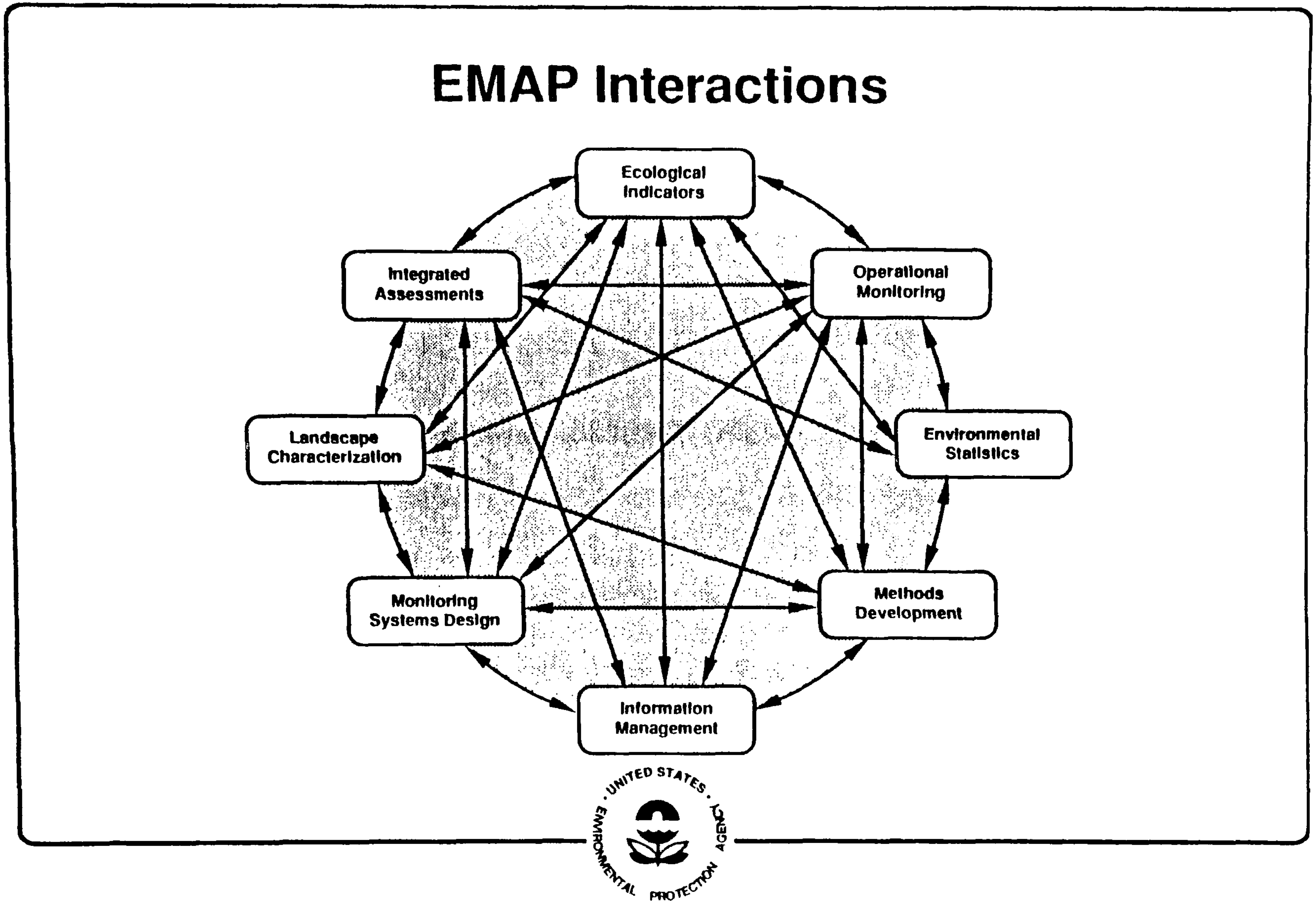

Figure 2-2. **Potential interactions among the various elements of the EPA's Environmental Monitoring and Assessment Program. Notice the heavy interactions of Ecological Indicators with the other elements.**

2.2 ECOLOGICAL RESOURCE CLASSIFICATION

EMAP will provide regional and national estimates of the condition of ecological resources that have been hierarchically classified into ecological resource categories, classes and, in many cases, subclasses. The seven ecological resource categories include broadly defined components of the nation's ecological resources: surface waters, the Great Lakes, estuaries, wetlands, forests, agroecosystems, and arid lands. EMAP activities in each of these categories are the responsibility of an ecological resource group. Specific ecosystem types within the category (e.g., oak-hickory forest), are referred to as ecological resource classes. Subclasses of ecological resource classes represent further subdivisions, such as the oak-hickory-pine subclass of the oak-hickory class of the forest ecological resource category. EMAP's objectives require that the questions posed in 2.1.1 be answered for all of the resource classes.

2.3 ROLE OF INDICATORS IN ECOLOGICAL MONITORING

Determining the status of ecological resources at a known statistical level of confidence requires a sound statistical design, indicators that cover the observed range of ecological conditions, and methods for distinguishing among nominal, subnominal, and marginal resource conditions. The following sections discuss indicators and their usage in EMAP as well as in broader applications. This section relies heavily on the concepts discussed in Hunsaker and Carpenter (1990).

2.3.1 Endpoints as the Foundation for Assessment

EMAP will monitor the status and trends in ecosystem characteristics, or attributes. It is extremely important that the attributes being monitored in EMAP represent valued characteristics of the ecosystem and that changes in these attributes reflect the kinds of changes actually occurring in the ecosystem. Identification of valued attributes provides the initial step in the development of indicators, as described in Section 4. The following paragraphs discuss important concepts regarding ecosystem attributes in relation to indicator development.

Valued ecosystem attributes can be referred to as endpoints of concern, or assessment endpoints (Suter, 1990). Assessment endpoints, comprising both an entity (e.g., species richness) and an attribute (e.g., sustainable), are formal expressions of the actual environmental value that is to be protected, and as such should have unambiguous operational definitions, have social or biological relevance, and be accessible to prediction or measurement (e.g., extent of habitat for an endangered species, availability of sufficient habitat diversity to support big game, crop productivity). In many cases, they are identical to the ecosystem attribute of concern (e.g., crop productivity), and measurement of the desired ecosystem attribute is straightforward.

However, assessment endpoints often cannot be directly or conveniently measured. In such cases, indicators are used as surrogates for the assessment endpoints. To be useful, measurement endpoints must correspond to or be predictive of the assessment endpoint (e.g., reproductive performance of an endangered species, ecotone/edge ratio, crop biomass). Measurement endpoints can be thought of as indicators of condition for the valued ecosystem attribute. For example, lakes are valued, among other reasons, for their recreational fishing; the associated assessment endpoint is *fishability*, and the measurement endpoint is *catch of legal-sized sportfish per standard unit effort*. Lakes are also valued for swimming, aesthetics, and drinking water supply. Each of these attributes is affected by the lake's trophic status. Thus, *trophic status* has been identified as a major measurement endpoint for surface waters. Trophic status may also be used as an assessment endpoint if the trophic status of the ecological resource is the actual attribute of concern (e.g., oligotrophic high-altitude lakes).

2.3.2 Indicators within EMAP

A major use of indicators in EMAP will be to assess the condition, or health, of ecological resources. Rapport (1989) lists three approaches or criteria commonly used to assess ecosystem health: (1) identification of systematic indicators of ecosystem functional and structural integrity, (2) measurement of ecological sustainability or resiliency (i.e., the ability of the system to handle stress loadings, either natural or anthropogenic), and (3) an absence of detectable symptoms of ecosystem disease or stress. Thus, ecological health is defined as both the occurrence of certain attributes deemed to be present in a healthy sustainable resource and the absence of conditions that result from known stressors or problems affecting the resource.

An objective of EMAP monitoring is to determine the proportion of the resource in good condition or, by human analogy, healthy, as opposed to ecosystems that are unhealthy, or in poor condition. To avoid semantic problems that could arise from using words such as good or acceptable, the terms nominal, subnominal, and marginal have been adopted to refer to healthy and unhealthy conditions and the transition between these conditions, respectively. Ongoing investigations within the scientific community and EPA are addressing ways to better measure and express ecosystem condition.

A key element of EMAP's approach is the linkage of indicators to assessment endpoints. Important information about assessment endpoints falls into one of the following categories: (1) condition of the ecosystem, (2) exposure of the endpoint to potential stressors, and (3) availability of conditions necessary to support the desired state of the endpoint. To provide appropriate linkage between assessment endpoints and indicators, indicator development in EMAP will produce indicators that fall into one of four types (Hunsaker and Carpenter, 1990):

1. **Response indicators** represent characteristics of the environment measured to provide evidence of the biological condition of a resource at the organism, population, community, ecosystem, or landscape level of organization.

2. **Exposure indicators** provide evidence of the occurrence or magnitude of contact of an ecological resource with a physical, chemical, or biological stressor.

3. **Habitat indicators** are physical, chemical, or biological attributes measured to characterize conditions necessary to support an organism, population, community, or ecosystem (e.g., availability of snags; substrate of stream bottom; vegetation type, extent, and spatial pattern).

4. **Stressor indicators** are natural processes, environmental hazards, or management actions that effect changes in exposure and habitat (e.g., climate fluctuations, pollutant releases, species introductions). Information on stressors will often be measured and monitored by programs other than EMAP.

Potential indicators are identified using conceptual models of ecosystems, followed by systematic evaluation and testing to ensure their linkages to the assessment endpoints and their applicability within EMAP, as described in Section 4. The models used may be based either on current understanding of the effects of stresses on ecosystems or on the structural, functional, and recuperative features of healthy ecosystems.

2.3.3 Indicator Utilization

The evaluation of ecosystem condition will not rely on any single indicator, but on the full set of monitored response, exposure, habitat, and stressor indicators. One approach to using complete sets of indicator information is the development of formal indices that composite or aggregate more than one indicator into a single variable. For example, Karr et al. (1986) developed the Index of Biotic Integrity (IBI) to describe conditions in freshwater streams. Properly developed, indices of ecosystem condition can more easily be compared across regions than can the measurements from which they are derived (e.g., Hughes, 1989). However, the process of indicator aggregation can be highly controversial and mathematically complex; the results tend to be extremely dependent on the indicators and the aggregation procedures used (Westman, 1985). The utility of indices for EMAP assessments of ecosystem condition is an important concept for further investigation in the indicator development activities of each ecological resource group.

In addition to knowing resource condition, it is also desirable to identify plausible causes of degrading conditions. EMAP monitoring data will be used to examine the statistical association, on a regional scale, between ecosystem conditions and plausible causes of these conditions, using stressor, exposure, and habitat indicator data. Although these correlative analyses cannot establish causality, they do serve to narrow the range of probable causes for observed regional patterns and trends in resource status. More detailed monitoring and research efforts to determine cause-and-effect relationships (e.g., activities in Tiers 3 and 4) can then be focused on those geographical areas, stressors, and resource classes of greatest concern.

Interest in the use of indicators and indices extends beyond EMAP. Ott (1978) identified six basic uses of environmental indices of ecosystem health:

1. Prioritizing funding for dealing with environmental problems
2. Ranking locations (regional comparisons)
3. Conducting environmental trend analysis
4. Providing public information
5. Condensing and focusing scientific research
6. Enforcing standards

The National Academy of Sciences (1975) also highlighted the need for ecological indicators to monitor the environment (ecosystem health) and to judge the effectiveness of environmental protection programs. Research programs evaluating the extent and magnitude of effects from specific stressors (e.g., ozone effects on crop production, pesticide effects on nontarget plants and animals, acidic deposition effects on terrestrial and aquatic communities) often rely extensively on indicators. Finally, it is expected that ecological indicators will become increasingly useful in investigations into the effectiveness of alternative environmental management policies.

Further information on the use and interpretation of indicators within EMAP is provided within Hunsaker and Carpenter (1990).

3. FRAMEWORK FOR INDICATOR DEVELOPMENT

Indicators in EMAP must be developed by using a consistent strategy across ecological resource groups, completeness in the overall set of indicators (so that significant ecological changes on regional scales do not escape detection), and creativity in the program over time (so that the program can evolve to accommodate new knowledge). Strategic planning of indicator development must occur both within and among EMAP resource groups. These perspectives are addressed in the following two sections.

3.1 GENERAL STRATEGY FOR AN EMAP RESOURCE GROUP

This section provides an overview of the general strategy of indicator development for an ecological resource group; the strategy is considered in much greater detail in Section 4. Figure 3-1, an expansion of Figure 2-7 in the EMAP Indicators Report (Hunsaker and Carpenter, 1990), summarizes the steps each EMAP resource group must complete to advance its indicators to the point of regional and national implementation in EMAP. As shown in Figure 3-1, the overall process of indicator development within each EMAP resource group consists of six phases:

1. Phase 1: Identify environmental values, apparent stressors, and assessment endpoints.
2. Phase 2: Develop a set of candidate indicators that are linked to the identified endpoints and are expected to be responsive to stressors.
3. Phase 3: Screen the candidate indicators to identify those with reasonably well established data bases, methods, and responsiveness to be further evaluated as research indicators.
4. Phase 4: Quantify the expected performance of research indicators to identify probationary core indicators.
5. Phase 5: Quantify the performance of probationary core indicators on a regional scale to select core indicators.
6. Phase 6: Reevaluate and modify the set of core indicators.

Although this strategy has been written to address the development of individual indicators, it should also be used by each resource group to assess its full suite of indicators. Often multiple indicators may be under development at the same time. The objective of this process is to develop a comprehensive suite of indicators that complement each other and provide a clear picture of the status and trends of ecological resource condition through time. It is also anticipated that, due to limited financial or human resources, time, or scientific knowledge, an ecological resource group may concurrently be developing multiple indicators through different phases of this process, and at the same time may have suspended evaluation of other indicators until additional time, money, or knowledge becomes available.

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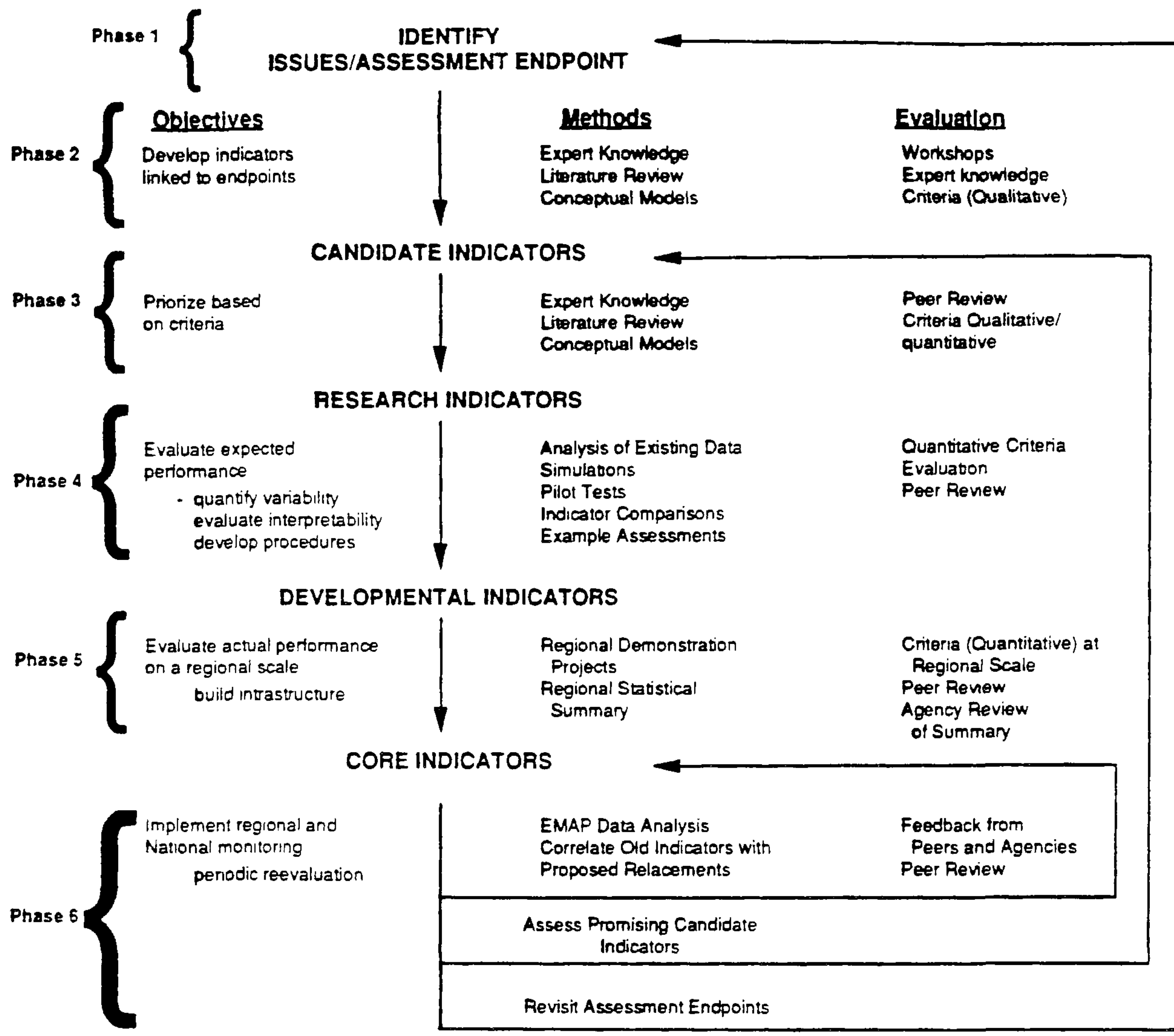

Figure 3-1. The indicator development process, showing the objectives, methods, and evaluation techniques used in each phase.

Each EMAP resource group's indicator program will be kept on track through the use of research plans, peer reviews, and interaction with other resource groups. Each EMAP resource group will produce research and monitoring plans that will be subject to written peer review. These plans will describe the evidence and rationale for all decisions made within each phase, identify the specific types of information needed to complete the evaluation of indicators being considered under each of the phases, and present the next year's research plans for each phase. Annually, the current status of all indicators and rationale for all decisions made during each phase will be documented in an indicator data base (described in Appendix A). This data base will be used to facilitate rapid review of both the current state and the evolution of all indicators used by each of the ecological resource groups.

In addition to annual peer reviews of program status and progress, every five years a peer review workshop will be held to examine each ecological resource group's comprehensive five-year research and monitoring plans. These plans will describe EMAP's results to date, outline future directions and promising new indicators, and provide research plans for each of the six indicator development phases.

The first two phases of the indicator development process are meant to generate ideas for endpoints and indicators. The processes used in these phases should therefore encourage broad-scale, lateral thinking, with the focus on breadth rather than depth of coverage.

Phase 1 (identifying environmental values, potential stressors, and assessment endpoints) requires a broad perspective on both desired ecosystem attributes (as expressed by resource managers, scientists, private industry, legislators, and the general public) and ecosystem stresses (which may occur on local to global spatial scales, and over short- to long-term temporal scales). Proper identification of assessment endpoints also requires well-developed conceptual models of the ecosystems of concern, to ensure that identified endpoints are connected to the current and anticipated stresses of concern. Developing these models is one of he most important aspects of the indicator development process, and may be one of the most difficult. The process of developing these models, and the considerations that each model must address (e.g., the degree of quantification required, whether the models focus primarily on ecosystems structure or on processes), are the responsibilities of each of the EMAP resource groups. A summary of the environmental values initially identified by the different EMAP ecological resource groups (Table 3-1), shows a strong overlap, reflecting commonality in the perceptions of key issues among these groups. This commonality highlights the need for integration and coordination among the ecological resource groups to ensure that all important information is collected efficiently, as discussed in Sections 5 and 6, respectively.

Phase 2 (identifying candidate indicators) similarly requires a broad sampling of scientific opinion, through both detailed literature reviews and interactions with scientists conducting relevant research.

Table 3-1. **Environmental Values Selected by Different EMAP Resource Groups[a]**

EMAP Resource Group	Environmental Values
Estuaries	Ability to support harvestable and contaminant-free fish, maintenance of habitat structure, aesthetics
Surface waters	Fishability, biological integrity, trophic condition
Wetlands	Area of wetlands, water quality functions, water quantity (hydrologic) functions, ecological support for aquatic and terrestrial organisms
Forests	Spatial extent, sustainability, productively, aesthetics, biodiversity
Arid lands	Sustainability, productivity, biodiversity, water balance
Agroecosystems	Productivity, sustainability, biodiversity, contamination
Great Lakes	Fishability, water quality, trophic conditions

[a] These values direct the selection of assessment endpoints and response indicators; in some cases they are synonymous (after Hunsaker and Carpenter 1990).

This is a continuing process, as scientific and technological advances will generate new candidate indicators, or improve the feasibility of previously rejected indicators (see return arrows in Figure 3-1). In identifying candidate indicators, it is useful to consider various components of ecosystem health (e.g., species composition, physical structure, and ecological function) and various levels of biological organization (e.g., landscape, ecosystem, community, population, or individual). As in the previous phase, each ecological resource group should use one or more explicit conceptual models linking appropriate response indicators and stressor information with assessment endpoints. Conceptual models should serve as reference points, both for identifying needed indicators for assessing ecological resource condition, and for guiding data analyses and pilot tests during later phases.

The next three phases of the indicator development process provide critical evaluation and iterative filtering of the set of candidate indicators to obtain a defensible, practical set of core indicators. Whereas Phases 1 and 2 are designed to include all possible relevant indicators, the next three phases are designed to systematically eliminate indicators that fail to satisfy specific criteria for adoption, that are not amenable to complete evaluation, or that do not perform as well as alternative indicators of the same resource conditions.

The process of testing and prioritization is guided by a set of criteria for indicator selection and peer reviews of the decisions and by research plans made in each phase. Indicator selection criteria were developed through workshop discussions with all EMAP ecological resource groups using the criteria presented in the EMAP Indicators Report (Hunsaker and Carpenter, 1990) as a starting point. These criteria are described in detail in Section 4.3; they cover issues such as responsiveness, appropriateness for regional application, ability to integrate effects, quantifiable spatial and temporal variation, interpretability, and cost effectiveness. The evidence and rationale needed to satisfy the indicator selection criteria and the peer review process that oversees these decisions become more stringent with each phase. For example, evidence from the literature regarding responsiveness along laboratory or field exposure gradients is sufficient at the research stage, but quantitative evidence of responsiveness in most of a region's habitats is required before the indicator can be accepted as developmental. Also, the emphasis of the criteria shifts from concerns about the indicator's responsiveness, to issues relating to the feasibility of sampling the indicator using the EMAP integrated monitoring design. During any of these phases, evaluation of a specific indicator may be suspended due to insufficient data or technology for evaluation, or an indicator may be either accepted or rejected for the next phase of evaluation or implementation.

Phase 3 (selecting research indicators) relies on literature review and expert knowledge (e.g., workshops) to provide further qualitative evaluations and to initiate quantitative indicator assessments. Quantitative assessments in this phase should focus on whether or not adequate information exists (or can be readily obtained) to assess the likelihood that candidate indicators will be able to satisfy the indicator selection criteria, and to begin evaluating the expected responsiveness of the candidate indicators to changes in the assessment endpoints. Key considerations at this stage are whether or not: (1) the indicator can be measured effectively using an index sample, and (2) there is strong spatial and temporal evidence of the responsiveness of the indicator, in monitoring an identified assessment endpoint. The primary product of this phase is the set of research indicators for evaluation in Phase 4. All decisions are documented in the indicator data base and the annual research plan.

In Phase 4 (selecting probationary core indicators), the selection criteria are applied more stringently to quantitatively address questions concerning spatial and temporal variability, data interpretability (in regard to EMAP's objectives to monitor status and detect trends and associations), and proposed methods. Satisfying the criteria quantitatively will require more intensive analysis than was provided in previous phases. Such analyses may require a variety of activities, such as (1) intensive searches for useful (often unpublished) data bases, (2) analyses of these data, (3) simulations to determine minimum detectable trends, preferred index periods, ability to track sensitive subpopulations, etc., (4) example assessments to evaluate the utility of the complete suite of indicators, and (5) field studies to test and evaluate indicators across a suite of regional habitats (pilot studies). All results and decisions will be documented in periodically updated research plans and annually in the indicator data base. The primary product of this phase is the set of probationary core indicators.

Phase 5 (identifying core indicators) addresses issues that can be answered only by testing the probationary core indicators using the EMAP integrated sampling design and data analysis protocols at regional scales. Regional demonstrations will be used to test whether or not data collected on these indicators are regionally interpretable and to confirm the results of site-specific pilot studies on regional scales. Data from regional demonstration projects will be assessed through peer, agency, and public review of statistical summaries, associated interpretive reports, and special study reports. The primary product of this phase is a set of core indicators for implementation in routine EMAP monitoring efforts.

Phase 6 (reevaluating and modifying the suite of core indicators) is an ongoing process that begins upon initial implementation of core indicator monitoring at regional and national spatial scales. This continual process of reinspecting the indicator suite ensures completeness of indicator coverage of important environmental values, assessment endpoints, and stressors; incorporation of appropriate advances in technology and information; and adequate ability to detect changes and identify trends in the status of ecological resources. In this phase, it is important that EMAP balance continuity of methods (to maximize trend detection capability) with procedures for refining or replacing indicators that fail to perform optimally. This phase is implemented through procedures designed to critically review the performance of core indicators through time, evaluating alternative indicators to address emerging issues and inadequate core indicator performance, adding new indicators as deemed desirable, and substituting superior indicators for inadequate core indicators.

3.2 INTERGROUP INTEGRATION

Integration both among EMAP resource groups and between EMAP and other state and federal agencies is critical to the success of EMAP. Organizationally, the responsibilities and authorities of individuals involved in these integrative activities rest with management personnel in the EMAP resource groups and with the Indicator Coordinator. Many line-of-responsibility issues remain to be resolved for these individuals. However, the primary concerns related to internal and external integration are discussed in the following sections.

3.2.1 Internal Integration

At present, individual EMAP resource groups have the primary responsibility for implementing the indicator development process. However, to fully achieve EMAP's goals will require integration and coordination of these activities across EMAP resource groups. Important issues to be addressed include (1) consistency in the definition and use of response, exposure, habitat, and stressor indicators, (2) consistency in collecting and applying off-frame stressor information, (3) inclusion of special indicators within EMAP that integrate across EMAP resource groups (e.g., migrating birds), (4) encouraging the use of common indicators and compatible sampling and analysis methods, and (5) co-locating sampling units for special studies. Thus, it is essential that all EMAP resource groups formally communicate on a regular basis to facilitate intergroup information exchange, avoid redundant data collection efforts, and improve the amount of information available for each EMAP resource group to use in assessing status and trends in ecological resource condition. In addition, because the EMAP resource groups proceed at different rates in implementing their programs, intergroup integration to foster learning will improve the efficiency and effectiveness of the overall program. Section 5 provides a detailed discussion of the proposed process and approach for achieving an integrated EMAP indicator development program.

3.2.2. External Integration

The Science Advisory Board's Ecological Monitoring Subcommittee recently stressed the importance of interagency coordination and integration to the success of EMAP (U.S. EPA Science Advisory Board, 1990). Although integrating results from other monitoring efforts into EMAP is both efficient and essential, interagency cooperation should also include information and expertise sharing. For example, in addition to valuable data that can be obtained from the USDA Forest Service's Forest Inventory and Analysis program, Forest Service personnel can be active participants in the indicator development process for EMAP-Forests. Similarly, the National Oceanic and Atmospheric Administration (NOAA) and numerous other federal agencies can contribute to the indicator development efforts of EMAP resource groups.

Formal arrangements will be established by EMAP resource groups as necessary, to assist the indicator development process and ensure that EMAP develops appropriate tools to monitor the condition of ecological resources. For example, it may be appropriate for EMAP resource groups to obtain indicator information from sources that could include state agencies (e.g., for regional resource management actions), other federal agencies (e.g., USDA for soil erosion rates and crop production data), and other EPA programs (e.g., Office of Water for pollutant discharge information).

4. INDICATOR DEVELOPMENT PROCESS

The following pages describe in detail the phases of the indicator development process outlined in Section 3.1 and Figure 3-1. Sections 4.1 and 4.2 describe Phase 1, identification of environmental values, assessment endpoints, and major stressors (Section 4.1), and development of conceptual models (Section 4.2). The criteria for indicator selection are listed in Section 4.3, and then applied as the indicator proceeds from the candidate to the core stage in Phases 2 through 5 (Sections 4.4-4.7). Finally, issues and procedures for indicator reevaluation and modification (Phase 6) are discussed in Section 4.8.

The objective of this section is *to define a common framework within which indicator development* will proceed in each ecological resource group. This framework will be fostered in all EMAP resource groups through the activities of the Indicator Coordinator (see Section 6), who will provide training and otherwise facilitate the use of this strategy in developing indicators. It is not necessary that all indicators for a single EMAP resource group proceed through this development process at the same rate, nor is it necessary for all EMAP resource groups to proceed at the same rate in developing indicators.

4.1 PHASE 1: IDENTIFICATION OF ENVIRONMENTAL VALUES AND ASSESSMENT ENDPOINTS

It is critical to the success of EMAP that the environmental attributes monitored are appropriate to the program's objectives, defined in Section 2.1.2. The first phase of the indicator development process, therefore, is intended to establish a framework for indicator interpretation, by identifying the environmental values, assessment endpoints, critical ecosystem components and processes and environmental stressors of primary concern for each EMAP resource group. This phase defines the boundaries of the problem, the functional relationships among indicators and assessment endpoints, and stressor inputs for the conceptual model (Section 4.2), and thus the basis for indicator selection and evaluation.

4.1.1 Environmental Values

Ecological resources have both intrinsic and extrinsic values, ranging from the societal value placed on the protection of pristine ecosystems to more direct economic values derived from resource harvests, such as agricultural and timber production and commercial fisheries, and to inherently ecological values or characteristics that are necessary for ecosystem function, such as nutrient cycling and population reproduction rates. Results from the EMAP monitoring network will be used to track changes in the condition of the nation's ecological resources. A logical first step, therefore, is to develop a listing of the major environmental values associated with each EMAP resource category. Forest ecosystems, for example, are of value for timber production, wildlife habitat, water storage, erosion control, and aesthetics. Wetland ecosystems may moderate downstream flooding, improve water quality, control erosion, and provide breeding, shelter, and feeding habitat for both aquatic and terrestrial organisms. A preliminary listing of the environmental values identified by each EMAP resource group is provided in Table 3-1.

4.1.2 Assessment Endpoints

Assessment endpoints are quantitative or quantifiable expressions of environmental values (see Section 2.3). In some cases, the assessment endpoints may be identical to the environmental values; for example, sustainable crop production is both an environmental value and an assessment endpoint for agroecosystems. It not only expresses an important societal value associated with agricultural lands, but can also be quantified. In other cases, environmental values may not be amenable to quantitative assessment (e.g., aesthetics). In these instances, one or more distinct assessment endpoints must be defined that are related to the environmental value but more amenable to prediction or measurement. For example, the abundance of harvestable sportfish may be an appropriate assessment endpoint for evaluating fishability, an important environmental value for surface waters.

Suter (1990) lists five characteristics of good ecological assessment endpoints:

1. Social relevance
2. Biological relevance
3. Unambiguous operational definition
4. Accessibility to prediction and measurement
5. Susceptible to the environmental stressors of concern (and those that are unknown)

In addition, an assessment endpoint should be susceptible to the cumulative effects of complexes of stressors, including both currently known and unknown stressors, (James R. Karr, pers. comm.). A complete operational definition of an endpoint requires both a subject (e.g., bald eagles or endangered species in general) and a characteristic of the subject (e.g., local extinction or a percentage reduction in range). Examples of potential regional assessment endpoint characteristics are noted in Table 4-1.

4.1.3 Response Indicators

EMAP response indicators must correspond to or be predictive of an assessment endpoint. Indicators, however, must be directly measurable, on the EMAP monitoring network. It is possible, as with agro-ecosystem production, that the response indicator directly measures either the assessment endpoint or a specific portion of it; or the assessment endpoint and indicator may be equivalent. Often, however,

Table 4-1. Examples of Potential Assessment Endpoints[a]

Traditional

- Population
  - Extinction
  - Abundance
  - Yield/production
  - Frequent gross morbidity
  - Contamination
  - Massive mortality
- Community
  - Market/sport value
  - Recreational quality
  - Change to less useful/desired type
- Abiotic
  - Air and water quality standards

Characteristics of Regions

- Population/species
  - Range
- Productive capability
  - Soil loss
  - Nutrient loss
  - Regional production
- Pollution to other regions
  - Pollution of discharged water
  - Pollution of outgoing exported air
- Susceptibility
  - Pest outbreaks
  - Fire
  - Flood
  - Low flows
- Landscape aesthetics
- Long-term climate changes
  - Continental glaciation
  - Sea level rise
  - Drought
  - Increased UV radiation

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[a] From Suter (1990). A complete operational definition of an assessment endpoint requires both a subject (e.g., bald eagles) and a characteristic of that subject, such as the variables listed. Assessment endpoints can represent either ecosystem elements (e.g., grassland species composition) or processes (e.g., germination rates).

the assessment endpoint cannot be directly measured and multiple response indicators may need to be monitored to estimate or evaluate changes in the assessment endpoint. Examples of the linkages between environmental values, assessment endpoints, and response indicators are simplistically portrayed in Figure 4-1. Table 4-2 illustrates the association between EMAP-Agroecosystem assessment goals and indicators.

4.1.4 Stressors

In addition to monitoring status and trends of ecological condition, the EMAP data also will be used for diagnostics, to identify plausible causes of adverse or subnominal conditions. Together with stressor information, exposure and habitat indicators provide the basis for linking plausible causes to observed effects. The starting point for assembling stressor information, in Phase 1, is the listing of the major problems currently impacting or threatening the resource and the possible associated stressors. For example, EMAP-Arid Lands has identified the following as some of the major environmental problems of concern: (1) loss of riparian habitat, (2) over-grazing and the introduction of exotic species, (3) increased fire frequency and effects of global warming, and (4) the reduction of water supplies. EMAP-Estuaries noted the following stressors: (1) additions of excessive amounts of pollutants to the air and water, (2) modification and destruction of ecologically important habitats, such as wetlands and forested areas along the shoreline, (3) changes in land use that increase the amount and types of pollutants that reach coastal environments, and (4) over-harvesting of fish and shellfish populations. Explicitly defining potential stressors serves to increase the relevance of the selected response indicators to current and future environmental concerns.

Most of the data on stressors will not be collected by EMAP (i.e., off-frame data collected by other programs). Listing potential stressors, and placing them in context with response, exposure, and habitat indicators, is the first step in allocating efforts to acquire and organize off-frame data.

Lists of environmental values, assessment endpoints, and major stressors are not static, but rather must be periodically reevaluated as new issues emerge, environmental values shift, and experience is gained with the use and interpretation of EMAP monitoring data. In addition, unforeseen stressors may begin to operate on ecological resources, or ecosystem relationships may change. Either of these circumstances could require alterations to the suite of indicators in order for monitoring of changes in the status and trends in resource condition to continue.

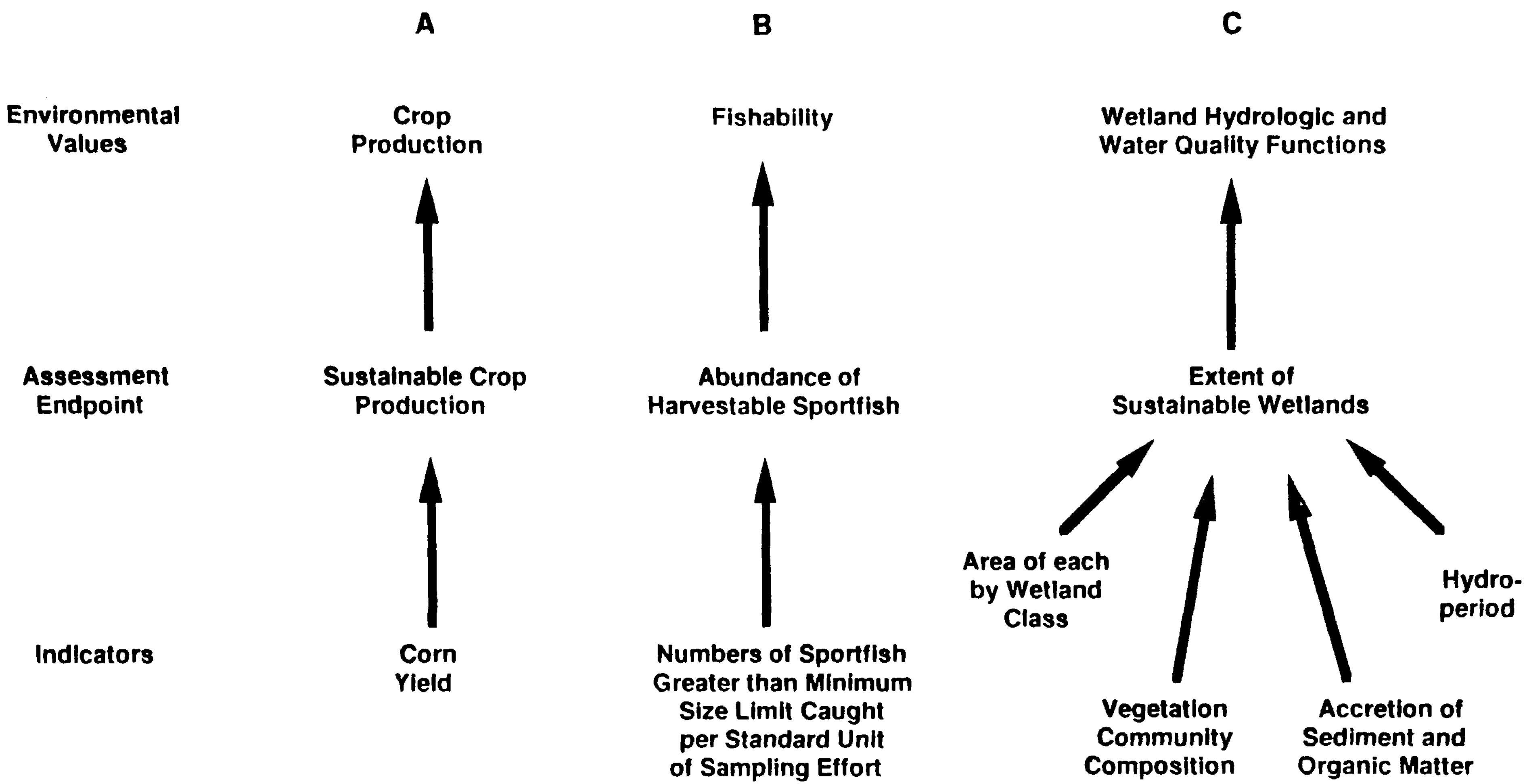


Figure 4-1. **Example of relationships among environmental values, assessment endpoints, and indicators. Column A represents a situation where an indicator directly measures a portion of the assessment endpoint and environmental value of concern. Column B demonstrates a direct relationship between a single indicator and its associated assessment endpoint and environmental value, which cannot be directly measured. Column C depicts a situation where multiple indicators are required to provide needed information about the assessment endpoint and environmental value of concern.**

Table 4-2. Association between EMAP-Agroecosystem Assessment Endpoints and Indicators[a]

INDICATORS	ASSESSMENT ENDPOINTS: Sustainability of Commodity Production	Contamination of Natural Resources	Quality of the Agricultural Landscape
Crop productivity	X		
Soil productivity	X	X	
Nutrient holding capability	X		
Erosion	X	X	
Contaminants	X	X	
Microbial component	X	X	
Irrigation water quantity	X		
Irrigation water quality	X	X	
Density of beneficial insects	X		
Pest density	X		
Foliar symptoms	X	X	
Agricultural chemical usage	X	X	
Socio-economic factors	X		X
Exports (chemical, sediment)		X	
Status of biomonitor species		X	X
Land use			X
Landscape descriptors			X
Wildlife populations			X

a After Meyer et al. (1990)

4.2 CONCEPTUAL MODELS

Conceptual models define the linkages between assessment endpoints, stressors, and important ecosystem components and processes. The delineation of the conceptual model for each resource class is an essential part of the indicator development process. The model serves four primary purposes:

1. To explicitly define the framework for indicator interpretation, for example, how the response indicators relate to the assessment endpoints, the role that they play in determining endpoint status, and how they will be used to assess that status.

2. To identify any gaps within the proposed set of indicators, that is, missing indicators for the assessment endpoints or links for which additional or new indicators are needed.

3. To guide the data analysis strategy for diagnosing plausible causes of subnominal conditions.
4. To promote an integrated program and facilitate coordination among EMAP resource groups.

Indicators used in EMAP must be linked to ecosystem resources through conceptual models. These models are important representations of scientific understanding of the ecological resource for monitoring purposes. They must be descriptive and should clearly demonstrate linkages between the indicators and the environmental values being monitored. Developing conceptual models is not a simple task, nor can models be extracted from the literature for all the ecological resources of concern. Furthermore, the temporal and spatial scales of these models can prejudice monitoring results (Wiens, 1989). Developing such models, however, is an extremely important exercise that is required to substantiate the choice of a particular indicator. For example, *annual wood increment* can be linked directly to forest productivity and can be incorporated into a conceptual model. Data can be readily obtained at the temporal scale appropriate to EMAP. On the other hand, *soil microbial respiration* is more difficult to link to forest productivity, and is fraught with interpretation problems at the temporal and spatial scales.

Conceptual models can be constructed at many scales, ranging from simple, single-linkage models (e.g., Figure 4-2) to complex ecosystem models identifying the full complement of ecosystem functional and structural attributes. Each of these approaches may be useful, and should be developed or reviewed as appropriate by individual resource groups. However, the critical EMAP conceptual model for indicator development is of intermediate complexity, and focuses on indicators and the relationships among indicators, and between indicators, assessment endpoints, and external stressors. An example of such a model developed for the estuarine environment is provided in Figure 4-3.

Like the lists of values, endpoints, and stressors, the conceptual model linking these components should not be viewed as static. The utility, validity, and completeness of the model should be continually reevaluated as part of the data interpretation process. Both the lists of issues and assessment endpoints described in Section 4.1 and the conceptual models should be subject to external comment and review in the workshops conducted and the research plans prepared during Phases 2 and 3 (identification of candidate and research indicators).

4.3 CRITERIA FOR INDICATOR SELECTION

The identification of environmental values and assessment endpoints represents only the first of six phases of indicator evolution, as detailed in Figure 3-1. Four succeeding phases of indicator development and evaluation will occur before indicator implementation in the full-scale EMAP program:

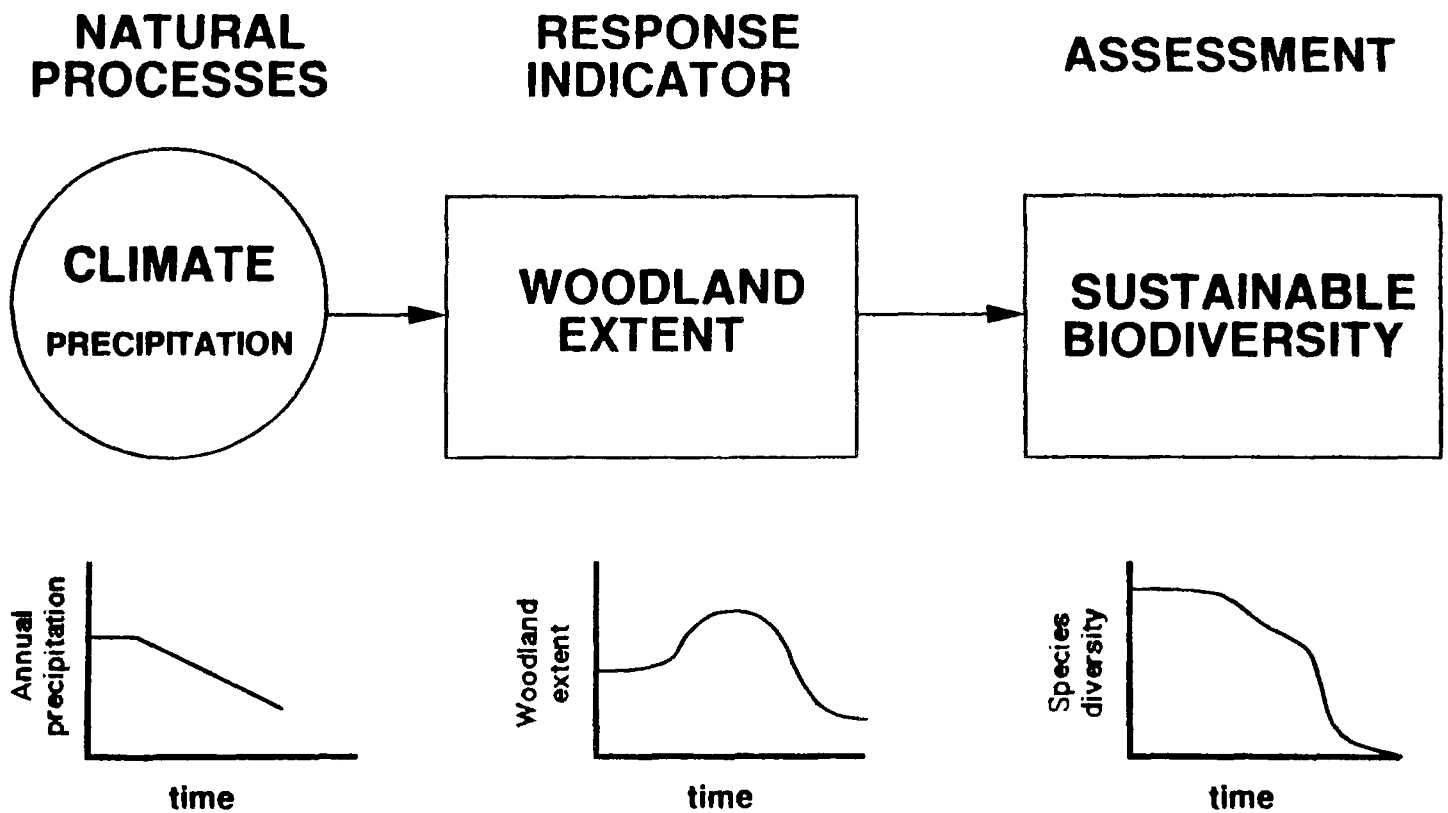


Figure 4-2. General conceptual model linking a response indicator (woodland extent) with the environmental value of sustainable biodiversity. Data from the literature suggest that if climate changes and precipitation decreases, the woodland will initially expand its range and out-compete other vegetation types, then decline. The result will be a decline in both habitat type and species number, thus decreasing the biological diversity of the region.

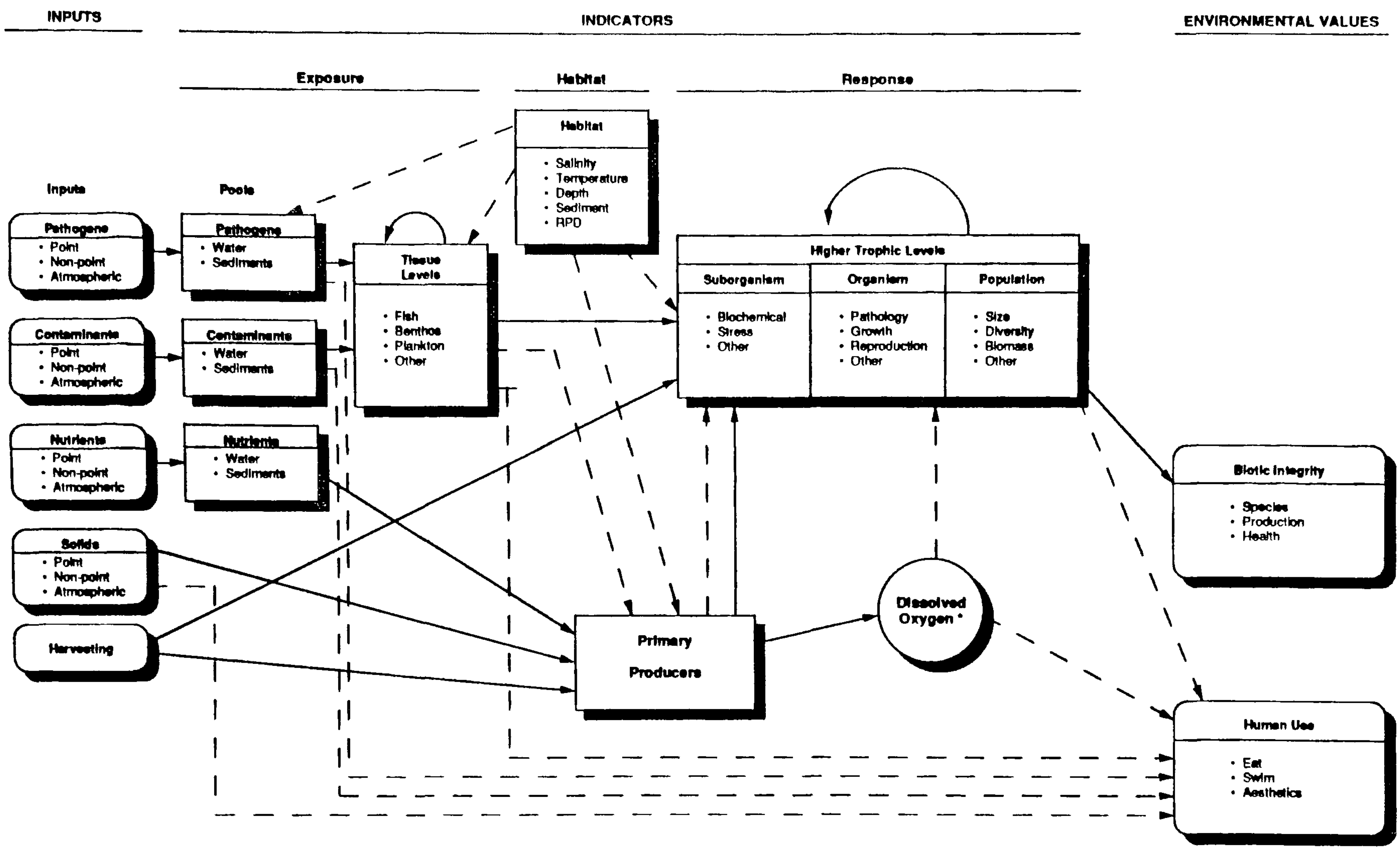


Figure 4-3. **Conceptual model of the estuarine ecosystem. Solid lines indicate material flows and dashed lines indicate interaction. Dissolved oxygen can be considered both an exposure and a response indicator.**

1. Phase 2: identification of a set of **candidate** indicators
2. Phase 3: selection of indicators for further **research**
3. Phase 4: evaluation of **research** indicators
4. Phase 5: selection of **core** indicators

Once the full-scale EMAP program is in place, reevaluation of the core indicators (Phase 6) will be an ongoing process intended to periodically confirm the appropriateness of each indicator, and to modify, add, or replace indicators as necessary.

For the indicator selection process to be scientifically defensible, each ecological resource group must use a consistent evaluation procedure, employ specific criteria to judge each proposed indicator, and document each step in the evaluation process. This section outlines the criteria that will be used throughout EMAP to guide the evaluation and selection of indicators. Details on the application of these criteria at each phase in the indicator development process are provided in Sections 4.4-4.7.

Each phase in the evaluation of an indicator involves two stages: (1) an assessment of the sufficiency of the available data to support an evaluation of the indicator and (2) if sufficient data exist, a screening of the indicator based on the selection criteria. This screening results in one of three outcomes: (1) acceptance for consideration at the next stage of evaluation or implementation, (2) temporary suspension of consideration due to insufficient data, technology, time or resources for proper evaluation, or (3) rejection for failure to satisfy one or more of the selection criteria. The latter two outcomes may lead to new approaches to collecting, synthesizing, and analyzing data.

As discussed in the following sections, both the focus and the level of scrutiny given to each indicator during evaluation change with each evaluation phase. This affects the assessment of the quality and quantity of data needed for indicator evaluation and the standards applied in indicator screening. It is likely that many candidate indicators will end up in a state of suspended evaluation, to be revived at some future date when evidence, time, and resources are sufficient to thoroughly evaluate them. Generally, a candidate indicator will be rejected only if it fails certain critical criteria and there is no anticipated improvement in the indicator's weaknesses over the next decade. In contrast, in the Phase 5 evaluation, it is likely that a much higher proportion of indicators will either advance or be rejected, rather than being suspended, because sufficient data on regional responsiveness and feasibility will be available to make a firm decision. The results of all data sufficiency and screening evaluations are to be recorded in an indicator data base, described in detail in Sections 4.4-4.7.

4.3.1 Purpose of Indicator Selection Criteria

The use of clearly defined criteria increases the objectivity, consistency, and depth of indicator evaluations. Criteria also guide scientists in developing new indicators and facilitate the documentation of indicator screening decisions. Although certain decisions made in the evaluation process will be subjective, the goal of the selection procedure is to provide an appropriate amount of information at each step of the evaluation, so that another, independent evaluation, by peer reviewers, for example, would be able to quickly assess the validity of the original decisions. A record of the decision process also simplifies the subsequent identification of additional information needed to complete the evaluation of suspended indicators.

4.3.2 Indicator Selection Criteria

The indicator selection criteria, listed in Table 4-3, consist of sets of critical and desirable criteria that should be used by EMAP resource groups to test for acceptance or rejection of potential indicators. Specific tests will be developed by each resource group in a manner that is appropriate for the indicators under consideration. Table 4-3 is based on discussions by EMAP scientists at the Indicator Strategy Workshop (June 1990), and subsequent efforts by the authors of this report, to simplify the initial set of criteria developed in Messer (1990).

In general, the critical criteria are those considered essential for satisfying EMAP's first two objectives. The first two critical criteria (regional responsiveness and unambiguous interpretability) should be the dominant focus of evaluations in Phases 2 and 3, which lead to the selection of research indicators. Though these two criteria continue to be important in the evaluation of subsequent phases, other critical criteria relating to the utility and feasibility of sampling the indicator within EMAP (index period stability, simple quantification, low year-to-year variation, environmental impact) rise in importance.

Indicators that fulfill some or all of the desirable criteria have obvious advantages over those that do not. These advantages may include an improved assessment of associations between stresses and ecological conditions (the second objective of EMAP), an increased timespan over which the indicator can be quantified, higher information value per unit cost, greater ease of implementation, or special value for early detection of widespread ecological changes. The desirable criteria should be applied to assist in distinguishing among alternative indicators for the same assessment endpoint, or to assist in obtaining the best set of indicators if all desirable indicators cannot be developed for implementation (e.g., due to funding constraints).

Table 4-3. Indicator Selection Criteria

	Critical Criteria
Regionally responsive	Must reflect changes in ecological condition, pollutant exposure, or habitat condition, and respond to stressors across most pertinent habitats within a regional resource class.
Unambiguously interpretable	Must be related unambiguously to an assessment endpoint or relevant exposure or habitat variable that forms part of the ecological resource group's overall conceptual model of ecological structure and function.
Simple quantification	Can be quantified by synoptic monitoring or by cost-effective automated monitoring.
Index period stability	Exhibits low measurement error and stability (low temporal variation) during an index period.
High signal-to-noise ratio	Must have sufficiently high signal strength (when compared to natural annual or seasonal variation) to allow detection of ecologically significant changes within a reasonable time frame.
Environmental impact	Sampling must produce minimal environmental impact.
	Desirable Criteria
Sampling unit stable	Measurements of an indicator taken at a sampling unit (site) should be stable over the course of the index period (to conduct associations).
Available method	Should have a generally accepted, standardized measurement method that can be applied on a regional scale.
Historical record	Has an existing historical data base or one can be generated from accessible data sources.
Retrospective	Can be related to past conditions by way of retrospective analyses.
Anticipatory	Provides an early warning of widespread changes in ecological condition or processes.
Cost effective	Has low incremental cost relative to its information.
New information	Provides new information; does not merely duplicate data already collected by cooperating agencies.

The amount, quantification, and quality of data necessary to satisfy each of the critical criteria increase at each stage. During the evaluation of candidate indicators, it is not critical to satisfy each criterion completely; rather, there should be reason to believe that the criterion can be satisfied when the appropriate data and models for detailed analyses are assembled in later stages of the evaluation process. The unavailability of detailed, extensive data bases and models should not result in the rejection of a candidate or research indicator. By Phase 5, there must be strong evidence demonstrating that the indicator fulfills each of the critical criteria and preferably some of the desirable criteria. Examples and further specifics on the application of the indicator selection criteria at each phase of the indicator development process are presented in the following sections.

4.4 PHASE 2: IDENTIFICATION OF CANDIDATE INDICATORS

4.4.1 Objectives

The identification of candidate indicators (Phase 2 of the indicator development process shown in Figure 3-1) provides the raw material for the subsequent phases of indicator screening and refinement. Candidate indicators include all the potential measures of ecological condition (response indicators) and the natural or anthropogenic factors that could influence that condition (exposure and habitat indicators). Identifying candidate indicators calls for scientifically well-grounded creative thinking, review, and evaluation of published literature, and investigation of available data to prepare lists of potentially useful indicators. Although discrimination among potential indicators at this stage may be appropriate in some cases, it will usually be better to err on the side of listing too many candidate indicators than to overlook a potentially useful indicator.

Identification of candidate indicators is an ongoing process that must be documented. It is necessary for each EMAP resource group to continually reassess its suite of indicators for completeness, to reassess indicators previously rejected or suspended pending new findings, and to identify additional potentially useful candidate indicators. Newly developed indicators may either augment or substitute for existing indicators. New candidate indicators serve to capture advances in environmental sciences and monitoring technologies (e.g., new methods of remote sensing), as well as to consolidate insights gained through analysis of data collected by EMAP and other research programs.

The EMAP resource groups made preliminary identifications of numerous candidate indicators and have conducted initial assessments of them, as summarized in Hunsaker and Carpenter (1990). These groups have progressed through at least the first iteration of Phase 2 (see Figure 3-1). Though most of the groups' efforts are being directed towards the later phases of indicator screening, there is a need to periodically reassess and update the list of candidate indicators.

4.4.2 Approach

This phase of indicator development involves three steps:

1. Generating lists of candidate indicators
2. Preliminary screening to eliminate ineffective or impractical indicators
3. Recording each candidate indicator in a computerized data base

4.4.2.1 Generating Lists of New Candidates

The key to continual replenishment of the set of candidate indicators is active and effective communication with the scientific community. Although workshops were heavily utilized in the initial development of candidate indicators, other approaches should increase in importance in Phase 2. These approaches include annual systematic literature reviews to identify potential improvements to the current suite of indicators, attendance at major conferences, solicitation of involvement of the scientific community through presentations and published articles, and continued personal contact with leading scientists researching relevant topics.

The annual literature reviews should supplement rather than duplicate previous syntheses of information, and provide preliminary evaluations according to the criteria in Table 4-3. Though these reviews are not intended to involve new data collection or analyses, they should examine ongoing, unpublished work to the extent possible.

4.4.2.2 Conducting Preliminary Screening of Candidate Indicators

The list of candidate indicators should be as comprehensive as possible. Application of the criteria in Table 4-3 should not be too restrictive at this stage, since it is important for the candidate list to include all potential indicators. Critical evaluation of candidate indicators in subsequent stages of the indicator development process will eliminate inappropriate indicators or suspend evaluation of indicators that cannot be fully evaluated.

The main issue in this phase is whether or not each indicator appears *likely* to satisfy the criteria, given that enough data become available for a thorough evaluation. Figure 4-4 provides an example of how nonstringent application of the indicator selection criteria can still be useful in refining the list of candidate indicators. At this stage, it isn't necessary to consider the relative merits of similar indicators that could potentially be used to measure the same assessment endpoint.

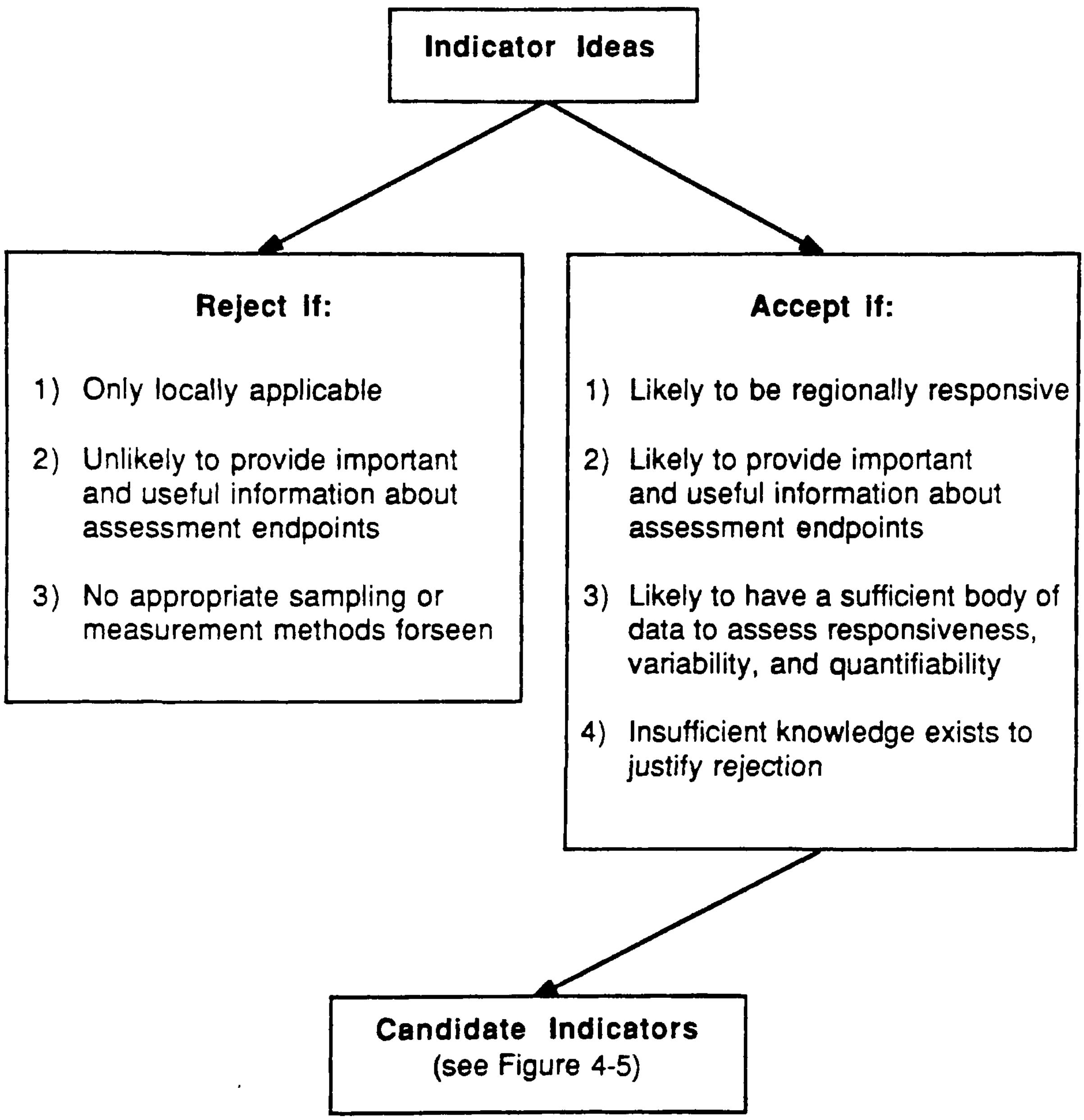


Figure 4-4. **Example preliminary screening to identify candidate indicators (see text, Section 4.4.2, for further explanation).**

4.4.2.3 Establishing and Maintaining a Computerized Indicator Data Base

During the evaluation of candidate indicators, each ecological resource group should develop and maintain a computerized list of all indicators that have been evaluated at this level of screening, including categories for those that have been accepted, rejected, or suspended. This list will form the initial template for the development of a computerized indicator data base. The data base should contain information about each indicator that has been considered, the sources of information employed in evaluation, the current status of the evaluation, reasons for accepting, suspending, or rejecting each indicator as it moves through each phase of evaluation, and references to both extramural and EMAP documents that provide more detailed information and analyses.

4.4.3 Evaluation

Little critical evaluation is to be expended in identifying candidate indicators, and little additional evaluation is desirable at this stage. It is not necessary to provide substantial amounts of evidence as to the behavior of the indicator, nor is it necessary to conduct peer reviews of the selection process and documentation. Satisfaction of criteria at a minimal level of scrutiny (as per Figure 4-4) is sufficient for an indicator to be included as a candidate. More problems may arise from not including a good candidate indicator than from listing too many indicators as candidates. At this stage of the indicator development process, it is more important to establish a process for identifying candidates, develop an innovative set of possible indicators, and establish a data base to be used in documenting subsequent assessments of the indicator, than to spend time eliminating indicators from further consideration.

4.5 PHASE 3: SELECTION OF RESEARCH INDICATORS

4.5.1 Objectives

Whereas Phase 2 of the indicator development process has the objective of generating new indicators, Phase 3 begins the process of indicator screening. The primary objective of Phase 3 is to prioritize evaluation activities by selecting candidate indicators with sufficient promise to merit further research, rejecting those candidates which clearly do not fulfill the EMAP indicator selection criteria, and placing in suspended status those candidates that either have not yet been evaluated or are considered to be at a less advanced stage of development than the selected candidates.

The indicators selected during Phase 3 will become research indicators that will be subjected (in Phase 4) to intensive data analyses, simulations, and possibly laboratory or limited-scale field pilot tests to determine their applicability for regional demonstration. A research indicator can be operationally defined as an indicator that appears to fulfill the EMAP indicator selection criteria based on published information, but requires more detailed, quantitative assessments before being included in a regional demonstration project.

It is important in this phase to gather all readily available information to evaluate candidate indicators against the selection criteria (i.e. their variability, interpretability, and methods for sampling and measurement). The level of intensity of this evaluation is intermediate between Phases 2 and 4. Enough information is needed to determine which indicators merit further investigation as research indicators, but such investigations will not actually be carried out. Expert judgment therefore plays a particularly important role.

4.5.2 Approach

Figure 4-5 provides a general algorithm for deciding whether to advance or reject a given candidate indicator. This figure is an adaptation of the indicator selection criteria list (Table 4-3), focusing on the issues most relevant to this phase. All of the activities of Phase 3 focus either on providing enough information to assess the issues raised in this figure or on documenting the decisions made.

The evaluation of a candidate indicator has three outcomes, as shown in Figure 4-5: rejection, acceptance (advancement to research status), or suspension of evaluation. If the assembled information is sufficient to conclude that the candidate indicator has any of the seven critical weaknesses listed on the left side of the figure, it should be rejected. The criteria for acceptance (right side of the figure) are generally the converse of the rejection criteria. Criteria 2 through 6 are essential for a candidate indicator to advance to research status. Notice that absolute proof of desired indicator qualities is not required at this stage. The other two criteria (#1 and #7) are qualifiers. If a candidate indicator has overwhelming importance for assessing endpoint status and trends (criterion #1), then it should receive priority in a resource group's list of research activities, even though some of the other indicators may have stronger evidence of responsiveness or more standardized methods. The final criterion (#7) recognizes that some indicators may not totally fulfill criteria 2-6, but still merit advancement due to their small incremental cost. Candidate indicators without enough information to support either rejection or acceptance should be placed in suspended status. The activities required to evaluate candidate indicators and implement the decision algorithm in Figure 4-5 include the following four steps:

1. Complete literature reviews that focus on quantifying indicator response characteristics.
2. Assess indicator utility using conceptual models.
3. Conduct structured workshops to evaluate indicators.
4. Update the Indicator Data Base.

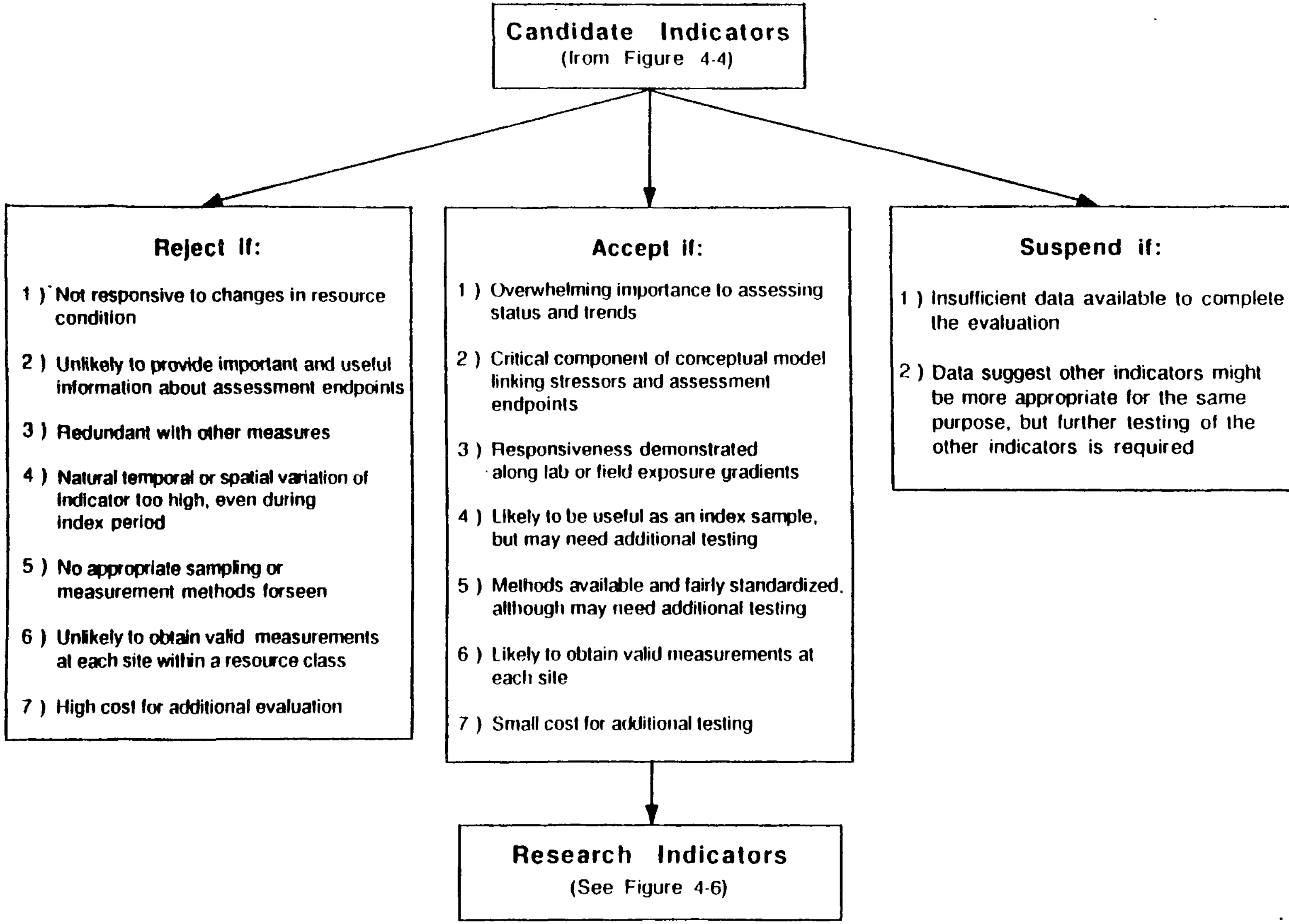


Figure 4-5. **Example of an evaluation of candidate indicators to identify research indicators (see text, Section 4.6.2, for further explanation).**

No field activities nor data analyses need be conducted during this phase. The results of the information syntheses and evaluations should be documented in the indicator data base and research plans for indicator development.

4.5.2.1 Literature Review

The literature review initiated in Phase 2 (Identification of Candidate Indicators) should be expanded to address issues pertaining to both individual indicators (Figure 4-5) and the larger issue of the completeness of the overall suite of indicators for a resource class. As previously discussed, reviews are conducted both within EMAP, covering the full range of indicators being considered, and by outside scientists, generally focusing on specific indicator types related to the investigator's area of expertise. These reviews should be updated annually, to ensure that new data are included in the selection of research indicators. The reviews of individual candidate indicators should be organized around the issues raised in Figure 4-5 and around the other criteria in Table 4-3.

4.5.2.2 Critical Review of Conceptual Models

Particularly important in establishing priorities among potential research indicators is the degree to which an indicator provides information to an assessment endpoint, fills gaps in the current set of indicators, contributes to a balanced EMAP design that includes different indicator types, or provides a link among EMAP resource groups. These questions about an indicator's role can best be addressed by critical analysis of each EMAP resource group's conceptual models (prepared in Phase 1), as well as analysis of other conceptual models that link several resource classes together (discussed in Section 5).

4.5.2.3 Expert Workshops

The primary method for assessing candidate indicators is an annual technical workshop to be conducted by each EMAP resource group. These workshops, comprising small working groups of scientists, have the primary objective of applying expert judgment to the individual indicator issues raised in Figure 4-5, the larger issues pertaining to the overall suite of indicators, and the priorities for research activities. These working groups may also identify gaps in the indicator suite and generate additional ideas for candidate indicators. To facilitate effective workshops the Technical Director of an EMAP resource group should prepare information summarizing the status of indicator development and distribute it before the workshop. This information should include, at a minimum: (1) a description of EMAP in general, (2) the EMAP resource group's current implementation design, (3) examples of results to date, (4) a list of the current research indicators and copies of their fact sheets, and (5) the proposed list of new research indicators and justification for their selection.

4.5.2.4 Indicator Data Base Expansion and Update

Decisions about the selection of research indicators must be recorded in a timely manner into the Indicator Data Base. The results of, and rationale for, changes in indicator status (see Section 4.4.2), whether the decisions occurred at the staff level or in a workshop, should be clearly documented. After completion of this step, the status of all previously identified candidate indicators should be changed to reflect these decisions. All indicators that have progressed through this phase of the indicator selection process will fall into one of the following three status categories: research-active, candidate-hold (suspended), or candidate-rejected.

4.5.3 Evaluation

As described at the start of Section 4.5.2 (Approach), candidate indicators should be selected for further research if they: (1) appear likely to fulfill the indicator selection criteria presented in Section 4.3 and Figure 4-5 (i.e., have a reasonable chance of becoming a core indicator), and (2) fill an existing gap in the EMAP indicator suite, improve the balance among existing indicators, or represent an improvement in an existing EMAP core indicator (see Section 4.8). This prioritization is a major output of the annual technical workshop, and is evaluated through peer review of the annual research plans and five-year research and monitoring plans.

Each ecological resource group should establish a small panel of outside experts to serve as peer reviewers for their specific program activities and plans. Individuals should serve for multiple years, with overlapping periods of assignment. The panel can function to provide oversight peer review of EMAP resource group activities and program directions and serve as reviewers for indicator research proposals (see Section 4.4.2). The oversight peer review panel should meet once per year to (1) review and discuss the peer review comments on the annual (and five-year) research plans, and (2) provide constructive comments and guidance on all phases of the general program.

4.5.4 Research Plan Update

Every five years, research and monitoring plans will be prepared by each of the resource groups in EMAP, under the direction of the resource group's director, and each resource group's program will be thoroughly reviewed at a peer review workshop. Results of Phase 3 activities will feed into these plans as descriptions of selected research indicators, the rationale for their selection, the results of previous indicator testing and evaluation efforts, and proposed research activities to overcome past problems and advance the testing and evaluation of selected research indicators. Other sections of the plans will address proposed pilot testing and regional demonstration activities planned for Phases 4 and 5 (described in Sections 4.6 and 4.7). Annual updates, addressing the specific research and indicator evaluation activities proposed for the following year, are also likely to be required.

4.6 PHASE 4: EVALUATION OF RESEARCH INDICATORS TO SELECT PROBATIONARY CORE INDICATORS

4.6.1 Objectives

In Phase 4, research indicators will be screened to achieve two general objectives: identification of probationary core indicators (i.e., indicators ready for full-scale regional demonstration), and evaluation of the expected performance of proposed indicators relative to EMAP's overall objectives. Identification of probationary core indicators requires the quantitative evaluation of research indicator performance across different EMAP sampling units. This objective can be accomplished through literature reviews, analyses of existing data, simulations of expected indicator performance over varying temporal and spatial scales, statistical evaluations of minimum detectable trends, limited-scale field pilot tests and laboratory experiments, and assessments of the logistical requirements for field sampling. The second objective, evaluating the expected performance of indicators relative to EMAP's overall objectives, obviously overlaps with the identification of probationary core indicators, but the aim is somewhat different. Here, the focus is on the ability of indicators to meaningfully reflect assessment endpoints; to detect associations between response indicators, exposure/habitat indicators, and stressor information; and to possibly be combined into useful indices of ecological condition. For example, it is important to consider whether or not the regional cumulative frequency distributions of individual response indicators and indices are likely to be stable over the index period. Another consideration regarding selection of usable indicators or indices is whether or not ways can be devised to extract the signal of changing condition from noisy data gathered from inherently variable ecosystems.

4.6.2 Approach

Figure 4-6 illustrates several key questions that drive many of the indicator evaluation activities in this phase. To fulfill the first criterion on the right side of Figure 4-6, there must be quantitative evidence that an indicator can: (1) respond to changing stressor levels, (2) respond in most resource classes, and (3) have a signal-to-noise ratio stable enough during the index period not to mask this responsiveness. This criterion demands that indicator testing consider both spatial and temporal variation within the index period. For example, fulfilling criterion #2 on the right side of Figure 4-6 requires data on the costs and logistical constraints associated with sampling, and criterion #4 demands estimates of natural annual variation, using simulations and statistical analyses. In addition, since properties and relationships can

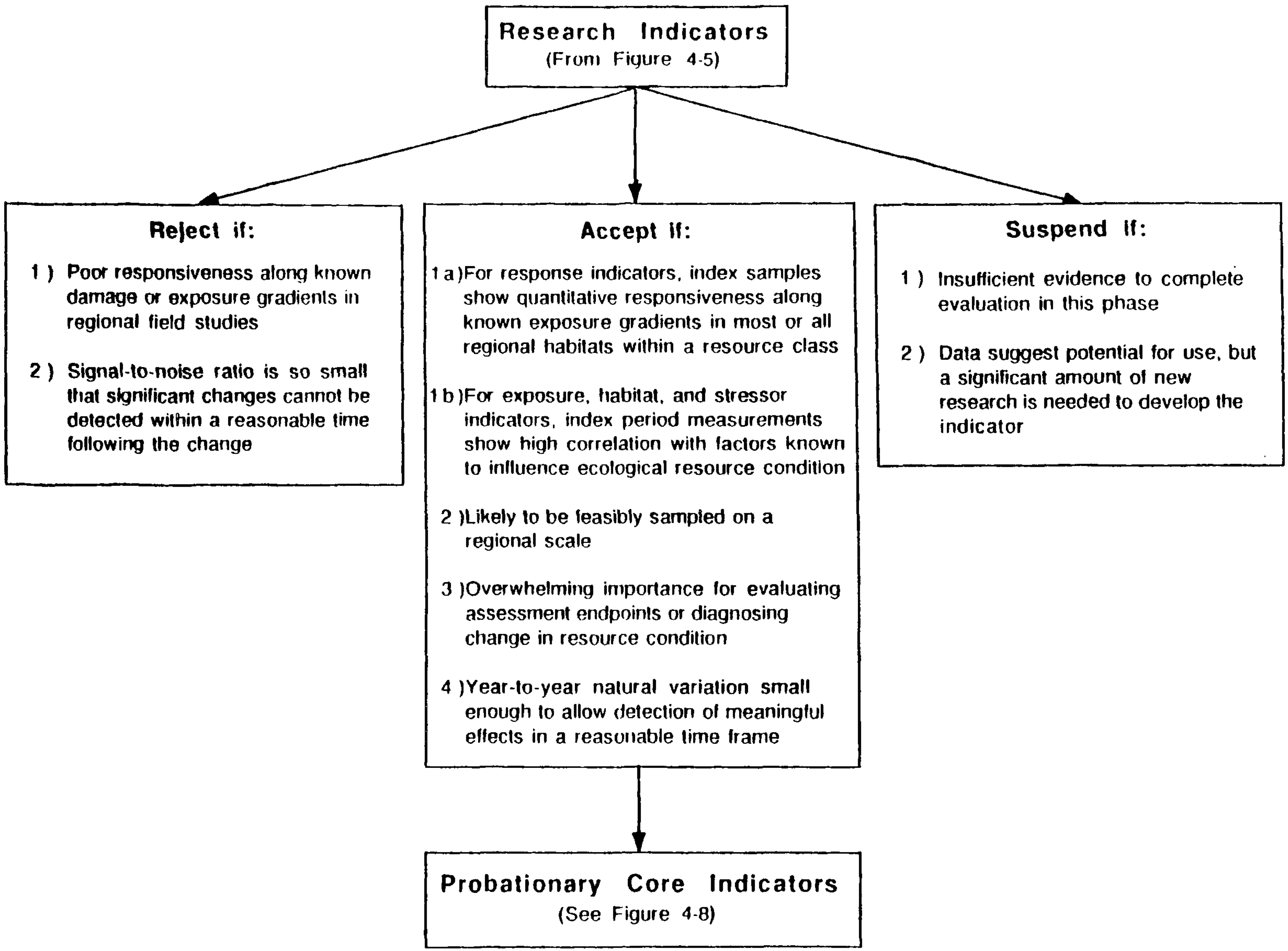


Figure 4-6. **Example of an evaluation of research indicators to identify probationary core indicators (see text, Section 4.6.2, for further explanation.**

change over time as environmental conditions alter underlying mechanisms, there is a need to provide a process for continually reevaluating and reassessing the adequacy of each resource group's indicator suite for meeting the overall program goals (see Section 4.8).

Different intensities of investigation of these issues produce different levels of proof. The overall strategy should be to pursue the simplest approaches first, until there is enough evidence to decide on acceptance or rejection. Insufficient evidence will lead to suspension of the indicator at the research stage. Because of the expense of performing quantitative evaluations of indicators, research activities should focus first on those indicators with the strongest relationship to assessment endpoints.

To implement the decision algorithm in Figure 4-6 and address the adequacy of indicators with respect to EMAP's overall assessment objectives, we propose that the evaluation of research indicators follow an eight-step process:

1. Formulate research questions
2. Complete literature reviews targeted to these questions
3. Identify useful data bases
4. Analyze existing data
5. Perform analyses of expected indicator performance
6. Produce example assessments
7. Conduct limited-scale field pilot studies
8. Update the Indicator Data Base

These eight steps are described in the following sections.

Since steps 1 through 7 involve increasing costs, they should be completed in sequence, with the higher order tasks being implemented only if needed (i.e., the indicator passes evaluation in earlier steps). To the greatest degree possible, the performance of research indicators should be evaluated using existing data. However, much of the existing data are not appropriate at the temporal and spatial scales required by EMAP. Most of the data needed to evaluate research indicators may need to be gathered from field pilot studies at non-EMAP sites, because spatial representativeness is not evaluated until Phase 5. However, because assessment of logistical constraints is also an objective of this phase, it may be beneficial to evaluate some of the proposed indicators at EMAP sites. The next phase of evaluation involves demonstration projects, and will probably be significantly more costly and logistically difficult. This implies that by the time Phase 4 is completed, there should be a high degree of confidence that the selected probationary core indicators will indeed be ultimately accepted as core indicators. Therefore it is essential to resolve all issues that can help in avoiding unnecessary expense and effort during the demonstration project.

4.6.2.1 Formulation of Research Question

The first task in evaluating whether a research indicator should be accepted as a probationary core indicator is to formulate specific research questions. Figure 4-6 provides an initial set of questions, and others are provided in Tables 4-3 and 4-4. The questions should be as detailed and indicator-specific as possible and should consider issues of interpretation, methods, and variability.

Key questions of interpretation must be answered at this time to determine the merits of implementing each indicator. These questions include:

- How will the data be used?
- How will the monitoring results from the indicator be used in the EMAP Annual Statistical Summaries?
- How will indicators be combined to determine the condition of assessment points?
- How will the indicators aid in identifying the likely causes for patterns and trends in ecological condition?

In addition to these general questions, it may be necessary to formulate questions unique to the specific indicator data requirements (e.g., sufficiency of sample size, environmental impacts associated with the sample collection effort).

4.6.2.2 Literature Reviews

The existing literature should be reviewed and used, to the greatest degree possible, to prepare a summary response to each research question listed above. Questions that the available literature (including unpublished studies) may best be able to address are issues of interpretability, sampling methods, and analytical techniques. This literature review should be more exhaustive than the reviews previously conducted for Phases 2 and 3 (Sections 4.4 and 4.5). After this step, it will be determined whether additional data or indicator research projects are needed to address the questions, what specific information is lacking, and what approaches could be used to acquire it.

4.6.2.3 Identification of Useful Data Bases

The next step is to determine what types of data and data bases currently exist that may be useful for addressing unanswered issues for each of the research questions defined in Step 1. For example, retrospective data, such as diatom assemblages and tree ring chronologies, may be useful in assessing the

Table 4-4. Example Questions for Evaluating Research Indicators

Questions related to data interpretation

- How will the data be used?
- How will the monitoring results be summarized in the Annual Statistical Summaries?
- How do the data relate to the assessment endpoints?
- How does the indicator contribute to defining the percentage of the ecological resource considered to be degrading, improving, or impacted?
- How will the indicator aid in identifying likely causes for observed patterns or trends in ecological resources status?
- Does the indicator provide important information about the status of the ecological resources of concern?

Questions addressing methods for sample and data collection

- Are accepted methods available to collect the samples and data?
- At what time of the year should measurements be made (definition of the index period)?
- At what location in the resource sampling unit should an indicator be measured (identification of the index sampling site/area)?
- What field sampling methods should be used for sample collection, and what are the logistical constraints on the use of these methods?
- What are the best analytical techniques for measurement of the indicator?
- Does this indicator provide a cost effective way of obtaining the needed information?

Questions addressing variability of the measurements

- How precisely can the indicator be measured?
- What is the background spatial variability among concurrent samples collected at different locations within a resource sampling unit?
- What is the background spatial variability among non-concurrent samples collected within the index window, but from different ecological resource sampling units within the same region?
- What is the spatial variability among samples collected within the index period in different regions during the same year?
- What is the temporal variability among samples collected from the same ecological resource sampling unit, during the same year, and at the same locations, but during different potential index periods?
- What is the temporal variability among samples collected within the same region, during the same index period, but spanning a number of years?
- How responsive is the indicator to change or stresses?

Miscellaneous questions

- Can sufficient measurements of the indicator (e.g., numbers of target organisms) be collected, given the sampling design, logistical constraints, and the need to minimize the environmental impacts of the sampling process?
- Can the information be used to conduct retrospective investigations?

natural temporal variability (noise) of an indicator, such as sedimentation rate, water chemistry constituents, moisture availability, forest productivity. Data from long-term plot experiments can be very useful in assessing local spatial and temporal variability (e.g., Franklin et al., 1990). Data on indicator values at regional reference sites or data on indicator responses across gradients of damage or stress are very valuable in addressing many of the questions in Table 4-4. Similarly, data sets that include more intensive sampling than that being considered for EMAP can be extremely valuable in defining the best index period given intra-annual variability, identifying the best index location for sampling, and assessing spatial variability.

4.6.2.4 Analysis of Existing Data

The data bases identified in Step 3 should be analyzed to address, as far as possible, the key research questions. These data should be used to explore plausible patterns and trends in ecological resources and to assess whether or not these patterns are reflected in the values of particular indicators. Data sets from spatial exposure gradients or changing exposures over time are particularly valuable. Analyses of data bases should be used to investigate questions related to the appropriate form for data presentation, methods for statistical summarization, apparent redundancy among different indicators, responsiveness of indicators to specific types of stresses, temporal and spatial variability, possible index periods, and the relative merits of alternative sampling and analytical methods (including considerations of sampling and analytical error). These data analyses provide the raw material for the next step, simulations of expected indicator performance.

4.6.2.5 Analysis of Expected Indicator Performance

Analyses should be conducted to assess the performance of research indicators during hypothesized index periods. Analyses may use simple hand-calculator analytical techniques to determine levels of detectable effect for given levels of confidence and temporal variation, more sophisticated statistical assessments, or simulation models. The analyses may be repeated (and improved) with any additional data collected in field pilot studies (4.6.2.7).

The results of these analyses can be used to estimate the preferred index period for sampling, the time needed for an indicator to detect changes of a specified magnitude, or the usefulness of a response indicator for defining the regional extent of degraded systems. Data acquired from frequently monitored sites can be used to assess indicator stability during different index periods. Spatially intensive survey data, where available, can be used to obtain estimates of spatial variability in indicators for specific times of the year, and these data can be subsampled at various densities, both less than and greater than those of the EMAP frame, to assess the stability of regional cumulative frequency distributions. This kind of analysis may suggest forms of spatial stratification (e.g. new resource classes) that had not previously been considered.

Ideally, simulation models would be run for sufficient numbers of monitoring locations to explore the change in cumulative frequency distributions of indicators during different index periods and also over longer time frames of several years. Simulated data streams for longer time periods can be fed into statistical programs to determine minimum detectable trends in response indicators (e.g., 2% change per year in indicator value over 10 years). Such simulations should reflect the varying sensitivity of different subpopulations (e.g. the tails of the cumulative frequency distribution may be more likely to respond to changing exposures). If only limited data are available, it may be possible to use bootstrapping techniques or simple process models to generate hypothetical data with reasonable spatial and temporal variability.

4.6.2.6 Example Assessments

Example assessments explore the types of data analysis, data presentation, indicator responsiveness, and indicator variability that can be expected. These assessments may be conducted using either plausible (i.e., simulated) or real data. Conducting an example assessment is intended to assist in selecting among alternative indicators, identifying redundant indicators, identifying gaps in the suite of indicators, deciding how data from each indicator would be used in EMAP for assessing status and trends, and exploring the ability of the indicator suite to ascribe plausible causes to observed patterns and trends in the region's percentage of subnominal areas. An EMAP resource group's conceptual model, which links stressors with assessment endpoints, should be used throughout the example assessment to guide the analysis and interpretation of both empirical and simulated data.

4.6.2.7 Limited-scale Field Pilot Studies

In general, field pilot studies should be used to gather any additional data needed to address the questions defined in Step 1, except for issues that can only be addressed through a regional demonstration project (Phase 5, described in Section 4.7). As observed above, many or all of the sampling sites for field pilot studies need not be on the EMAP sampling grid, particularly if data can be collected more efficiently at other sites, still addressing the critical issues of ecological health with enough confidence to permit proceeding to the regional demonstration.

If necessary, questions identified in Step 1 should be redefined to specifically address the hypotheses that need to be tested during the pilot study. Examples of subjects to concentrate on in a pilot study include:

- Intensive temporal sampling to define the best boundaries for the index period (e.g., fall turn-over in lakes, seasonal low water in wetlands) and to quantify the within-index period sampling variability.

- Extensive spatial sampling within a regional resource class to determine the value of data collected at index sampling sites relative to more intensively or randomly located sampling sites, to quantify indicator variability within the index sampling area (e.g., the central basin of the lake), where permanently fixed monitoring sites cannot be established.

- Sampling along gradients, from *polluted* to *unpolluted*, or *impacted* to *natural* sites to (1) evaluate the responsiveness of the indicator to stress, (2) aid in defining nominal and subnominal classifications (or similar schemes for data interpretation), and (3) evaluate the specificity of the indicator to particular types of stress or change and the repeatability of the indicator response in different regions or ecological resource classes.

The optimal pilot study design will depend on the specific questions to be addressed. However, two examples from the EMAP-Estuaries resource group illustrate the types of studies that may be useful.

- **Definition of the index period**. Levels of dissolved oxygen (DO) in estuaries are highly variable, yet DO also serves as an important exposure and response indicator for assessing estuarine condition. Therefore, field studies were conducted in 1990 to determine (1) the optimal boundaries for the summer index sampling period and (2) the utility of point-in-time measurements of DO. At about 100 sites in the Virginian Province, three point-in-time measurements of DO were collected during three sampling intervals (early, mid-, and late summer). Comparison of the DO cumulative distribution functions for the three periods provides information of the regional stability of the DO indicator. In addition, DO was measured continuously at a subset of 30 sites, selected by experts as sites expected to experience problems with low DO. These continuous records will be used to both refine the index period and to evaluate the utility of point-in-time measurements as an indicator of the frequency, severity, and extent of low DO episodes.

- **Indicator responsiveness to stressors**. Using expert judgement, 24 sampling sites were selected to reflect important gradients of both pollutant exposure (DO gradient) and habitat (salinity) within two geographic regions (latitudinal gradient) (Figure 4-7). A variety of indicators (e.g., benthic biomass, species abundance) were sampled at each site, three times during the summer index period. Response indicators that consistently reflect the effects of pollutant gradients across a range of habitats and regions are obviously preferred, and fulfill the prime criterion for acceptance as EMAP probationary core indicators (see Figure 4-6).

In choosing sampling sites and regions for the pilot study, an attempt should be made to include the full range of conditions expected in EMAP. Answers to some of the above questions (e.g., best index period) may vary from region to region or among ecological resource classes or types. If so, it may be necessary to include multiple regions in the pilot, or to evaluate the indicator in regions that are expected to represent the extreme conditions for the indicator. Multi-regional pilot testing should be limited to investigation of issues that cannot be resolved within a single region, and should be designed to obtain only the minimum information needed to complete the assessment.

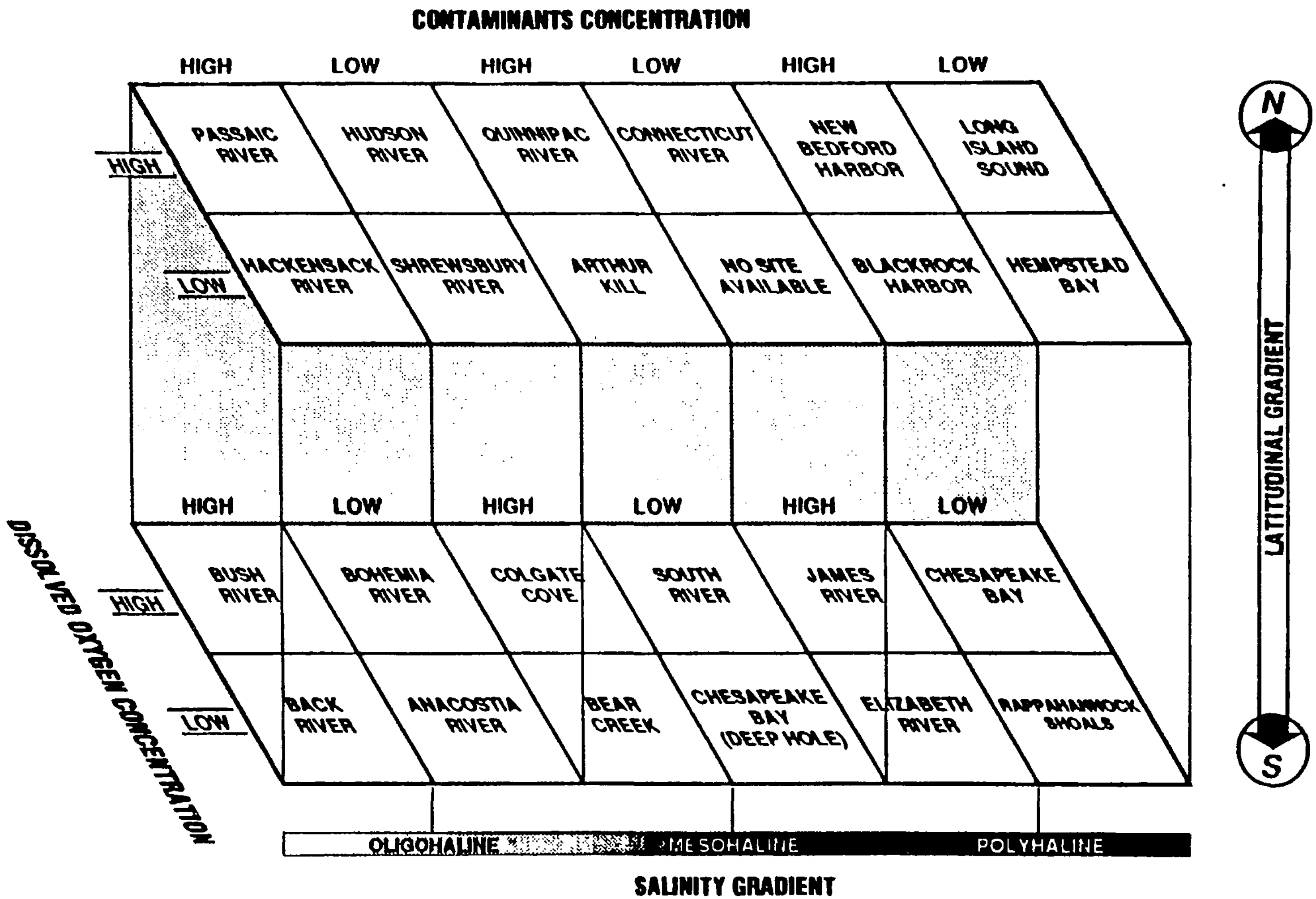


Figure 4-7. Example of an indicator testing and evaluation strategy (for the 1990 EMAP-Estuaries Demonstration Project in the Virginian Province).

4.6.3 Evaluation

As soon as sufficient evidence has been assembled, research indicators should be evaluated against the selection criteria described in Figure 4-6 and Table 4-3. This evaluation is intended to be more stringent and specific than previous evaluations. Throughout this phase, high priority should be given to indicators that have definite regional applicability, relevance to assessment endpoints, and importance as integrators across EMAP resource groups.

The peer review panel for each EMAP resource group should review the following documents that result from the evaluation of research indicators to identify probationary core indicators: literature reviews, summary of data analyses, pilot study reports, indicator status sheets, and an indicator evaluation report (see expert workshops discussion in Section 4.5.2). The indicator evaluation report should be formatted to present similar information for each indicator evaluated and should be arranged to present all information about each indicator in a concise manner. Attempts should be made to publish the results in the open literature, both to provide another level of peer review, and to make advances in knowledge widely available to the scientific community.

4.6.4 Update of Indicator Status Documents and Research Plan

The indicator status report should be updated to summarize the results of each evaluation. This report should draw upon all of the sources of information used or generated in the evaluation of research indicators and should summarize the available data on research indicator application, interpretation, evaluation, and testing. The indicator status sheets should be updated to reflect all decisions and summarize their justifications.

As discussed in Section 4.5.4, the annual research plans and more comprehensive five-year research and monitoring plans must be updated to describe the selected probationary core indicators, their associated justifications, and the activities proposed for Phase 5 to evaluate probationary core indicators for inclusion in the core EMAP program. With respect to Phase 4, the five-year plan will describe the current list of probationary core indicators, summarize the results of prior research indicator evaluation and testing efforts, and describe plans for further evaluating new indicators that have advanced from research to developmental status.

4.6.5 Indicator Data Base Update

The only new category of information added to the data base during this phase is the location of field pilot tests, if conducted. The results of evaluations should be used, however, to expand, improve, or verify data for each of the previously established information categories in the data base. Citations should direct the reader to more detailed information contained in summary reports and pilot study reports. Each indicator record should be updated to indicate changes in status, as well as the justification for the change. All research indicators that have progressed through this phase should be classified as either *developmental-active*, *research-hold*, or *research-rejected*.

4.7 PHASE 5: SELECTION OF CORE INDICATORS

4.7.1 Objectives

Following the detailed scrutiny of research indicators, it is necessary to confirm that the selected probationary core indicators are appropriate for implementation in the EMAP core program. Regional demonstration projects are used for this purpose since they allow full-scale testing of the utility and applicability of the indicator. During this phase of the indicator evaluation process, the objectives of the demonstration projects focus more on confirming the validity of the selected indicator over a broad range of conditions than on eliminating indicators that fail to satisfy fundamental criteria relating to responsiveness and interpretability.

The specific objectives of this phase are similar to those described for evaluating research indicators, but they focus more on regional scale feasibility and utility and less on indicator procedures and methods, which should already be well defined by this phase. A key function of this phase is to determine whether the proposed density of resource sampling unit is sufficient to assess associations between regional patterns in ecological condition and anthropogenic stresses. Activities during this phase will build up the EMAP infrastructure for conducting regional monitoring activities, through the field implementation activities that are necessary to conduct regional demonstrations. Also during this phase, the first outputs are obtained from monitoring by EMAP resource groups.

4.7.2 Approach

Figure 4-8 illustrates some of the key issues that need to be resolved for identification of core indicators. Criteria #1 and #3 on the right side of Figure 4-8 are the critical tests for each probationary core indicator: regional feasibility and stability of the regional cumulative frequency distribution over the index period. Figure 4-9 illustrates similarity among cumulative frequencies suggesting that a summer index period would be appropriate for monitoring the Index of Biotic Integrity, and that late spring monitoring may not be expected to represent the same general conditions as the summer index period. Criterion #2 (regional utility) is obviously important, but not critical, since some indicators (e.g. those sensitive to global warming) may not be useful for several decades, although establishing baseline data early may be

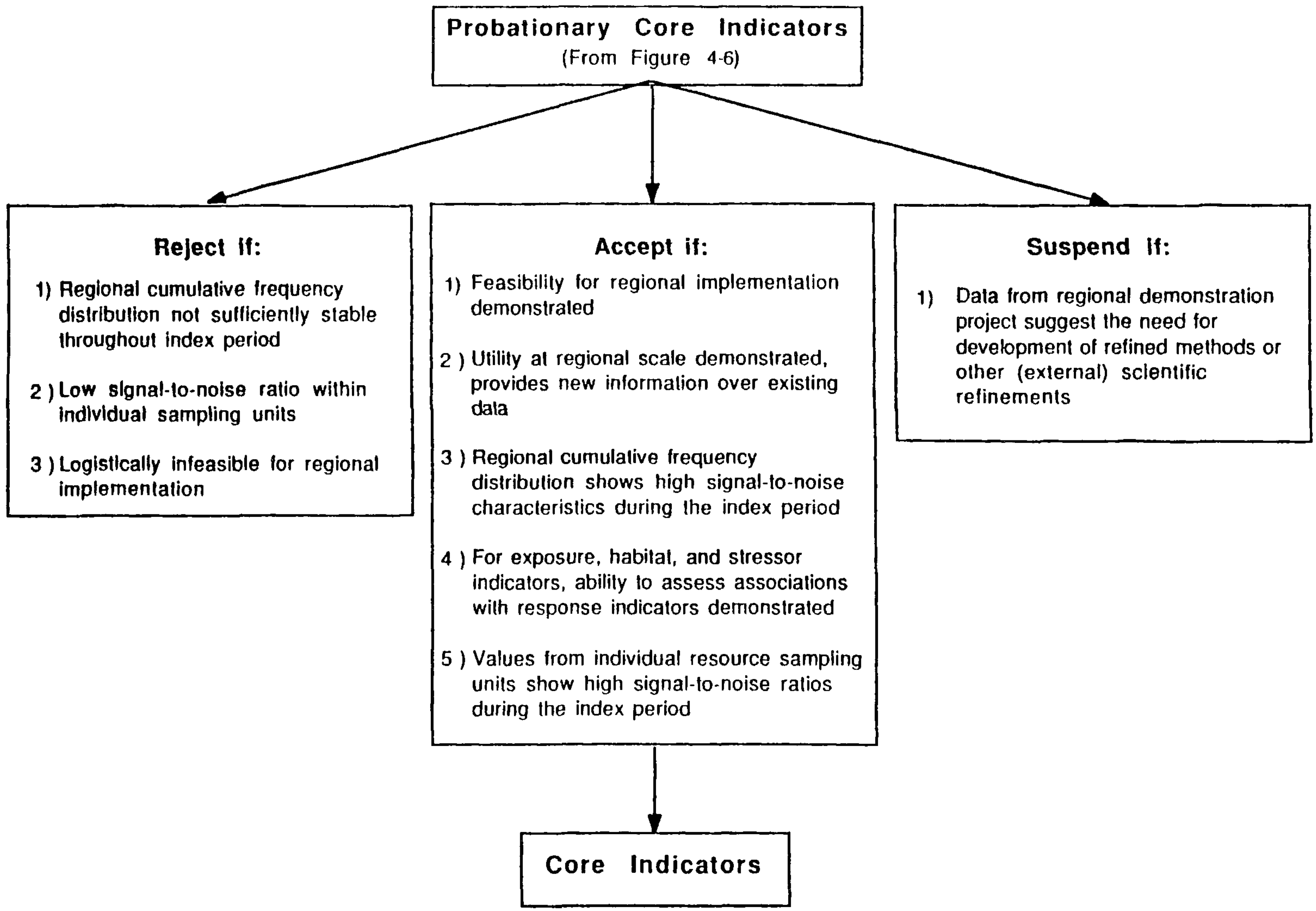


Figure 4-8. **Example of an evaluation of probationary core indicators to identify core indicators (see text, Section 4.7.2, for further explanation).**

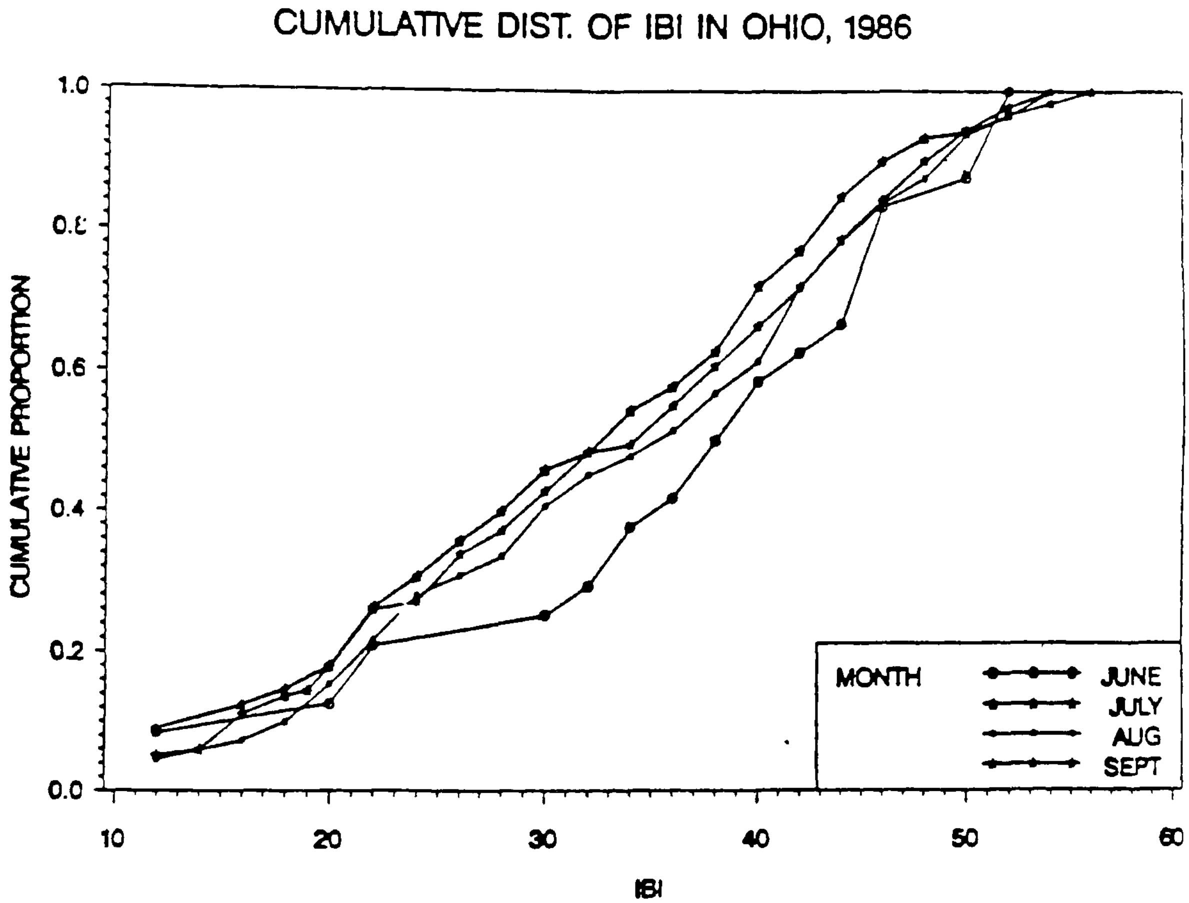


Figure 4-9. Cumulative frequency distributions (CDF) for Index of Biotic Integrity in streams in Ohio during four months of 1986. The dissimilarity of CDFs for spring and summer months suggests that June should not be included in the index period for IBI in Ohio streams (after Paulsen et al., 1990).

critical to detecting changes in these indicators at a later time. For response indicators, criteria #4 and #5 on the right side of Figure 4-8 (ability to assess associations, stability of values from individual sampling units over the index period) are desirable for determining the probable causes of subnominal conditions in parts of the region, but are not critical to the determination of ecological condition in a region. However, exposure indicators must have high signal-to-noise ratios at each sampling unit over the index period, since the primary function of exposure indicators is to assist in determining plausible causes of subnominal conditions in parts of a sampled region. Hence, failure to demonstrate sampling unit stability is enough to cause the rejection of exposure indicators.

Each indicator must be evaluated for all pertinent resources classes. Rejection of an indicator for one resource class should not affect decisions regarding the utility of that indicator for other resource classes (e.g., failure of nutrient concentration indicators to adequately characterize the condition of one agro-ecosystem resource class should not result in rejection of this indicator in other agroecosystem resource classes).

The acquisition of information to follow the decision algorithm in Figure 4-8 will involve the following three-step process:

1. Designing and conducting regional demonstration projects
2. Completing an Annual Statistical Summary
3. Updating the Indicator Data Base

4.7.2.1 Regional Demonstration Project Design and Implementation

This step constitutes implementation of the probationary core indicators in one or a few regions, using the sampling frame proposed for the EMAP core program. This implementation will require the indicator development team to work closely with EMAP field crews and other members of the ecological resource group to ensure that any new indicators being tested are implemented appropriately.

To verify the findings from the field pilot studies (Phase 4) in new regions or across regions, it may be appropriate to include intensive temporal or spatial sampling at a subset of EMAP sites. Specific objectives and approaches for these tests would be similar to those defined for the pilot studies in Section 4.6.2. In some cases, the differences among regions and/or ecological resource classes may be large enough to require additional demonstration projects, for other areas or ecological resource classes, prior to full-scale implementation. However, the amount of testing required is expected to decline substantially as additional regions and ecological resource classes are added. An example of a regional demonstration project, the National Stream Survey - Phase I Pilot Study, was conducted during the National Surface Water Survey. The project was performed during the first year of the National Stream Survey on streams in a single region of concern, the Southern Blue Ridge Province. Although most of the analytical methods and logistic methods for collecting and analyzing stream samples had been developed and tested previously, three questions could not be answered without testing on a regional scale:

1. Could streams selected using a regional probability-based experimental design be reliably sampled on a routine basis to provide estimates of regional stream status?
2. Could an index period be defined during which streams would display low natural variability?
3. Could data of known high quality be collected using a probability-based stream survey?

The National Stream Survey was implemented in the Southern Blue Ridge Province to answer these questions in a geographic region where overcoming logistical problems would indicate a high probability of implementation success in all other regions of concern, and where a large enough data base could be developed to identify an appropriate index period and assess the expected quality of data collected in such a survey. Following successful completion of this project, the same approach was implemented by the National Stream Survey throughout the eastern United States in the following year. This regional demonstration project was useful as a relatively low-cost method of investigating questions that could only be answered on a regional scale, without incurring the cost and complexity of implementation on a program-wide basis.

4.7.2.2 Annual Statistical Summary

The Annual Statistical Summary is a major output from each ecological resource group. Results from the demonstration study should be analyzed as proposed for each EMAP resource group's core program to confirm the utility of the data. Although the degree of evaluation possible is extremely limited during the first year of data collection, this assessment will allow confirmation of the basic rationale for including each indicator. Subsequent annual summaries will be increasingly important for evaluating the abilities of each indicator to identify changes and trends in the status of ecological resources.

4.7.3 Evaluation

Critical issues for evaluating probationary core indicators are listed in Figure 4-8, although the complete set of indicator selection criteria (Table 4-3) should be re-examined. The primary objective of this evaluation is to determine to what degree data obtained through the use of the indicator, as analyzed in 4.7.2.2, aid in achieving the overall EMAP assessment objectives: (1) estimating the current status, extent, changes, and trends in the condition of the nation's ecological resources and (2) identifying associations between human-induced stresses and ecological condition. Probationary core indicators that are found to produce satisfactory results and to contribute to the achievement of these assessment objectives will be accepted as core indicators for full implementation.

The results of these evaluations, and the data gathered at this and subsequent stages of implementation, will be subjected to extensive peer, agency, and public review. Unless the indicator fails to advance from probationary core to core status, the outputs from the demonstration studies will be incorporated into the Annual Statistical Summary and associated interpretive reports, which will be part of the continuing legacy of EMAP. Outputs from regional demonstration studies when the indicator fails to advance to core status will be prepared as summaries of the reasons for rejection and included in the Indicator Data Base.

4.7.4 Update of Research Plan and Indicator Status Documents

All indicator status documents, including the research plan, the indicator fact sheets, and the indicator status report, should be updated to identify newly proposed core indicators, and to identify those probationary core indicators that are rejected or suspended for inclusion in the core group, along with the justifications for these decisions. Similar notations should be made in the five-year research and monitoring plan. Decisions to accept probationary core indicators as core indicators should be subjected to peer review before full-scale implementation of these indicators in EMAP.

4.7.5 Indicator Data Base Update

The Indicator Data Base should be updated on an annual basis, by providing additional insights derived from analysis of data from the regional demonstration. A listing of core indicators with appropriate documentation will be compiled within this data base.

4.8 PHASE 6: REEVALUATION AND MODIFICATION OF INDICATORS

4.8.1 Objectives

Scientific advances and technological innovations will occur during the ongoing implementation of EMAP and may improve the precision, accuracy, representation, cost effectiveness, and overall applicability of EMAP indicators. This may necessitate modifying specific indicators, replacing indicators with others that provide improved information or equivalent information at reduced cost, or adding indicators that address emerging issues of importance. To accommodate these changes, it will be necessary to specify appropriate procedures. This section presents a preliminary outline of a systematic approach to indicator reevaluation and revision that will ensure the use of the best possible set of indicators for achieving EMAP objectives. This section should be revised and expanded as EMAP begins to mature and modification of the set of core indicators is considered.

An EMAP resource group's set of core indicators should be revised only after a thorough assessment indicates that it is clearly necessary (i.e., when revision results in a significant improvement in the quality of the assessment of status and trends of ecological condition, without diminishing the continuity of the assessment record). Once the current EMAP program has been assessed, and a recommendation has been made to modify the list of core indicators or replace a current indicator, the recommendation and a plan for the transition will be included in the annual research plan, which is the vehicle for overall programmatic peer review of EMAP. Recommended changes will not be implemented until after the recommendation is approved by the peer review process. Once a determination has been made to modify the set of indicators, the primary objective is to accomplish a smooth transition. Continuity of the data base and the assessment resource is extremely important for ensuring that the ecological monitoring effort is detecting any trends or changes in condition. Situations that may require reexamination of the core indicators include the following scenarios:

- A new indicator may be identified that appears to be superior to the EMAP core indicator currently in use for measuring an assessment endpoint. The decision to replace the current indicator with the new one and to discontinue monitoring the current indicator must be made after obtaining adequate information to ensure continuity of the assessment record and comparability of the new assessments with those that have relied on the old indicator.
- The environmental conditions have changed such that underlying mechanisms are altered. Because of this, previous linkages between the indicators and environmental values may not be representative of the existing situation.
- A method improvement may occur that promises to provide similar quality data at lower cost, or higher quality data at a similar cost using the improved method. The impact of using the improved method to assess endpoints and to detect trends must be assessed before replacing the original method, to ensure that data quality actually equals or exceeds that available using the current method.

Assessment method evolution may also result in changes in the data analysis, presentation, or evaluation procedures for the Annual Statistical Summary (see Paulsen et al., 1990), such as developing a new index or redefining the threshold for assessing ecological condition (nominal/subnominal) for selected resource classes. Although these changes will not directly affect the set of indicators, they may result in an opportunity for modifying or adding core indicators. Therefore, the impact of these changes on the assessment process should be evaluated as early as possible, to increase the ability of the indicators to provide needed information.

4.8.2 Approach

The primary approach for evaluating core indicators is routine review, evaluation of assessment outputs, and searches for new ideas for indicators. This calls for continual tracking of the published literature and ongoing research programs (see Sections 4.4 and 4.5), to identify promising new information; it is an ongoing, institutionalized Phase 1 effort, as described in Section 3.1.

Once potential new or revised indicators or methods are identified, the process of investigation and assessment of the idea should proceed through Phases 2-5 of the indicator development process, as described in Sections 4.4 through 4.7. Implementation of this review process ensures that indicators or methods cannot be revised or replaced without (1) carefully conducting the evaluations needed to ensure that the new indicator or method provides a meaningful improvement in assessment capabilities and (2) quantifying the relationship between the new and old indicators or methods (i.e., calibrating the new indicator).

Evaluation of proposed changes to core indicators (using the approaches described in Sections 4.4-4.7) should be conducted with the added objectives of evaluating the relative merits of the new and old indicators or methods and quantifying the relationship between the two. This evaluation requires that field pilot studies and demonstration programs be designed and conducted to test for comparability and relative responsiveness of the two indicators or methods under a range of conditions. Field demonstrations should be conducted to test alternative indicators or methods in one to several regions for a number of years, to verify the consistency of that relationship. Field pilot studies and regional demonstration projects will be conducted to calibrate the relationship between the old and new indicators (or measurement techniques), and both the old and new (or modified) indicators will be monitored long enough to ensure comparability of the data sets from both indicators, before phasing out the old indicator. Once the spatial and short-term temporal relationships between the alternatives are well established, simultaneous collection of data for both indicators may be desirable for an extended period of time at a limited number of sites to ensure the similarity of the relationship over an extended time period.

4.8.3 Evaluation

Revision of core indicators requires all assessments described in Sections 4.4 through 4.7 to be conducted and all criteria for adoption of the changes to be satisfied. The advantages of new indicators or methods must be significant and must represent improvements over existing indicators. These advantages must be well documented, and the documentation of the research efforts (laboratory, pilot, and demonstration studies) must include the following information:

- Quantification of the calibration between the old and new indicators or methods under the full range of conditions observed during EMAP monitoring to date.

- Evaluation of how the proposed change in indicators or methods would affect the Annual Statistical Summary and data interpretation and integration (may require recalculation of indices).

Each EMAP resource group will formally reevaluate its indicator suite every five years (see Section 4.5) under the direction of the resource group's Technical Director. Proposed revisions to the EMAP core indicators, and the associated justifications, should be included in the five-year plan. These proposed revisions will be subjected to peer review along with the rest of the program at this time. Therefore, revisions to the core indicator suite can only occur during the overall program evaluation that occurs every five years.

4.8.4 Update of Research Plan and Indicator Status Documents

The research plan, indicator status report, and data base will be updated at each stage of evaluation of proposed new indicators and methods. It will also be necessary to ensure that the documentation for each of the new indicators identifies the reasons for the investigation (e.g., identified gaps, inadequate precision of current indicators). All information developed through comparison of alternative methods should also be summarized in these documents.

5. INTEGRATION AMONG RESOURCE GROUPS

As discussed in Section 2.2, seven broad ecological resource categories have been defined within EMAP: Surface Waters, the Great Lakes, Estuaries, Wetlands, Forests, Agroecosystems, and Arid Lands. At present, individual ecological resource groups have the primary responsibility for selecting and evaluating EMAP indicators to address these ecological resource categories. Section 4 outlines the process of indicator development for an individual resource group. Integration of indicators and monitoring data across these resource groups is necessary, however, to fully achieve the program goals. This section describes the issues and steps required to ensure that effective integration and coordination among ecological resource groups occur during the indicator development process.

Integration occurs at two levels: (1) during indicator selection, to ensure that all important inter-group linkages are considered and (2) during data interpretation. Because this document focuses on indicator selection, the second level of integration is beyond its scope. Tasks relating to an integrated interpretation of the EMAP monitoring results are the responsibility of the EMAP Integration and Assessment Task Group. Procedures for EMAP integration and assessment will be described elsewhere. However, the utility of each indicator for interpreting resource status and trends is an important consideration in the indicator selection process. Thus, close cooperation between ecological resource groups and the Integration and Assessment group is essential. Integrating monitoring results among ecological resource categories will enable EMAP to address a wide range of issues, including:

- Source apportionment and diagnostic analyses across resource boundaries (e.g., nonpoint sources to surface waters)
- The status of whole regions, encompassing all ecosystem types
- The extent and magnitude of environmental problems that impact multiple ecological resource categories
- The effectiveness of regulatory actions
- Emerging environmental problems and new questions that EMAP can address

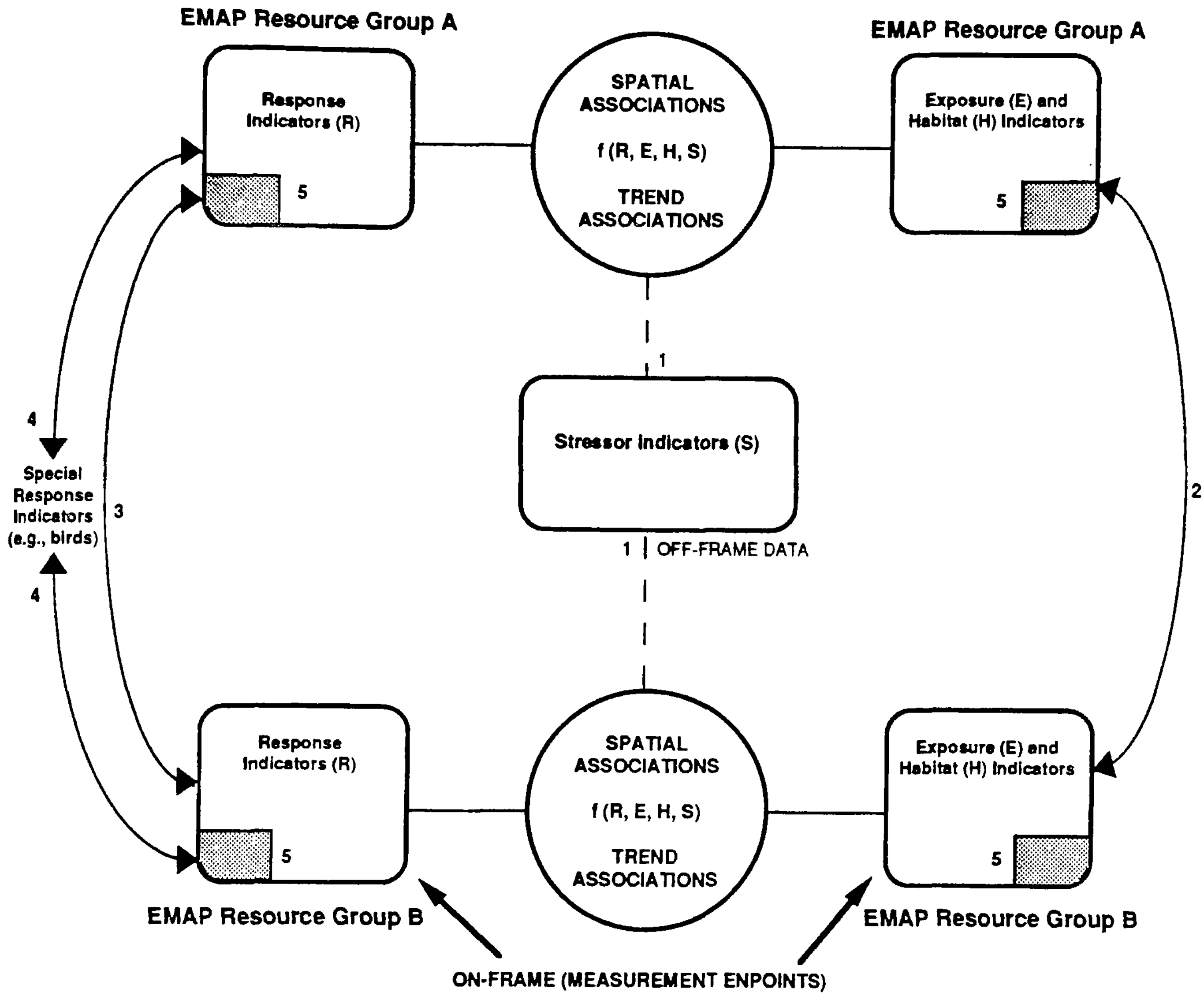
The primary approach to achieving an integrated set of indicators across all resource groups is through communication and information exchange. Within EMAP, the Indicator Coordinator has been assigned responsibility for facilitating and encouraging these activities as they relate to the selection and evaluation of EMAP indicators. The role of the Indicator Coordinator is discussed in greater detail in Section 6. The following subsections describe (1) types of indicators that integrate across ecological resource categories (Section 5.1), (2) extension of the conceptual models described in Section 4.2 to encompass multiple resource categories and linkages among resource groups (Section 5.3), (3) coordination of the indicator development process among groups (Section 5.4), and (4) problems arising from displacement of indicators in space and time (Section 5.5).

5.1 CONCEPTUAL MODEL OF INDICATOR INTEGRATION

Integration of indicator development and application of indicators across all EMAP resource groups involves consideration of a number of factors, including (1) maintaining inter-group communication and interaction to foster development of indicators that will integrate ecosystem level information among different ecological resource groups, (2) assimilating new knowledge, (3) ensuring consistency in the definition of indicator types, (4) providing for consistency in the collection and use of off-frame stressor indicator data, (5) collaborating in identifying special response indicators that integrate across EMAP resource groups (e.g., wide ranging or migratory organisms that use multiple habitats, food sources, etc.), and (6) co-locating sampling units for special studies. Figure 5-1 illustrates these factors. This figure has been expanded from concepts originally presented by Messer (1990) to illustrate interaction between two EMAP resource groups, "A" and "B."

Within EMAP, diagnosing plausible causes of changing trends is secondary to documenting the status and detecting trends in ecological resource condition. Diagnoses will be facilitated, however, if the pathways of interaction between ecological resources are explicitly identified (i.e., what stresses does each ecological resource receive as a result of processes or conditions in other resource categories?). For example, the nutrient balance of a lake may be highly dependent on nutrient fluxes in the surrounding forest. Nutrient flux from the forest may be measured as a response indicator in the forest, but as a stressor indicator for the lake. Such identification will help clarify the off-site stressor indicator data requirements of each EMAP resource group and the level of mutual assistance that is needed to acquire such information. Consistency in using off-site information will improve the abilities of all EMAP resource groups to detect spatial and temporal associations among exposure, habitat, and response indicators and the natural and anthropogenic stressor affecting them, particularly inter-system problems and issues.

Substantial consistency already exists among EMAP resource groups in the definition of response, exposure, habitat, and stressor indicators. This parallelism provides EMAP with opportunities for identifying plausible causal relationships on large regional scales. For example, if the EMAP-Surface Waters resource group detects that nutrients are significantly increasing in streams across a broad region, but data from the EMAP-Agroecosystems resource group indicate no increase in nutrient export from agricultural lands, then other non-point sources (e.g., atmospheric loadings) or point sources (e.g., discharges) may be responsible for the observed trends in aquatic nutrients. Conversely, these noncomplementary data may indicate that the conceptual models being used are inappropriate or incomplete, and should be reexamined. Investigation of associations among indicators to identify potential causes of



This figure shows the types of integration possible for two hypothetical EMAP resource groups, "A" and "B." Response, exposure, and habitat indicators (R, E, and H) represent data collected from EMAP (on-frame), and stressor indicators (S) represent data collected from off-frame investigations. The same relationships apply for all seven resource groups. The types of integration, in general order of priority from EMAP implementation, are:

1. Cross-resource group consistency in off-frame stressor information (external indicators), and intergroup exchange of such data.
2. Cross-resource group consistency in exposure and habitat indicators (e.g., nutrients, chemical contaminants), and indicators that link two or more resource categories.
3. Consistency in thrust of response indicators (e.g., relative abundance of selected animal species).
4. Special response indicators that integrate across resource groups (e.g., birds).
5. Co-location of sampling units for special studies.

Figure 5-1. Methods of indicator integration across EMAP resource groups.

such trends may require cooperative studies by different EMAP resource groups at co-located sites, (sites in the same hexagon monitored by more than one EMAP resource group). These special studies may be conducted as part of Tier 3 or Tier 4 EMAP activities.

At present, different EMAP resource groups are at different stages of implementation: EMAP Great Lakes has identified some core indicators for implementation; EMAP-Near Coastal is conducting a regional demonstration study (Phase 5); EMAP-Forests is undertaking pilot studies (Phase 4); other EMAP resource groups are in Phases 3 or 4 of their indicator selection activities. The differences in phasing among EMAP resource groups is very valuable for learning, as it allows the pioneering groups to pass on lessons learned to other groups. This process began at an indicator strategy workshop in Las Vegas, Nevada, in June 1990, and should be maintained and fostered in EMAP. Circulation of annual research plans, communication of lessons learned through the Indicator Coordinator, and informal inter-group discussions will all be very important for maintaining learning (Section 6.2).

5.2 CATEGORIES OF INDICATORS THAT FACILITATE INTEGRATION

Section 2 identifies four types of indicators: response, habitat, exposure, and stressor. Although all indicators fall within one of these four indicator types, many indicators can also be classified in terms of their contributions to integrative understanding of status and trends and their abilities to contribute to diagnostic evaluations. For these purposes, four categories of integrative indicators have been defined: external (or off-site), linking, common, and migratory. The following paragraphs discuss these categories of indicators.

5.2.1 External or Off-site Indicators

External or off-site indicators reflect external stresses or pressures that arrive from outside a sampling grid cell (hexagon) to affect ecological resource conditions within the grid cell. These indicators are most often anthropogenic in origin (e.g., pesticide applications), but they also include natural forcing functions, such as precipitation or solar radiation, which in turn may be affected by anthropogenic factors (e.g., global climate change) or indirectly by the ecological resources themselves. Many external indicators are anthropogenic, including: human population densities, livestock grazing pressures, atmospheric deposition, emissions of atmospheric pollutants, applications of fertilizers or other nutrients, numbers of fishing and hunting permits, and numbers of discharge permits. Generally, these external indicators are measured or estimated by other EMAP groups, EPA programs, or agencies, rather than by the EMAP resource groups. Gathering and using these data may be extremely important in developing indicators. However, considerable effort may be needed to assemble these data and put them in the proper format.

5.2.2 Linking Indicators

Linking indicators interface one EMAP resource group with another and are often an output from one resource category and an input to another (e.g., nitrogen present as fertilizer applications in agroecosystems and as subsequent runoff to surface waters and wetlands). Thus, linking indicators are measured on the EMAP frame, and the data can be used by more than one EMAP resource group. For example, an index of soil erosion measured by the Forest or Agroecosystem resource group would provide the Wetlands, Surface Waters, and Estuaries resource groups with an indicator of the potential export of sediment, nutrients, or pesticides. Soil and sediments represent sinks for chemical contaminants in all ecosystems. As a result, soil and sediment contaminant data can be used as important links between ecological resources. For example, soil and sediment contaminant measurements would be of importance not only in evaluating forest status but also in assessing potential effects on aquatic receiving systems. However, linking indicators may not be sampled at co-located sites or with common metrics, thus complicating data analyses, synthesis, and integration, as discussed in Section 5.4.

5.2.3 Common or Shared Indicators

Common or shared indicators are measured in multiple resource categories using similar techniques. Examples include wildlife biomarkers, landscape attributes, and commonly used metrics of population or community status, such as relative species abundance. By using consistent sampling and analysis techniques in all resource categories, interpretation of multi-resource patterns in ecosystem status and trends is facilitated. Landscape-level indicators (e.g., mosaic diversity, patch fractal dimensions) may be applicable for many or all resource categories as measures of habitat quality or as surrogates for other indicators that are more difficult to measure (e.g., wildlife density). Biomarkers (e.g., DNA alterations, cholinesterase levels) are common indicators that can be used as a metric of exposure to metals or organic constituents, whether the organism is a plant, fish, or mammal.

5.2.4 Migratory Indicators

Migratory indicators are measures of organisms that move across resource boundaries, from one resource category to another and back again (e.g., honey bees, migratory birds, white-tailed deer). Migratory indicators would be expected to reflect changes in exposure or habitat in one or more ecological resources, and in some cases might indicate cumulative impacts in several resource classes or categories within or outside a region.

Also, response indicators that integrate the effects of ecological resource conditions in multiple regions, resource classes, or resource subclasses (e.g., some birds, amphibians, top carnivores) may be particularly important for detecting the cumulative effects of changes in more than one resource category. Observing such indicators may lead to the detection of stress pathways that had not previously been recognized (e.g., DDT and reduced reproduction in raptors due to eggshell thinness).

5.3 USE OF CONCEPTUAL MODELS TO FACILITATE INTEGRATION

As discussed in Sections 3 and 4, conceptual models are an important tool for formalizing possible relations among indicators, assessment endpoints, and stressors, and for identifying data or knowledge gaps that could be filled through the selection and development of additional indicators. In a similar manner, conceptual models also play a key role in identifying indicator-endpoint-stressor relationships and interactions across resource groups.

Each EMAP resource group will be asked to prepare a conceptual model that emphasizes the major inputs, outputs, and structural and functional attributes of interest for the resource class. Figure 5-2 provides a preliminary example of a model from the EMAP-Agroecosystems resource group depicting, among other linkages, soil erosion as an output from agroecosystems and a potential input to wetland, surface water, and near-coastal environments. These resource-specific conceptual models then provide the basis for integration of needs and results, the framework for which is defined in Section 4.2.

As a first step toward integration among ecological resource group efforts, the individual models developed for each group (e.g., see Figure 4-3) will be compared. This process will (1) help to formalize expected relationships among indicators in different resource groups, (2) ensure consistency in the definitions of response, exposure, habitat, and stressor indicators, (3) encourage the identification and use of linking, common, and migratory indicators, (4) identify commonalities in approach and indicator use among resource groups, and (5) ensure that important processes and linkages are considered within the EMAP monitoring network. Developing, updating, and revising the structural aspects and the inputs and outputs of the individual conceptual models will form the focal point for workshops and small working group discussions, and also the framework for coordinating EMAP indicator development, as outlined in Section 5.3.

5.4 COORDINATION OF THE INDICATOR DEVELOPMENT PROCESS AMONG RESOURCE GROUPS

Five major tasks are planned to facilitate coordination and integration of the indicator development process among ecological resource groups:

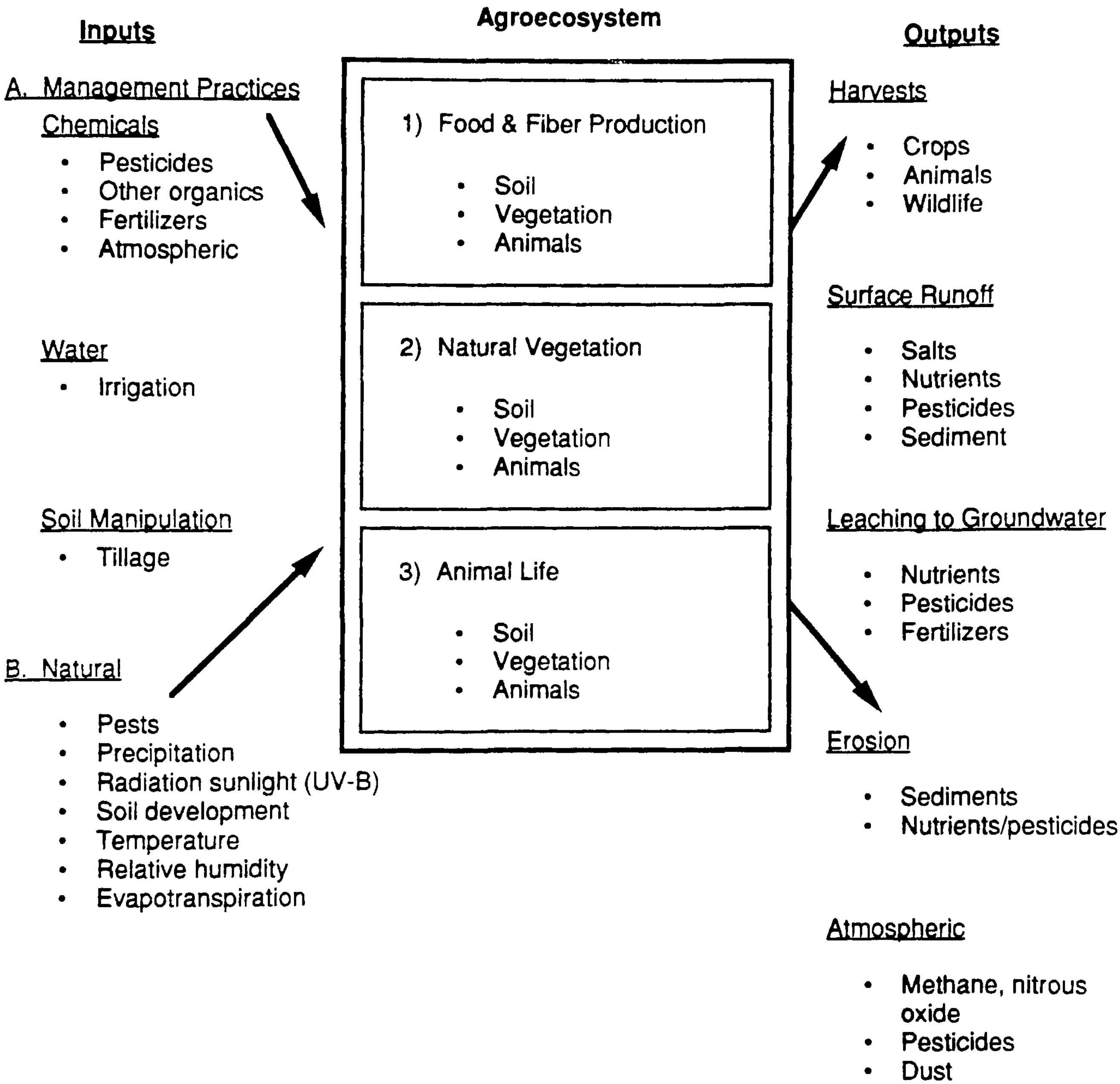


Figure 5-2. Conceptual model of the agroecosystem ecological resource with associated inputs and outputs.

1. Compile and cross reference lists of assessment endpoints, environmental values, stressors, and indicators proposed by each resource group to identify areas of similarity or commonality. Assessment endpoints and environmental problems in different resource categories are, in general, highly interdependent and linked to common stressors. Foliar damage, fish loss, and estuarine eutrophication, for example, can all be related to atmospheric deposition. Compilation of the proposed endpoints, stressors, and indicators serves as the first step towards identifying areas of overlap or, on the other hand, inconsistencies in approach among resource groups. A preliminary listing of the environmental values identified by each resource group is provided in Table 3-1.

2. Conduct one or more workshops involving looking-outward (interaction) matrix exercises to identify linking and stressor indicators that have become necessary or have been overlooked. Interaction matrices are commonly used to develop and chart linkages in computer or simulation models. This same principle or approach can be used to identify possible linkages among resource groups for indicator development. The conceptual models identifying major inputs and outputs for each resource group (see Figure 5-2) provide a starting point for these discussions.

3. Develop conceptual models that identify cross-resource linkages and relationships (see Section 5.3 and Figure 5-1).

4. As appropriate, propose alternate assessment endpoints and indicators that would provide information similar to that provided by the ecological resource group, but would be common or improve comparability with endpoints and indicators being monitored by other resource groups. For example, sustaining biodiversity is an environmental value common to all resource groups. To the degree possible, therefore, it makes sense to assess biodiversity using similar assessment endpoints and indicators in each group. The greater the compatibility of indicators, assessment endpoints, and off-frame stressor information used in the different resource groups, the easier and more direct will be program integration and cross-resource analyses. Direct comparison of responses and effects among resource categories allows for a weight of evidence approach to diagnosing possible causal factors and mechanisms, and thus greater confidence in the EMAP results.

5. For indicators selected by more than one group, examine and compare the proposed field sampling and measurement methods and suggest modifications as needed to improve comparability among groups. Comparable methods and units are also important if comparisons are to be made across resource groups. In some cases, further research may be needed to develop methods applicable to several resource categories. For example, nutrient and pesticide exports from terrestrial systems are typically measured using different techniques and expressed in different units than are estimates of inputs of these constituents to aquatic systems. Selection of the optimal approach for satisfying the needs of both the terrestrial and aquatic resource groups may require additional simulation analyses and/or field testing.

Efforts related to each of the above tasks will involve continually, and the lists, matrices, and models will be updated as needed. Communication among groups will be ensured through regular meetings and workshops involving the technical leads for indicator development from all ecological resource groups. Many of the tasks will also assist in interpreting the EMAP monitoring results, and thus will be conducted cooperatively with the EMAP Integration and Assessment Task Group.

5.5 PROBLEMS ASSOCIATED WITH DIFFERENCES IN INDICATOR SPATIAL AND TEMPORAL SCALES

Indicators monitored by different ecological resource groups will typically not be sampled during the same index period or be co-located in the same sampling unit. This will result in the displacement of indicators in both space and time. Methods for dealing with this displacement, during data analysis or by supplementing the network design (e.g., during Tier 3; see Section 2.1.4), are currently being investigated as part of the EMAP design activities.

For some stressor and exposure indicators, temporal displacement might be desirable; the observed response may be displaced in time from the perturbation that caused the response. For example, soil erosion indices measured during the spring period in agroecosystems and forests, combined with nutrient export coefficients, might correspond better with estimates of summer chlorophyll concentrations in lakes than would export estimates for the summer period. Selection of the optimal index period for indicator measurements must consider, therefore, hypothesized stress-response relationships and the potential displacement that might be required to associate a dependent response variable with an independent stressor or exposure indicator. Expert opinion, obtained during workshops (see Sections 4.4 and 4.5), and peer review will be used to assist in evaluating the importance and effects of temporal displacement.

Spatial displacement is, perhaps, more difficult to evaluate and address. Paired comparisons are generally used for association, and regression analysis is used to relate dependent and independent variables. Indicators linking multiple resource categories, however, may not be co-located. Data analysis techniques are being developed, therefore, to deal with non-co-located data, relying largely on aggregation of regional or subregional EMAP results before conducting diagnostic analyses. For example, aggregation of data by subregions was used during the National Acid Precipitation Assessment Program to identify a linear relationship between sulfate deposition and surface water sulfate concentrations (Figure 5-3).

Analysis of associations at regional or subregional scales is consistent with EMAP's design objectives of determining regional patterns and trends in the status of ecological resources. Most environmental analyses to date, however, have focused on causal relationships at local or site-specific scales. Extension of these techniques to larger spatial scales will require new perspectives and approaches for data aggregation and analysis, and perhaps the development of new indicators better suited for application and interpretation on regional scales. The potential utility of regional-level analyses also hinges, in part, on the degree of intra- versus inter-regional indicator variability, and the spatial scale over which indicator values and variability are relatively homogeneous.

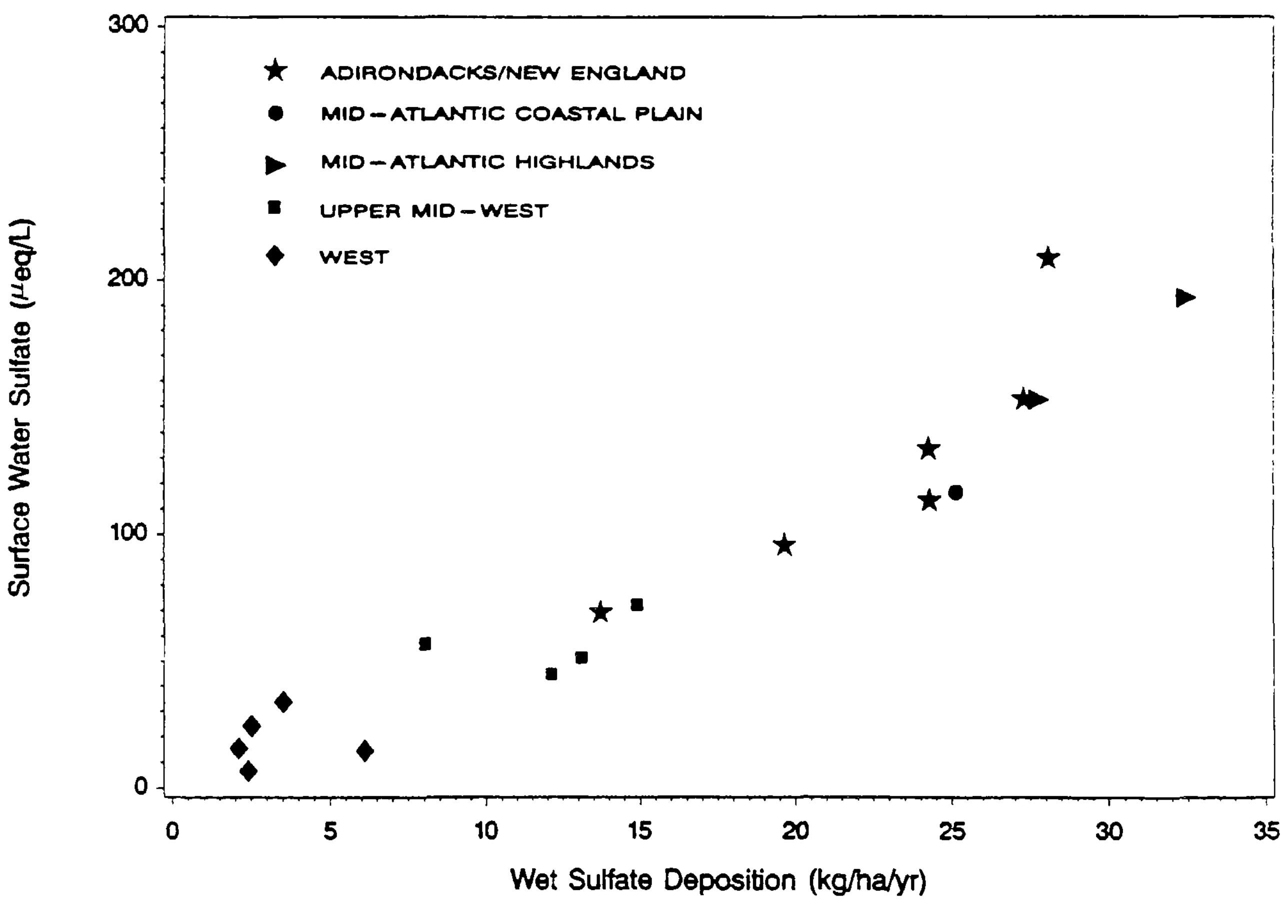


Figure 5-3. **Precipitation sulfate inputs versus surface water sulfate concentration for National Surface Water Survey subregions without significant sulfate absorbing soils.**

Indicator integration both within and across ecological resource categories represents a major challenge; however, the benefits resulting from a successfully integrated program are substantial. The process of integration will require a considerable amount of cooperation, communication, and coordination. The Indicator Coordinator (discussed in Section 6) and the Integration and Assessment Task Group will work jointly to ensure that these necessary levels of interaction and cooperation occur.

6. INDICATOR COORDINATOR

6.1 NEED FOR AN INDICATOR COORDINATOR

It is clear from the preceding sections that indicator development within EMAP will require extensive cooperation and coordination both among ecological resource groups and between these groups and other EMAP components (e.g., task groups dealing with landscape characterization, atmospheric deposition, and statistical design). It will also be necessary to coordinate the monitoring responsibilities of different EMAP resource groups when changes in land use or other landscape changes alter the resource classes being monitored by these groups (e.g., when forests become agroecosystems, or wetlands are created). Furthermore, interactive relationships with other, non-EMAP indicator research programs (e.g., within EPA's Core Research Program) would be highly beneficial. The responsibility for coordinating these efforts, both within EMAP and between EMAP and other research programs, has been assigned to the EMAP Indicator Coordinator and staff.

6.2 ROLE OF THE INDICATOR COORDINATOR

The Indicator Coordinator will play a pro-active role in facilitating communication and the flow of information on indicators among groups, promoting implementation of the indicator development strategy, supporting the integration of indicator development and research results, creating and maintaining an indicator data base, and reviewing indicator research proposals. These functions of the Indicator Coordinator are described in the following paragraphs. In addition, the Indicator Coordinator will identify, enlist, and supervise appropriate staff; prepare annual budget requests; and prepare reports of indicator coordinator activities.

6.2.1 Facilitate Communication

One of the two primary roles of the Indicator Coordinator will be to ensure that all relevant information about indicators is continually exchanged between the ecological resource groups and the appropriate components of the EMAP hierarchy (e.g., Steering Committee, Statistical Design Group, Integration and Assessment Task Group). Within the EMAP organization, the Indicator Coordinator will work closely with all Technical Directors, Technical Coordinators, and Assistant Directors, and their designated representatives. Close contact will be maintained with each ecological resource and task group and with appropriate elements of EPA's Core Research Program and other relevant research programs. The Indicator Coordinator will also review all EMAP and EPA documents relating to indicators, and pass on relevant information to the respective resource groups. In addition, the Indicator Coordinator will provide regular status reports on indicator development to the EMAP Steering Committee and EPA program

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managers. At EMAP management meetings, the Indicator Coordinator will represent concerns relating to indicator development and evaluation. Finally, the Indicator Coordinator will act as a centralized contact point and source of information on EMAP indicators for the external scientific community. Requests for information or funding will be directed to the appropriate resource or task group as needed.

6.2.2 Promote Implementation of the Indicator Development Strategy

The second primary role of the Indicator Coordinator will be to help ensure that the steps and procedures outlined in Sections 4 and 5 of this document are implemented by each ecological resource group. The Indicator Coordinator will work with the EMAP resource groups and the Integration and Assessment groups to (1) develop integrative conceptual models to assist with indicator selection and evaluation, (2) identify linking indicators (that serve as an output from one resource category and an input to one or more other resource categories), and (3) ensure the use of comparable sampling and measurement methods for common or shared indicators. Interactions among resource groups will be promoted through periodic (approximately twice per year) inter-group meetings and workshops on indicators as well as regular exchange of written materials and information. At least one workshop per year will focus on broad indicator issues of broad relevance to EMAP. Based largely on discussions at this workshop, the Indicator Coordinator will update this Indicator Development Strategy on a yearly basis until at least 1995. The Indicator Coordinator will attend key meetings (e.g., annual reviews) organized by the individual ecological resource groups and related task groups (e.g., landscape characterization). As needed, the Indicator Coordinator can be called upon by individual EMAP resource groups to provide assistance in obtaining information or cooperation in monitoring indicators from other EMAP groups. As noted in Section 5, many of these tasks will be conducted in close cooperation with the Integration and Assessment Task Group, responsible for ensuring a coordinated and integrated interpretation of the EMAP indicator monitoring results. The Indicator Coordinator should assist EMAP resource groups in preparing descriptions of their needs for indicators and their long-term plans for meeting those needs.

6.2.3 Create and Maintain an Indicator Data Base

The purpose and format of the indicator data base are described in Appendix A. Management of this data base will be coordinated with the EMAP Information Management Center (Information Management Group, 1990). The Indicator Coordinator, however, will be responsible for technical oversight of the content, accuracy, and completeness of the data base as a record of the indicator development process. The Indicator Coordinator will work with the Information Management Center to develop the data base design and procedures for quality control, and to facilitate access to the data base by all interested parties. The data base will be used to obtain up-to-date information on the status of all indicators and as a means of cross-checking indicators among ecological resource groups. Beginning on the first day of the first complete quarter following appointment, the Indicator Coordinator will generate quarterly reports from the data base and distribute them to all ecological resource groups and other appropriate EMAP personnel. These quarterly reports will subsequently be produced on the first day of the months of January, April, July, and October of each year.

6.2.4 Review Indicator Research Proposals

Research to identify new indicators or evaluate existing indicators within the EMAP framework will be initiated and directed primarily by the EMAP resource groups. Such research will be initiated either from within EMAP or by interested researchers in other agencies or institutions, as described in Section 7. A role of the Indicator Coordinator will be to work with the Steering Committee to develop a process to receive, review, and select for funding proposals for indicator research from EMAP resource groups and from outside EMAP The Indicator Coordinator will play an active role in reviewing research proposals as well as final project reports. On an as requested basis, the Indicator Coordinator will organize and implement external peer review of proposals received by EMAP resource groups or the Steering Committee. As EMAP develops, the Indicator Coordinator may initiate proposals to develop linking, shared, or migratory indicators, or any other indicators that may be needed by EMAP, but do not clearly fall within the responsibility of a single EMAP resource group. The Indicator Coordinator will also monitor ongoing and planned research on indicators outside EMAP by maintaining regular contact with appropriate research agencies and programs. The EMAP ecological resource groups and other relevant personnel will be provided with updates on major findings or new initiatives. A second objective of the regular contacts with other research programs is to encourage the funding of indicator research of direct relevance to EMAP.

7. PROCEDURES FOR INITIATING INDICATOR RESEARCH

Two types of indicator research are envisioned within EMAP: supplemental research and new initiatives. Supplemental research is conducted specifically to fulfil a defined need within the indicator development process for selected candidate, research, or probationary core indicators. Activities include literature reviews, data base searches, simulation modeling, methodology development, and participation in field pilot studies. By contrast, new initiative research is directed toward identifying new indicators needed to fill important gaps or data needs within the EMAP monitoring network. Funding levels and the relative effort applied for each type of research are decided principally by the individual resource groups and the Steering Committee. Research can be proposed and performed by any qualified researcher in EMAP groups, federal and state agencies, universities, or other research organizations or businesses. The Indicator Coordinator's (see Section 6) role is to advise, encourage, and facilitate research on indicators, especially those that integrate across resource groups.

Requests for specific supplemental research tasks originate within the ecological resource groups. Solicitations will be announced as needed. New initiative research, however, may arise as either solicited or unsolicited proposals. Requests for proposals will be issued annually by the ecological resource groups. To the degree possible, these solicitations will be coordinated closely with research planning and proposal requests from EPA's Core Research Program. Interactions with EPA's Core Research Program are primarily the responsibility of the Indicator Coordinator. Unsolicited proposals for research on indicators pertinent to a single EMAP resource group should be sent to the Technical Director of the appropriate group. Research proposals involving indicators that integrate across resource groups (external, linked, or shared indicators) should be sent directly to the Indicator Coordinator.

Proposal reviews will be conducted jointly by members of the EMAP ecological resource group sponsoring the research, the Indicator Coordinator, and a panel of outside experts. The Indicator Coordinator is responsible for ensuring that consistently high standards of research quality are maintained across all resource groups. In addition, the Indicator Coordinator must be notified and will keep track of all funding decisions and provide regular reports on indicator research, planned and ongoing, to the EMAP Steering Committee.

This strategy document provides information that can be used to evaluate unsolicited and competitive proposals for research on specific indicators. It does not, however, provide guidance or criteria for prioritizing proposals for different types of indicators, or for establishing priorities for indicator research between different EMAP resource groups. These processes require evaluation of the relative importance of the various assessment endpoints being considered by specific EMAP resource groups. These evaluations must take into account user needs (both within the specific resource group and across resource groups), relative importance of issues, and political and funding realities. Most of the information for setting priorities should come from the EMAP resource group research plans. Additional information needed to guide the preparation and evaluation of research proposals can be obtained from the Indicator Data Base and annual statistical summaries of the different resource groups.

8. REFERENCES

Einhaus, R.L., D.M. McMullen, R.L. Graves, and P.H.Friedman. 1990. Environmental Monitoring and Assessment Program Quality Assurance Program Plan. U.S. EPA, Office of Research and Development. Environmental Monitoring Systems Laboratory, Cincinnati, OH.

Fava, J.A., W.J. Adams, R.J. Larson, G.W. Dickson, and W.E. Bishop. 1987. Research priorities in environmental risk assessment. Soc. Environ. Toxic. Chem. Washington, D.C.

Franklin, J.F., C.S. Bledsoe, and J.T. Callahan. 1990. Contributions of the long-term ecological research program. Bioscience 40:509-523.

Hughes, R.M. 1989. Ecoregional biological criteria. Pages 147-151 in Water Quality Standards for the 21st century. U.S. EPA, Office of Water, Washington, D.C.

Hunsaker, C.T., and D.E. Carpenter (eds.). 1990. Ecological indicators for the Environmental Monitoring and Assessment Program. EPA 600/3-90/060. U.S. EPA, Office of Research and Development, Research Triangle Park, NC.

Information Management Group. 1990. Environmental Monitoring and Assessment Program Information Management Program Plan--FY 90/91. Draft Report. U.S. EPA Environmental Monitoring Systems Laboratory, Las Vegas, NV.

Karr, J.R., D.D. Fausch, P.L. Angermeir, P.R. Yant, and I.J. Schlosser. 1986. Assessing biological integrity in running waters: A method and its rationale. Spec. Pub. No. 5. Illinois Natural History Survey, Champaign, IL. 28 pp.

Messer, J.J. 1990. EMAP Indicator Concepts. Pages 2-1 through 2-26 in C.T. Hunsaker and D.E. Carpenter, eds. 1990. Ecological Indicators for the Environmental Monitoring and Assessment Program. EPA 600/3-90/060. U.S. EPA, Office of Research and Development, Research Triangle Park, NC.

Meyer, J.R., C.L. Campbell, T.J. Moser, J.O. Rawlings, and G. Hess. 1990. Indicators of the ecological status of agroecosystems. Presented at the International Symposium on Ecological Indicators, Ft. Lauderdale, FL.

National Academy of Sciences. 1975. Planning for Environmental Indices (Report of Planning Committee on Environmental Indices to the Environmental Studies Board). Washington, D.C.

O'Neill, R.V. 1988. Hierarchy theory and global change. Pages 29-45 in T. Rosswall, R.G. Woodmansee, and P.G. Risser, eds. Scales and global change: Spatial and Temporal Variability in Biospheric and Geospheric Processes. John Wiley & Sons, New York.

Ott, W.R. 1978. Environmental Indices: Theory and Practice. Ann Arbor Science Publ., Ann Arbor, MI. 371 pp.

Overton, W.S., D.L. Stevens, C.B. Pereira, P. White, and T. Olsen. 1990. Design Report for EMAP, Environmental Monitoring and Assessment. Program (Draft). A report to the U.S. EPA Environmental Research Laboratory - Corvallis. Oregon State University, Corvallis, OR.

Paulsen, S.G., D.P. Larsen, P.R. Kaufmann, T.R. Whittier, J.R. Baker, D.B. Peck, J. McGue, D. Stevens, J.L. Stoddard, R.M. Hughes, D. McMullen, J. Lazorchak, and W. Kinney (with contributions by: S. Overton, J. Pollard, D. Heggem, G. Collins, A. Selle, M. Morrison, C. Johnson, S. Thiele, R. Hjort, S. Tallent-Halsell, K. Peres, S. Christie, and J. Mello). 1990. EMAP-Surface Waters Monitoring and Research Strategy - Fiscal Year 1991. Peer Review Draft. Prepared for U.S. EPA Environmental Research Laboratory, Corvallis, OR.

Rapport, D.J., H.A. Regier, and T.C. Hutchinson. 1985. Ecosystem behavior under stress. Amer. Nat. 125:617-640.

Rapport, D.J. 1989. What constitutes ecosystem health? Perspectives in Biology and Medicine 33(1):120-132.

Reilly, W.J. 1989. Measuring for environmental results. Pages 2-4 in EPA Journal, May/June, 1989.

Ritters, K., K. Hermann, and R. Van Remortel. 1990. Forest Task Group Annual Statistical Summary, Hypothetical Example. Prepared for U.S. EPA, Office of Research and Development, Research Triangle Park, NC.

Sala, O.E., W.P. Parton, L.A. Joyce, and W.K. Lauenroth. 1988. Primary productivity of the central grassland region of the United States. Ecology 69:40-45.

Suter, G.W. 1990. Endpoints for regional ecological risk assessments. Environ. Manage. 14:9-23.

Westman, W.E. 1985. Ecology, Impact Assessment, and Environmental Planning. Academic Press, New York.

Wiens, J. 1989. Spatial scaling in ecology. Functional Ecology 3:385-387.

U.S. EPA Science Advisory Board. 1990. Evaluation of the Ecological Indicator Report for EMAP. Report of the Ecological Monitoring Subcommittee of the Ecological Processes and Effects Committee. EPA-SAB-EPEC-91-001. Washington, D.C.

APPENDIX A

INDICATOR DATA BASE

Each EMAP resource group will compile and maintain information about its indicator development activities in the Indicator Data Base (IDB), which will be managed by the EMAP Information Management Center (Information Management Group, 1990). As described in Section 6, the Indicator Coordinator will be responsible for technical oversight of the content, accuracy, and completeness of the data base as it records the indicator development process.

The IDB should be used to store up-to-date information about each indicator being evaluated or considered by each EMAP resource group. The data base should contain all pertinent information about each indicator ever considered by the resource group, including at least the level of detail presented on the indicator fact sheets in the appendices to the Indicator Report (Hunsaker and Carpenter, 1990). Once an indicator is listed, it should never be deleted from the data base, although it can be deleted from further consideration (status: rejected) or revised and refined during later stages of indicator development.

As information is developed in the process of evaluating indicators in each of the phases of this strategy, it should be added promptly to the IDB. Data base listings for each indicator should be initiated during the identification of candidate indicators (Phase 2) and updated during each of the subsequent phases of the indicator development process (described in Sections 4.5-4.8). Indicator information entered into the data base should be kept simple and short, to make the data base easy to update. It is extremely important for each ecological resource group's indicator data base to be updated frequently. Not all informational categories accommodated by the data base will be evaluated during the first phases of indicator development; therefore, it will not be possible to complete all data base entries while updating records for each indicator. The appropriate results from each phase of the development process should be entered into the data base following completion of that phase of development.

Although the design of the data base has not been completed, the structure and format of the indicator data base must be consistent across all EMAP resource groups. This consistent structure will allow for information exchange and synthesis. Data base entries should be brief and reasonably easy to complete. Possible information categories in the final IDB could include the following:

- ***EMAP Resource Group:*** *This is the EMAP resource group that is evaluating the indicator* (e.g., Arid Lands, Forests).
- ***Indicator Title:*** This is a brief, descriptive name (e.g., agricultural pest density, tree growth efficiency, fish gross pathology).

- **Endpoint Assessed by the Indicator:** This is the name of the assessment endpoint (taken from the group's conceptual model) and whether the indicator is a direct metric of the endpoint or is one of several metrics necessary for assessment of the endpoint (see Figure 4-1).

- **Indicator Type:** This entry is composed of the indicator type and the descriptor (e.g., Response-Community Structure; Exposure-Bioassay). Indicator types include response, exposure, habitat, and stressor. A given indicator may fit into more than one type. Descriptors include those structural or functional features of the indicators that most clearly and concisely describe the purpose of measuring (e.g., ecosystem process rates, community structure, populations, sensitive species, bioassay, ambient concentrations, tissue concentrations, pathology, pathogens, landscape, habitat, biomarkers, exotics, genetically engineered microorganisms). Other descriptors (e.g., retrospective) should be added for clarification.

- **Status:** This information includes two components: (1) the indicator's present position in the selection process and (2) the current level of evaluation activity associated with the indicator. The position in the selection process is assigned one of four conditions: candidate, research, developmental, or core, depending on the level of evaluation the indicator has passed (all indicators addressed in Phase 1 should be identified as potential candidate indicators, even though they may be rejected in Phase 2). The current level of evaluation activity represents one of three conditions: active, rejected, or suspended. Active indicators are currently being assessed or are scheduled for research and evaluation in the near-term. Rejected indicators have been identified as unacceptable for further evaluation, at least at the present time. Indicators that are suspended appear to be promising, but are not actively being evaluated due to limitations in the availability of funding, time, data, or technology. For example, Research-Active denotes that the indicator has reached the research stage of evaluation and is actively being tested. Core-Rejected denotes an indicator previously accepted as a core indicator, but subsequently deleted, replaced, or modified.

- **Application:** This is a concise description of the applicability of the indicator. This identifier should indicate the degree of interclass (as opposed to local or single ecological resource subclass) applicability. This entry should also display the degree of linkage of the indicator to other EMAP resource groups (e.g., more than one group measuring the same indicator, such as Agroecosystems and surface Waters both monitoring pesticide levels), and the degree to which the indicator integrates effects among resource classes (e.g., migratory birds that utilize both estuarine and wetland habitats).

- **References:** A brief listing of the sources of relevant information about the indicator should be included. This information should include the source of information leading to the selection of the indicator. It may include citations of workshop reports, unpublished reports, published literature, and personal communications. This section is not intended to be a comprehensive listing at this stage; however, it is important that all documentation be available to justify the process of moving an indicator from one position to the next.

- **Justification:** The summary of the reasons for accepting or rejecting the indicator as a research indicator should be concise, yet contain sufficient detail to allow verification of the validity of the decision. Providing the reasons for rejecting or suspending the indicator is just as important as the justification for acceptance. Justifications for acceptance and rejection should be based on the criteria listed in Figure 4-5, though there may be other valid reasons for either decision. Other reasons for acceptance include:

  - The proposed indicator fills an important gap covering an aspect of environmental condition that is not yet covered by a core indicator.

  - The proposed indicator promises to provide higher quality data (or data of equivalent quality at lower cost) than is being provided by existing indicators.

- The indicator provides important information for diagnosing ecological condition in another EMAP resource group's program.

The most probable reasons for suspending an indicator are:

Although the proposed indicator is potentially useful, research efforts are concentrating on other types of indicators (i.e., it is impossible to pursue all promising indicators at once).

- Additional basic information is needed about the candidate indicator before it can be properly evaluated as a research indicator.

Index Period: The preferred time period for measuring the proposed indicator should be addressed. Notes should be included on both the empirical justification for the proposed index period and practical problems associated with sampling during this period. Reference should be made to temporal variation of the indicator during the index period at different geographic locations.

Measurements: The database should list possible field and laboratory methods, identify the preferred methods, and provide references for each approach. The analytical and logistical details of each method should not be presented, but remarks highlighting differences in the type, quality, or cost of the data should be included.

Variability: Information and expert judgments concerning the relationship between natural spatial and year-to-year temporal variability in the indicator and the expected magnitude of a change in ecological condition should be included in the data base. Estimates of the measurement error associated with indicators (both sampling and analytical methods) should also be included.

Primary Problems: A list of the major issues that need resolution through subsequent EMAP research should be presented. This listing should identify the expected magnitude of the effort (i.e., literature search, pilot studies) needed to resolve the issues.

References: Both summary documents prepared for EMAP and selected key primary references should be recorded. These lists should be frequently updated.