INTEGRATING THE NATION'S ENVIRONMENTAL MONITORING AND RESEARCH NETWORKS AND PROGRAMS:

A PROPOSED FRAMEWORK

By
The Environmental Monitoring Team
Committee on Environment and Natural Resources
National Science and Technology Council

March 1997

The purpose of this report is to highlight ongoing Federal research efforts in this science and technology (S&T) field and to identify new and promising areas where there might be gaps in Federal support. The report is intended for internal planning purposes within the Federal agencies and as a mechanism to convey to the S&T community the types of research and research priorities being considered and sponsored by the Federal agencies. The administration is committed to a broad range of high priority investments (including S&T), deficit reduction, and a smaller, more efficient government. These commitments have created a very challenging budget environment--requiring difficult decisions and a well thought-out strategy to ensure the best return for the Nation's taxpayer. As part of this strategy, this document does not represent the final determinant in an overall administration budget decision-making process. The research programs in this report will have to compete for resources against many other high priority Federal programs. If these programs compete successfully, then they will be reflected in future administration budgets.

About the National Science and Technology Council

President Clinton established the National Science and Technology Council (NSTC) by Executive Order on November 23, 1993. This cabinet-level council is the principal means for the President to coordinate science, space, and technology policies across the Federal Government. The NSTC acts as a "virtual" agency for science and technology to coordinate the diverse parts of the Federal research and development enterprise. The NSTC is chaired by the President. Membership consists of the Vice President, the Assistant to the President for Science and Technology, Cabinet Secretaries and Agency Heads with significant science and technology responsibilities, and other senior White House officials.

An important objective of the NSTC is the establishment of clear national goals for Federal science and technology investments in areas that range from information technology and health research to improving transportation systems and strengthening fundamental research. The NSTC prepares research and development strategies that are coordinated across Federal agencies to form an investment package that is aimed at accomplishing multiple national goals.

To obtain additional information about the NSTC, contact the NSTC Executive Secretariat at 202-456-6100.

About the Committee on Environment and Natural Resources

The Committee on Environment and Natural Resources (CENR) is one of nine committees under the NSTC and is charged with improving coordination among Federal agencies involved in environmental and natural resources R&D, establishing a strong link between science and policy, and developing a Federal environment and natural resources R&D strategy that responds to national and international issues.

To obtain additional information about the CENR, contact the CENR Executive Secretary at 202-482-5917.

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The Office of Science and Technology Policy (OSTP) was established by the National Science and Technology Policy, Organization, and Priorities Act of 1976. OSTP's responsibilities include advising the President on policy formulation and budget development on all questions in which science and technology are important elements, articulating the President's science and technology policies and programs, and fostering strong partnerships among Federal, State, and local governments and the scientific communities in industry and academia.

To obtain additional information about the OSTP, contact the OSTP Administrative Office at 202-456-6004.

March 19, 1997

Dear Colleague:

I am pleased to introduce the National Science and Technology Council (NSTC) report “Integrating the Nation’s Environmental Monitoring and Research Networks and Programs: A Proposed Framework.” This report is the result of a thorough study of the Nation’s existing major Federal environmental monitoring and related research networks. It has benefited enormously from the insights of Federal and non-Federal stakeholders in the review process and in national and regional workshops.

In his written remarks to participants at the National Workshop on Environmental Monitoring and Research in September 1996, Vice President Gore stated that:

> Environmental monitoring is the foundation for the scientific information necessary to make wise decisions key to meeting the twin goals of continued vigorous economic growth and preservation of our magnificent natural heritage for generations to come. Environmental monitoring must also be available to the public to inform them and facilitate their participation in our democracy. The knowledge we gain from improved monitoring of our rivers, forests, oceans and air is the knowledge we need to make informed decisions. This understanding is one of the pillars of our bridge to the twenty-first century.

This report proposes a national framework for integrating environmental monitoring and related research on the Nation's ecological systems and resources. The framework links systematic observations and monitoring of ecological systems and resources with predictive modeling and process research. This linkage will provide the information needed to improve documentation of status and trends in the ecosystems and natural resources of the United States. Integration of our environmental monitoring and research networks will also provide the knowledge base required for selecting management approaches that ensure ecosystem and resource sustainability.

Sincerely,

John H. Gibbons
Assistant to the President
for
Science and Technology

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Executive Summary

A fundamental improvement in the way that the United States monitors its environment is required if we are to meet the challenges facing us during the next several decades. Current monitoring programs do not provide integrated data across multiple natural resources at the various temporal and spatial scales needed to develop policies based on current scientific understanding of ecosystem processes. New developments in science and technology provide new opportunities for collecting and organizing data that could greatly expand our capabilities for meeting agency missions. With the current fiscal limitations facing all levels of government, cooperation among agencies is essential to the long-term success of any individual program. The time is right for the integration of monitoring programs, even those aimed at specific resources, to create a vision for the environment as a whole.

The combined Federal environmental and natural resources research budget totaled more than $5 billion in fiscal year 1995. About $650 million of this amount was focused on activities in about 30 major Federal environmental monitoring and research networks and programs. Although the associated programs, activities, and networks were established in response to specific legislation about specific resources and issues, they can be better integrated to provide information needed for effective ecosystem management. Similarly, the networks can be better integrated to provide information synthesis across a range of spatial scales.

The Nation needs a strategy for environmental monitoring and research that will enable comprehensive assessments of its natural resources. Such a strategy is essential if we are to differentiate between actual and perceived environmental issues and address them appropriately to avoid unnecessary regulation and serious environmental problems. Federal agencies currently conduct assessments of resources, habitats, and specific issues (e.g., climate change and acid rain) at a variety of scales. For example, the U.S. Global Change Research Program is working through the Intergovernmental Panel on Climate Change to develop assessments of climate change and with the World Meteorological Organization to study changes in the stratospheric ozone layer. At regional scales, agencies routinely prepare assessments of the status of resources (e.g., fisheries and forests) and habitats (e.g., water quality and soil type). At local scales, assessments are performed daily in support of permit evaluations and other local or State decision-making.

These specific assessments are valuable and must be continued to meet current missions and mandates. However, a critical need exists to synthesize this information to increase our understanding of the significance of interactions among resources, their linkages to variations in the natural and human environment, and their responses to multiple drivers of change. These integrated environmental assessments should identify environmental and ecosystem trends, relate these trends to their causes and consequences, and predict outcomes of alternative future scenarios. These components should be developed in a sequential and coordinated manner as follows:

1. **Status of ecosystems.** Document coincident status and trends of multiple resources and related environmental and socioeconomic conditions.

2. **Causes and consequences of change.** Using the best scientific information available:
    - Relate status and trends to human and natural causes and consequences,
    - Predict future trajectories and rates of change,
    - Assess uncertainties, and
    - Identify data, information, and research needed to reduce future uncertainties.

3. **Options and outcomes.** Evaluate science-based approaches for ensuring sustained productivity, vitality, use, and enjoyment of ecological systems.

This report proposes a conceptual framework (hereafter, referred to as the "Framework") for integrating the Nation's environmental research and monitoring networks to deliver the necessary scientific data and information to produce integrated environmental assessments. These integrated assessments will allow understanding, evaluation, and forecasting of renewable natural resources at national and regional scales. The Framework can link inventories and remote sensing, national and regional resource surveys, and intensive monitoring and research sites with research and modeling to produce an integrated national environmental monitoring program. It can also enhance and support our understanding and predictive capability of the causes and consequences of environmental change and ecosystem response, address multiple scales of ecosystem and resource interactions, and allow ecosytem level syntheses and assessments of data and information. This is the "value added" that network integration can provide that our existing array of fragmented single-purpose monitoring and research networks cannot.

The proposed Framework is designed to be a collaborative effort building upon existing networks and programs, facilitated by any necessary standardization and data-management infrastructure. Most importantly, this Framework and related ecological research will provide both data and understanding of ecosystem condition and sustainability at the scale where policy and management decisions are most effectively made.

The following summary of recommendations suggests several ways to begin to design and implement the overall vision of the Framework.

RECOMMENDATIONS FOR A NATIONAL ENVIRONMENTAL MONITORING FRAMEWORK

1. Make integration of environmental monitoring and research networks and programs across temporal and spatial scales and among resources the highest priority of the Framework.

2. Increase the use of remotely sensed information obtained for detecting and evaluating environmental status and change by coordinating these analyses with ongoing in-situ monitoring and research efforts.

3. Ensure full utilization of the data standards being developed for map and remotely sensed data (by the Federal Geographic Data Committee) to ensure interoperability.

4. Evaluate existing surveys for coverage of environmental issues, resources, and geographic areas. Determine which surveys should be included in the Framework.

5. Ensure common definitions, models, data management systems, and areal coverage through cooperation with the Federal Geographic Data Committee.

6. Identify critical regional and national resources or issues that are not addressed by the current surveys and initiate surveys to address them.

7. Collect data for various national and regional resource surveys at the same or compatible locations, where appropriate.

8. Evaluate alternatives for selecting the number and distribution of index sites, including stratification by ecoregion in order to provide the geographical coverage necessary for national assessments, stratification by known and anticipated environmental stresses, location along environmental gradients or transition zones between ecoregions, and unique aspects of terrestrial, freshwater, estuarine, and coastal ecosystems.

9. Establish a network of "index sites" by integrating existing intensive monitoring and research sites and adding new sites as needed to provide standard information on major independent and dependent environmental variables that are known to influence resource conditions.

10. Collocate national and regional survey measurements at index sites.

11. Use data from resource inventories and remote sensing for characterizing and detecting changes at index sites.

12. Select a common set of core variables to be measured at all index sites.

13. Select variables that are responsive to policy needs.

14. Ensure that the variables being measured and the locations where they are measured are sensitive to environmental change.

15. Ensure that the measurements are comparable with those of appropriate international monitoring programs.

16. Establish and maintain strong linkages between integrated monitoring and research programs proposed by the Framework and similar international programs.

17. Support the efforts of the Federal Geographic Data Committee to develop a National Geospatial Data Clearinghouse to promote information access and data sharing.

18. Establish a geo-referenced data base of ongoing environmental monitoring programs on the INTERNET.

19. Establish standards and protocols for data comparability and quality as integral components of the Framework.

20. Disseminate all Framework information and data in a timely manner, employing a range of communication strategies.

21. Establish policies for data confidentiality, ownership, and accessibility.

22. Establish a national interagency coordinating body to implement the Framework and oversee recommended actions.

23. Establish an independent panel to provide scientific and technical review of activities within the Framework.

24. Adopt performance-based protocols for quality control and data and information management that apply to all components of the Framework, and establish a national quality control program.

1. Introduction

The Nation depends upon its abundant and diverse renewable natural resources. Whether one is concerned with sustaining resources to allow economic growth for current and future generations or believes that a healthy and diverse environment is an essential part of a quality life, continued ecosystem viability is the central environmental challenge facing society today. Furthermore, because environmental degradation, ecological damage, and depletion of natural resources can easily give rise to conflict among nations, continued ecosystem viability is an issue of national security (National Science and Technology Council, 1995a).

The Nation needs to know the status of its soil, water, air, plants, and animals and, if they are changing, why and how that change is taking place. Cases of economic losses resulting from both natural processes and anthropogenic changes to the environment are now common. A sustainable supply of critical renewable natural resources, healthful environmental conditions, and the capability to predict, understand, and resolve environmental problems must be a national priority for environmental and renewable natural resources programs. In this report, renewable natural resources include air, soil, water, plants, and animals of both terrestrial and aquatic systems. This report only addresses the monitoring of nonrenewable natural resources, such as oil, gas, and minerals, in the context of their association with renewable resources.

Currently, responsibilities for research, monitoring, and assessment of various natural resources are divided among various Federal agencies, whose activities are focused on achieving specific programmatic objectives. Consequently, a number of research and monitoring programs exist, but none is designed to support a comprehensive, scientifically based evaluation of the condition of the environment and its ability to sustain our population.

This report has the following main objectives:

1. To summarize information about major Federal environmental monitoring and related research networks and programs.

2. To propose a conceptual framework for integrating the Nation's environmental monitoring and research networks and programs across temporal and spatial scales and for multiple natural resources.

3. To provide general recommendations for achieving the integration prescribed by the conceptual framework.

4. To propose actions needed for a design and implementation phase for the conceptual framework.

Interpretation of observed changes in the environment and in renewable natural resources requires the hierarchical linking of monitoring programs across temporal and spatial scales and resources. Similarly, causes of observed changes in environmental conditions and prediction of potential future changes require an improved understanding of the structure and function of managed and wildland ecosystems, the interactions among ecosystem components, and the combined effects of natural and anthropogenic environmental changes on these systems.

The combined experience of scientists and resource managers over the past several decades has led to a national awareness that ecosystems are not made up of a set of separate and independent resources. Instead, the resources interact in ways that ultimately determine ecosystem condition. Current environmental monitoring programs, although effective at tracking specific components of ecosystems, are considered by many resource managers to be inadequate in providing critical information on how various components interact. This has been recognized in many reports and reviews by many independent groups (Council of State Governments (Center for Environment and Safety), 1995; Interagency Ecosystem Management Task Force, 1995; Government Accounting Office, 1994; United Nations Economic Commission for Europe, 1993).

While the potential value of and need for a national environmental monitoring strategy has long been recognized, previous attempts to establish and implement one have been unsuccessful. Common themes in many of the previously proposed strategies include the need for protected sites to have sustained, long-term observations in representative biomes and ecosystem types and to operate the sites as a national network. A congressional hearing in the 1970's on establishing such a national network of sites for ecological research and monitoring found that this country not only lacked a comprehensive network of sites for making systematic and continuous observations of its ecological systems and resources, but that the scientific potential of existing sites was undeveloped and underutilized. Other findings were that a method or approach for organizing the existing sites into a national network was needed and that to be successful, such a network should not be subject to the funding and institutional vagaries of individual administrative agencies (Council on Environmental Quality and Federal Council on Science and Technology, 1974; The Institute of Ecology and National Science Foundation, 1977; U.S. House of Representatives, 1977, 1978; University Corporation for Atmospheric Research, 1985; United States Man and Biosphere Program, 1993, 1994; Heal et al., 1993; American Academy of Microbiology, 1994; National Science Foundation, 1993).

In 1993, the National Science and Technology Council (NSTC) joined with the National Academy of Sciences to convene a panel of experts from across the Nation that discussed and recommended priority directions for Federal environmental science programs. The Federal agencies, through the NSTC Committee on Environment and Natural Resources (CENR), conducted a comprehensive review of how existing programs fit with the identified priorities and whether modification or redirection was needed (National Science and Technology Council, 1995b). Subsequently, the CENR Ecosystem Working Group was formed to synthesize ecosystem research priorities among the resource subcommittees of CENR.

The Ecosystem Working Group's report (National Science and Technology Council, 1995c) recommended a common national goal for the science of ecosystems: **"to understand, predict and manage our ecological systems for their sustained use (e.g., ensuring their continued and sustained vitality, diversity, and abilities to provide important resources, services for humans, and habitat) and enjoyment (e.g., recreational opportunities and cultural values)."** It also recommended actions to meet this goal, including the following:

1. Periodic regional and national environmental syntheses that integrate and evaluate information on the status, extent, trends, and projected changes of all relevant ecosystem and natural resource components; the social, economic, and ecological value of these resources; and possible future resource availability and productivity when various technological, management, and policy options are applied; and

2. A focused research and monitoring program that improves the information base needed to conduct regional, national, and international syntheses.

To provide the information required for regional and national environmental syntheses and assessments, a team of Federal scientists and program managers (the Environmental Monitoring Team) was convened by the CENR Steering Committee in July 1995 with the charge **"to develop a national framework for integration and coordination of environmental monitoring and related research through collaboration and building upon existing networks and programs."**

The CENR Environmental Monitoring Team responded to the charge by producing this report on a proposed framework (hereafter, referred to as the “Framework”) for integrating the Nation's major environmental monitoring and research networks and programs to allow understanding, assessment, evaluation, and forecasting of the Nation's renewable natural resources at national and regional scales. The Framework can enhance and support our understanding and predictive capability of the causes and consequences of environmental change and ecosystem response, address multiple scales of ecosystem and resource interactions, and allow ecosytem-level syntheses and assessments of data and information. This is the added value that network integration can provide, which our existing array of fragmented single-purpose networks cannot.

The guiding principles for the Framework require it to be driven by policy needs and by scientific understanding, based on sound scientific and statistical methods, and interagency cooperation (i.e., State, Federal, Tribal, private, and international). It should be built from existing successful "keystone" environmental monitoring and research networks and programs. It must also be cost-efficient, continuous over the long run, and interoperable (i.e., producing comparable data through standard procedures). It must be adaptive so that it can evolve and innovate without losing the value of historical data sets and be accessible to all public and private sectors.

A successfully integrated program must be able to address the variety of national environmental issues of current and potential future concern; for example:

1. How do air quality, atmospheric deposition of chemicals, surface- and ground-water quality, and climate vary across the country, and what are their effects on renewable natural resources?

2. How do the concentrations of potentially damaging pollutants and the spectral composition of sunlight vary across the country, and what are their effects on renewable natural resources?

3. Where and why are nonnative species of plants, animals, and pathogens becoming established across the country, and what are their effects on natural resources and human health?

4. How are patterns of land and water use changing across the country, and what are their effects on natural resources and human health?

At a recent workshop, a group of scientists and resource managers from the several Mid-Atlantic States posed the following set of questions as regional "reference" issues (i.e., representative of the kinds of issues faced in the region now and for the foreseeable future):

1. What are the changes in land use and land cover and the consequences of these changes to biotic and abiotic resources and the quality of human life?

2. What are the sources and transport rates of nutrients (particularly nitrogen and phosphorous) and the effects of increased nutrient loading on terrestrial, aquatic, and marine ecosystems? To what extent are control strategies effective?

3. What are the present status and future trends in the quantity and quality of water for human use?

4. What are the status and trends of air quality and the deposition of nutrients and toxicants from the atmosphere? What are the effects of emission control strategies?

5. What is the status of coastal fishery resources and how can depleted resources be rebuilt and sustained?

6. What are the exposure conditions of urban and suburban populations to important environmental health risks?

The above national and regional issues require that we design a monitoring and related research framework that will answer the following fundamental questions:

1. Is the environment getting better or worse?

2. Why?

3. What can we do about it?

The best scientific information will not provide the definitive answer to what society should do for any given issue. Environmental decisions are based on society's values and priorities, with the best possible scientific information supporting the assessment of various alternatives, and ultimately leading to informed policy decisions. Environmental monitoring and research provide essential inputs into the assessment process, and their planning and implementation must be closely tied to assessment and policy needs.

Major components of a national environmental monitoring program already exist. An important goal of the Framework is to increase the value of the information being collected through coordination of existing programs and by providing the missing components needed to fully integrate current efforts. Some environmental issues, such as the abundance and distribution of many bird species, are adequately addressed by existing programs. For other important issues, such as the health of forests, the amount of information is extremely limited.

One critical need for better integration and coordination of monitoring and research efforts is an overall assessment of the completeness, overlap, and quality of the existing programs that provide environmental information. Therefore, a summary of existing environmental monitoring and related research programs must be compiled and assessed for improved integration and efficiency. This effort was initiated at the interagency level within the past several years, and the monitoring team has continued this effort by developing a preliminary georeferenced metadatabase for Federal monitoring and research programs. Thorough analysis of the completeness, overlap, and quality of existing programs is a prerequisite for scientific and budgetary reasons. Full implementation of the Framework may eventually require modifying some monitoring and research programs in order to enhance other programs and to fill gaps with new monitoring and research capabilities.

A preliminary evaluation of the distribution of the national programs illustrates some of the features of the current mix of the Nation's major environmental monitoring programs (figure 1). The expected relationship between the number of sites and the frequency of measurement is clearly evident. Figure 1 shows that programs fall into three general groups related to their measurement frequency. The first group of programs (lower right), with measurements taken at several thousand or more sites, has a measurement interval of several years or longer. The second group (middle left) corresponds to measurement intervals of

weekly to monthly at hundreds to thousands of sites. The third group (upper left) consists of a few research sites with many measurements taken at intervals of an hour or less.

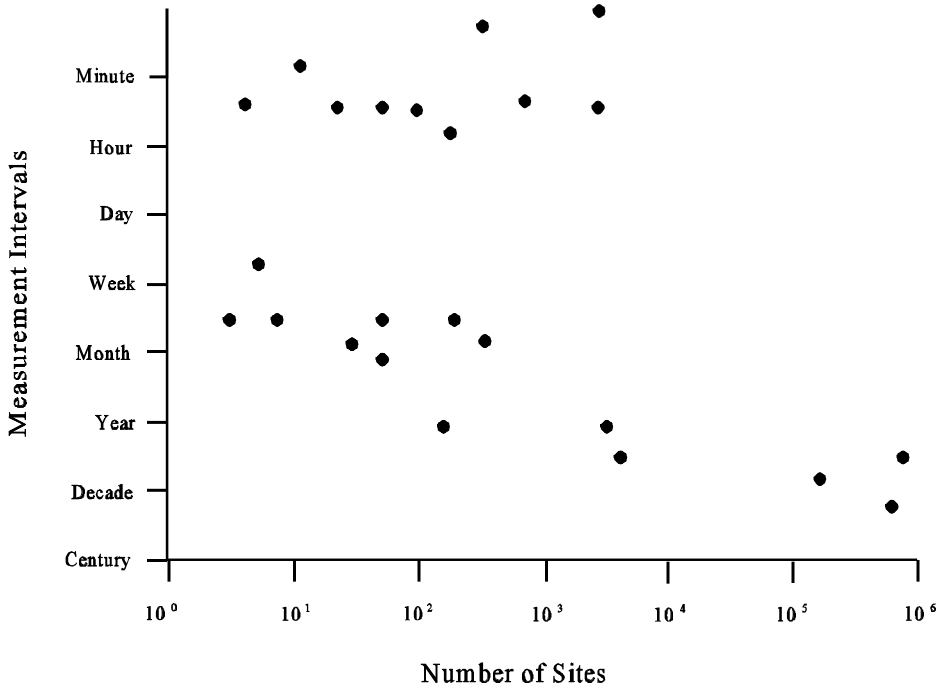

Figure 1. **Approximate number of sites and measurment intervals for major federal inventory survey, monitoring, and research networks (log -log scale).**

One weakness not explicitly revealed by Figure 1 is the lack of any significant integration between the intensively studied sites (upper left) and the national surveys and inventories (lower right). In general, these programs are not physically collocated, and they do not integrate or use comparable methods for commonly measured variables. The intensively monitored sites are often inadequate to determine the condition and trends in resources, while the national surveys and inventories are not designed to determine cause and effect or to relate to the intensively monitored sites. Although most of the intensively monitored sites were neither designed nor located with integrated environmental monitoring as an objective, there is great potential for enhancing the value of the sites and the surveys and inventories by collocating and coordinating sampling locations.

Programs related to ecosystem dynamics and vegetation span a range from infrequent measurements of forest and range conditions at many sites (e.g., National Resources Inventory, Forest Inventory and Analysis, and Forest Health Monitoring) to intensive research-level measurements at very few sites (e.g., Long Term Ecological Research Sites; Water, Energy, and Biogeochemical Budgets; Agricultural Research Service Experimental Watersheds; and Forest Service Experimental Forests). Measurements of air quality and atmospheric deposition, hydrology and water chemistry (e.g., National Atmospheric Deposition Program/National Trends Network, Clean Air Status and Trends Network, and the National Water Quality Assessment Program), and animal abundance or condition (e.g., Breeding Bird Survey and National Status and Trends) are generally made at fewer sites than forest and range inventories and at a lower frequency than ecosystem research locations. There are no programs that measure a full suite of environmental variables (e.g., air, water, soil, vegetation, and animals) at appropriate frequencies at more than a few sites. Thus, there is no national monitoring of the condition of air, water, soil, plants, and most animals or for determining the complex cause and effect relationships of environmental changes.

2. A Proposed Framework

The ideal environmental monitoring capability would provide the information needed to inform each American regularly of the quality of his or her local environment with regard to air and water quality, game and nongame species, ability to support local economic activities and recreational uses, and the expected future condition of these and other important components of environmental quality. This capability would provide the information necessary for informed public debate leading to effective policy decisions.

A fundamental premise of the Framework is that no single sampling design can efficiently provide all the information needed to evaluate environmental conditions and to guide policy decisions. For example, determining whether and how a specific environmental resource is changing requires repeated measurements, in contrast to the single set of measurements required for assessing the current condition of that resource. Similarly, different approaches are required for understanding the causes and consequences of changes than for detecting that change has occurred.

The National Weather Service Model

The National Weather Service monitors and predicts air temperature and precipitation with a system that has all the components of an environmental monitoring and research program. These components include (1) extensive ground-based monitoring with a high frequency of measurements using standardized methods, (2) remote sensing of system dynamics using radar and satellites, (3) research to better understand the mechanisms of weather and climate, and (4) process-based computer models to predict the future state of the system. A combination of mechanistic understanding and the input of data is used to continually update the current state of the system. The interaction of physical input data, process-based models, and model predictions that are revised and updated based on current conditions results in a national and global weather-forecasting capabilities that continue to improve.

Existing monitoring and related research programs are designed to address specific issues and programmatic goals often based on specific legislative mandates. This program-specific approach makes it difficult to link regional or issue-specific programs into an integrated evaluation of environmental quality at either the regional or the national level. Because these programs focus on different resources, use different methods, and have different temporal or spatial scales of resolution, it has been difficult to combine programs or provide an integrated national assessment of environmental conditions. We have never really anticipated an environmental problem and have had to scramble to assemble proper data for assessment, after the fact.

The task of developing a comprehensive program for ecosystem monitoring and prediction is extremely complex. Understanding the condition of the environment is difficult because the natural environment has many interacting components (e.g., soil, water, air, plants, and animals) that are affected by a variety of physical conditions. Just as the National Weather Service uses a combination of physically based computer models and data input to describe the current and future state of the weather, an analogous interaction between remote sensing, ground-based data, process research, and computer models is essential for assessing and interpreting the status and trends in the environment and for providing scientifically sound predictions of future environmental changes.

Design of an Integrated Framework

A conceptual framework that effectively addresses the multiple scales and processes of the environment can be assembled largely from existing methods that have been designed to monitor various aspects of the environment in the most effective manner possible. Logistical limitations impose inherent tradeoffs between the number of variables that can be measured, the frequency at which they can be measured, and the number of sites involved. These constraints lead to a hierarchical structure for the monitoring Framework, which can be represented by a triangle, with the measurements that can be made at the greatest number of sites at the base of the triangle (figure 2). The types of monitoring represented within the Framework can be divided into the following general classes: (1) those that characterize specific properties of large regions by simultaneous and spatially intensive measurements sampling the entire region, (2) those that characterize specific properties of large regions by sampling a subset of the region, and (3) those that focus on the properties and processes of specific locations.

At Level 1, **Inventories and Remote Sensing Programs** are based on methods that can measure specific properties simultaneously and uniformly across large regions. These programs typically use sensors on satellites or airplanes to detect such properties as cloud cover, vegetation and soil cover, and ocean temperature and can be used for one-time surveys and for continuous monitoring.

At Level 2, **National and Regional Resource Surveys** are designed to characterize specific properties of a region by sampling a subset of the total area, rather than the entire area. These programs are typically designed to address specific resources or environmental issues and may cover the entire country or only the region where a specific issue is important. Integration between Levels 1 and 2 can help identify changes in the environment detected by remote sensing (i.e., provide "ground truth"), but generally cannot indicate why a specific change has occurred. These two levels are essential for quantifying the extent, distribution, condition, and rate of change of specific environmental properties and for understanding processes that occur over large areas.

At Level 3, **Intensive Monitoring (Index) and Intensive Research Sites** typically provide a greater number of properties and at a higher frequency than either Levels 1 or 2 but at a much smaller number of locations. The critical feature of this level is that all the major potential causes of environmental change are measured at the same locations where environmental responses of concern to society are also measured. This level is essential for understanding processes that occur at local scales, for integrating the effects of multiple processes, for understanding the causes of changes detected at Levels 1 and 2, and for developing and testing predictive models of environmental response. Measurements at this level also provide information for determining the level of uncertainty associated with inventory, remote sensing and survey results, and model predictions.

The most significant aspect of the Framework is that inventories and remote sensing programs, national and regional resource surveys, and intensive site-specific monitoring and research will be conducted in a coordinated fashion and provide the types of integration that have so far been unachieved. All three types of monitoring identified in figure 2 are essential for an integrated environmental monitoring and research capability. Various approaches to monitoring (e.g., remote sensing, probabilistic surveys, and prestratified surveys) provide the capability to monitor the entire area of the country for a few limited characteristics. Such information can be used to evaluate resource extent, condition, and change at local, regional, and national scales. Regional surveys are necessary to identify and quantify changes detected with remote sensing and to quantify conditions and changes in specific resources. Regional surveys also provide the context within which the causes and effects that are measured at intensively monitored sites are interpreted (e.g., how frequently and where they occur). The addition of index sites to the Framework will provide a linkage between broad-scale survey and monitoring programs and the basic research and modeling required to understand cause and effect and to quantify uncertainty. Index sites are intensively monitored sites where various measurements are made in a coordinated and consistent manner. They will allow a more complete understanding than is possible with current networks and research programs.

Within each of these three levels research must be conducted at appropriate scales to improve survey and monitoring methods, to understand changes that are observed, and to develop descriptive or predictive models. Such research will generally be focused on a subset of the total monitoring effort at each level. In addition, research on cause and effect must integrate processes that occur across the range of scales from large regions to individual sites. Application of the understanding of environmental processes and how they are affected by environmental changes is accomplished by developing quantitative models that can be tested by using data from intensively monitored sites.

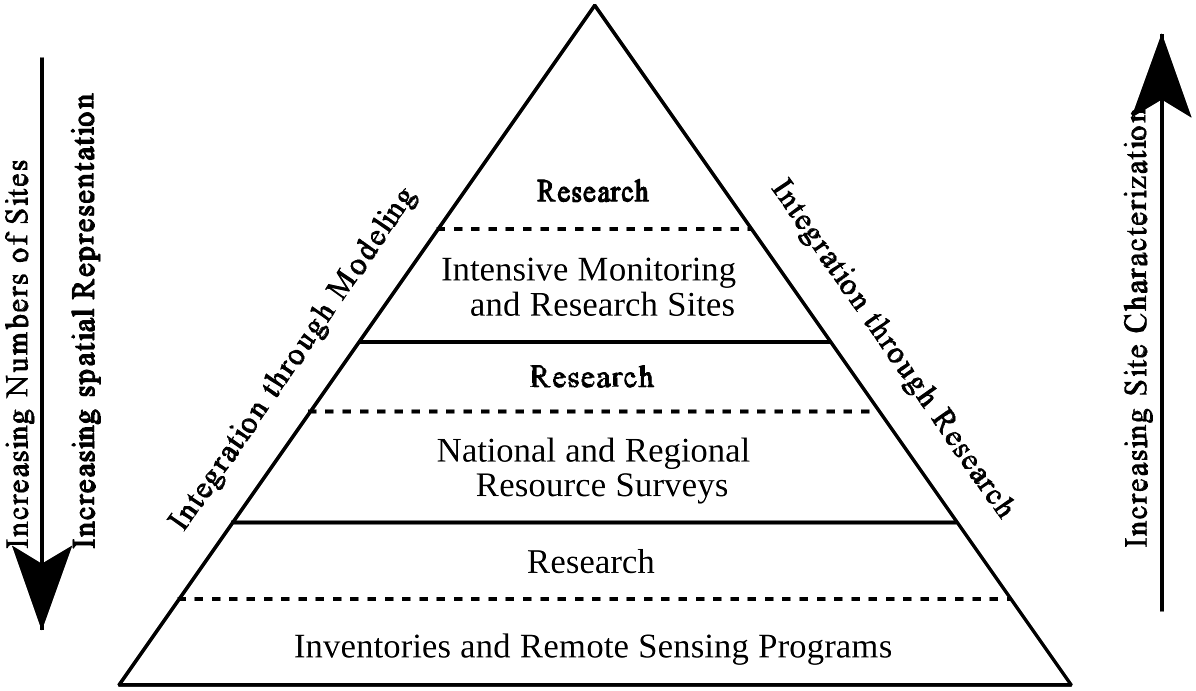

Figure 2. Conceptual framework for achieving the multiple goals of environmental monitoring and research.

Several benefits of integration are possible within the Framework. The first is process or resource integration, which is accomplished by measuring major independent and selected dependent variables at the same locations. Collocation of survey measurements at locations where a full suite of independent variables and ecosystem processes are also being measured is essential for the integration required to interpret observed changes. A second benefit of integration is temporal and is accomplished through time series analysis that allows separation of variability from trends, the identification of extreme events that may be far more important than average conditions, and the separation of processes that occur at different temporal scales. A third benefit is spatial and is accomplished by identifying the appropriate scale at which a specific signal is most effectively separated from noise. For certain air properties, this may be an area of thousands of square kilometers; for specific landscape processes, it may be a watershed of a given size; and for plant responses to specific stresses, it may be a small plot.

Many components of the Framework are represented among the monitoring and research programs of Federal, State, and local governments, as well as some private organizations. The challenge is to build upon and enhance existing successful keystone networks and programs to meet national and regional requirements for environmental information more effectively.

3. Assessment, Monitoring, Modeling, and Related Research

Scientific information alone is insufficient for the development of societal consensus and public policy. Public policies should be based on a process of social and economic evaluation to which research and monitoring can contribute. For example, review of the National Acid Precipitation Assessment Program, a large-scale environmental monitoring, research, and assessment program, suggested that the program did not fully realize its expectations. This was because the critical and interdependent elements leading to assessment (i.e., monitoring, research, and modeling) were not adequately integrated into the assessment process from the beginning (National Acid Precipitation Assessment Program Oversight Review Board, 1991). The ultimate usefulness of scientific research and monitoring to the public policy process is in the interpretation (assessment) in terms relevant to the needs of decision makers. It is essential, therefore, that a comprehensive and coordinated national program of environmental monitoring and research be focused on key questions. It is desirable for such a program to be responsive to current critical information needs, and yet anticipatory, providing the baseline against which to detect and monitor status and trends, and to provide an understanding of change and the factors responsible for it.

The Nation needs a strategy for environmental monitoring and research that will enable comprehensive assessments of its natural resources. Such a strategy is essential if we are to differentiate between actual and perceived environmental issues and to address them appropriately to avoid both unnecessary regulation and serious environmental problems. Federal agencies currently conduct assessments of resources, habitats, and specific issues (e.g., climate change and acid rain) at a variety of scales. For example, the U.S. Global Change Research Program is working through the Intergovernmental Panel on Climate Change to develop assessments of climate change and with the World Meteorological Organization to study changes in the stratospheric ozone layer. At regional scales, agencies routinely prepare assessments of the status of resources (e.g., fisheries and forests) and habitats (e.g., water quality and soil type). At local scales, assessments are performed daily in support of permit evaluations and other local or State decision-making.

These specific assessments are valuable and must be continued to meet current missions and mandates. However, a critical need exists to synthesize this information to increase our understanding of the significance of interactions among resources, their linkages to variations in the natural and human environment, and their responses to multiple drivers of change. These integrated environmental assessments should identify environmental and ecosystem trends, relate these trends to their causes and consequences, and predict outcomes of alternative future scenarios. These components should be developed in a sequential and coordinated manner as follows:

1. **Status of ecosystems.** Document coincident status and trends of multiple resources and related environmental and socioeconomic conditions.

2. **Causes and consequences of change.** Using the best scientific information available:

- Relate status and trends to human and natural causes and consequences,
- Predict future trajectories and rates of change,
- Assess uncertainties, and
- Identify data, information, and research needed to reduce future uncertainties.

3. **Options and outcomes.** Evaluate science-based approaches for ensuring sustained productivity, vitality, use, and enjoyment of ecological systems.

The Framework anticipates a monitoring and research program adequate to address (1) issues that have already been identified (i.e., what, where, why, how are changes in natural and managed ecosystems occurring) and (2) new issues that arise in the future. Specific questions will come and go over time, but the nature of the monitoring and research necessary to address current and future questions will depend on specific resources, regions, or policies under consideration. The overriding benefit of this coordinated monitoring and research program is in the availability of a conceptual framework by which the appropriate information (i.e., research and monitoring) and tools (i.e., modeling and interpretation) can be accessed across the many programs of the Federal Government and applied to specific issues or questions.

The essential interaction among monitoring, modeling, process research, and assessment is illustrated in Figure 3. Assessment leading to policy decisions is linked to monitoring through the development and application of ecosystem models. The monitoring side of Figure 3 (left) represents an integrated hierarchical program. At the top is a small number (100-200) of intensively monitored sites (index sites) where physical, chemical, and biological measurements of different ecosystem components are measured simultaneously at the same location on a long-term (multidecadal) time frame. At these sites, sufficient information is collected to develop time-dependent models to predict future changes in the state of the ecosystem.

At the middle level, there is progressively less frequent sampling at progressively more locations. All response variables in regional and national surveys will be measured by using compatible procedures at the index sites to relate them to the core variables and process models. This sampling level provides broad national and regional coverages and enables the detailed information collected at the index sites to be placed in a national or regional context. Data collected at these levels is useful for calibration and validation of ecosystem models developed at the index sites.

At the lower level, broad coverage of a small set of variables would be used to place the index sites and the ground-based survey points in a landscape perspective. Although the number of variables available through remote sensing is limited currently, it is anticipated that more parameters that are now time-consuming and costly to measure on the ground will be measured. This will lead to large-scale, synoptic pictures of key variables, providing the integration across scales necessary for model development, validation, and application.

The assessment side of Figure 3 is connected to monitoring through modeling. Models provide a tool to bridge the gap between the requirements of assessment and policy analyses, and the logistical and financial constraints associated with not being able to measure everything everywhere. The information provided by monitoring and research must be analyzed and interpreted through the use of models. Models range in complexity from simple descriptive statistics to complex, process-based computer simulations that can be used to predict future conditions. Such models attempt to integrate the most complete scientific understanding available (derived from process research) with the best data on current

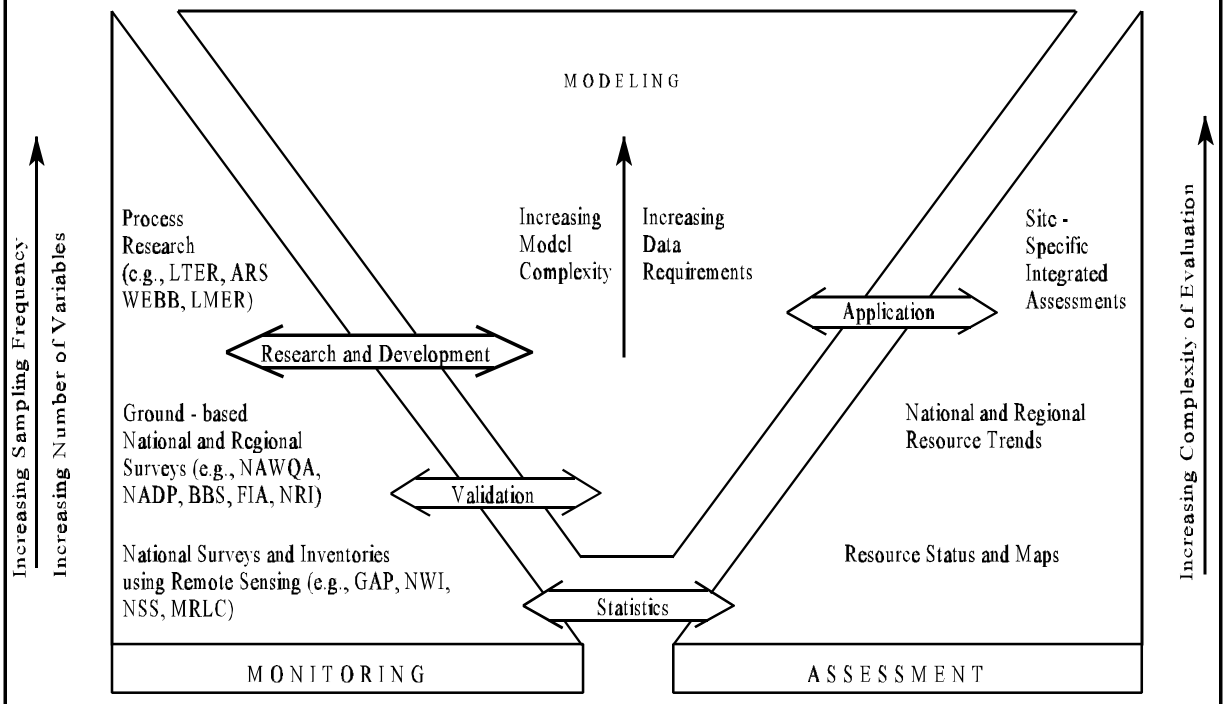

Figure 3. A conceptual model for supporting the development of environmental and natural resource policy and decision-making through a heirarchical program of monitoring, assessment, and related research and modeling. (After the UNECE Integrated monitoring on Air Pollution Effects Program, 1993)

conditions (derived from monitoring programs) to predict the future consequences of alternative policy decisions. Although assessments of single resources can often be based on simple statistical models, more complex integrated assessments require multiple levels of information and process-based predictive models. A critical role of modeling is to extrapolate the mechanistic understanding of the processes, obtained from a limited number of intensive process research sites, to large regions where they become relevant to policy decisions.

Multiple Monitoring Approaches Are Required

The wide range of questions and issues at both the science and policy levels requires a variety of approaches to monitoring and research. The scale of monitoring (local, regional, national and international) imposes additional constraints and requirements. For example, each of the following goals of environmental monitoring requires different methods and sampling designs:

Determining the status of specific environmental resources. This goal will provide a baseline or reference condition for ecosystems (e.g., EPA lake surveys, USGS water surveys, USGS Breeding Bird Survey) against which we can assess changes in the Nation's environmental resources. In general, a probabilistic sampling design is considered to be the most cost-effective method for providing valid estimates of the extent and condition of specific resources. In addition, baselines need to be established for ecological processes. These can be done only at the more intensively studied index sites.

Discerning changes and trends. Policy development and evaluation requires the capability to detect either spatial or temporal changes in specific components of the ecosystem and to determine the cause of these changes. A sufficiently high density and frequency of measurements within an appropriately stratified sampling design is required for detecting and quantifying changes at the regional or national level. Causes of the changes then need to be determined through related research programs at the index sites.

Understanding ecological processes. Improved understanding of ecosystem processes is essential for predicting the future conditions of the environment and for testing hypotheses about the causes of the observed changes. Detailed measurements, often using specialized research techniques, are needed to determine how interacting biological, chemical, and physical processes produce the observed patterns and responses of the environment. Research provides the basis for predictive modeling, which also requires monitoring to develop and test theories and models that relate to interacting processes. This capability is essential for separating natural environmental changes from the effects of human activity.

Detecting early warning. The economic and social costs of environmental problems can be greatly reduced or averted if the problem is detected before it becomes serious. All types of monitoring described above are capable of providing some form of early warning of environmental problems, but the effectiveness for early warning will be greatly enhanced if the methods described are integrated.

Assessing the efficacy of environmental policies. The Nation spends more than $100 billion annually on environmental protection measures. Therefore, it is essential to determine if these policies are having the desired effect or if the same goals could be achieved at a lower cost. The goals of the policies (e.g., attaining specific concentrations of chemicals or specific biological conditions) should determine the appropriate monitoring design.

The many types of environmental information required for effective public discourse, assessment, and environmental policy decisions require monitoring programs of various types and scales. The Nation currently has monitoring programs that provide most of the types of information discussed above but only for a few resources or limited locales and rarely in an ecosystem context. However, coordination of existing monitoring and research efforts to produce a comprehensive assessment of the state of the Nation's environment has not yet been achieved.

Two general approaches have been used to address environmental issues. The first is policy- or issue-driven research that is focused on a particular environmental issue and managed to answer specific questions. Examples of this approach include the interagency National Acid Precipitation Assessment Program (NAPAP), as well as specific programs of ARS, NASA, DOE, and EPA. The second approach is investigator- or curiosity-driven research, which allows researchers to pursue the most interesting or important scientific questions within a broad subject area (e.g., ecosystem processes). Examples of this strategy include the extramural research programs of NSF, NIH, and USDA. Both approaches have produced important scientific advances that contribute to improved understanding and assessment of environmental processes, and both have a role within the Framework.

Research is an integral component of all three levels of the environmental monitoring Framework (figure 2) and is essential for the needed integration among the levels. Currently, the most intensive research is concentrated at the top level of the Framework in networks such as LTER sites and USDA research stations. A national program must focus on monitoring that can provide high-quality data that can be interpreted in relation to policy needs. Research is particularly important for improving interpretation and assessment. The network of index sites will provide the physical and information infrastructure for much of the needed research. Research will be initiated at index sites or across regions in response to specific policy needs or scientific issues. The value of research conducted at any of the index sites will be greatly enhanced by the availability of data that relates each area to the conditions within its regions and to other areas across the country. This comparative approach will benefit both policy decisions and the development of scientific understanding.

Research to Understand Ecosystem Processes

The capacity to predict the response of ecosystems to anticipated uses and disturbances requires that we monitor change in ecological systems and understand the causes of those changes. Causes of change include both natural processes, such as weather and interannual climatic variability, and anthropogenic stresses, such as changes in atmospheric composition and long-term climate change.

Assessment and policy development require that we understand the components of ecosystems and the processes that govern their properties, control their natural dynamics, and regulate the ways in which they respond to natural or anthropogenic stimuli. Important processes occur at a variety of levels, including ecosystem processes, such as primary production, decomposition, and nutrient cycling; population and community-level processes, such as competition, predation, and symbiosis; and habitat and landscape-level processes, such as migration, recruitment, succession, air chemistry, hydrogeochemistry, and soil formation and loss. The need to understand processes is important not only as a scientific goal, but as a basis for better predictions of how ecological systems will respond to increased and novel stimuli. Some specific areas of research needed to improve our understanding of ecosystem processes include the following:

1. Ecosystem-scale studies to characterize and document structural and functional responses, interactions, and environmental feedbacks in and between managed and wildland ecosystems.

2. Linkages between ecosystem components and processes and anthropogenic (i.e., economic and cultural) activities.

3. Population and ecosystem responses to multiple stresses.

4. Physically based, spatially explicit partial and whole-system models that predict risk from multiple stressors and the exchange and interactions among atmospheric, terrestrial, hydrologic, and biotic components of systems.

5. Models to improve understanding of past conditions and future changes.

6. Ecological, social, and economic implications of resource use.

7. Uncertainty associated with predicted scenarios.

Research to Improve Environmental Monitoring

It is impossible to measure all properties of the environment. The goal of maximizing cost-effectiveness by collecting the most informative types of data has focused on the concept of "environmental indicators." Although a decade of research to identify such indicators has demonstrated that there are no simple answers, it is clear that certain types of measurements are superior for specific issues.

The ability to characterize ecosystem status in relation to the capacity to deliver desired products or services, to detect trends in status, to identify vulnerabilities (i.e., risk assessment), and identify, characterize and predict drivers of change (predictive monitoring) is fundamental to making effective policy decisions. Every monitoring program must strike an *a priori* compromise among cost; spatial and temporal scales of measurement; representativeness of the population of interest; completeness, accuracy, and precision of measurement; predictive uncertainty; and the desires of the public. Our ability to monitor effectively for these disparate purposes is limited not only by our lack of ecosystem-level understanding, but also by many technological, analytical, and logistical hurdles. Gaps in this capability require that we do the following:

1. Identify, integrate and synthesize data and information sets and assess their quality; i.e., completeness, precision, and accuracy.

2. Develop and apply remote sensing, molecular and isotopic technologies, genetic analysis techniques, and other new and promising methods of measurement to document and determine the cause of observed change.

3. Develop protocols and standards for aggregating existing information and collecting future information to ensure the maintenance of an integrated quality-assured data base that can be used with confidence by managers and scientists.

4. Maintain an adaptive/research approach to measurement, design, and statistical and interpretive analyses that ensures continued improvements in precision and accuracy.

5. Develop and support more efficient information management systems to control the flow and utility of the enormous amounts of data provided from the network and contributing sites. Research will be needed on database management systems, distribution vehicles, and analysis software.

6. Develop modeling and analysis approaches to link information and interpretation at multiple spatial and temporal scales.

7. Develop techniques to link air emission sources to receptors; e.g., spatial distribution, surface roughness, uncertainty reduction, and measurement requirements.

Because there are few environmental variables whose behavior we understand well enough to interpret and report on ecosystem conditions nationwide, it will be necessary to continue to improve existing predictive models, analytical procedures, sampling designs, and measurement capabilities, as well as, develop whole new technologies for characterizing ecosystem behavior and social interactions.

Research to Integrate Social and Economic Processes into Environmental Assessment

Many environmental "crises" might be avoided if sociologists, economists, and policy makers incorporated environmental science into long-term planning. Planning ahead to provide the renewable natural resources and environmental conditions needed to support changing population distributions and economic activities requires an integration of social, economic, and ecosystem science that has not yet been achieved. To achieve such a goal, research is needed to accomplish the following:

1. Improvement of partnerships and communication among scientists, managers, policy makers, and other stakeholders.

2. Development of techniques to analyze the economic, human health, and social impacts of environmental trends and conditions.

3. Development of research designs that incorporate economic, human health, and social goals into ecosystem capacity and response models, especially in the case of extractive uses of resources.

4. Development of valuation analyses of resources that are based upon values other than commodity uses (e.g., recreation, religion, and aesthetics).

5. Enhancement of mutual social, health, environmental, and economic benefits through long-term planning.

6. Strengthening of the environmental components of human health and epidemiological research.

Policy related to the environment and resource management must be developed and implemented on the basis of the best scientific knowledge available. The uncertainty and error associated with an incomplete understanding of ecosystem processes limit the accuracy and precision of the assessments and predictions required for policy evaluation. It is, therefore, imperative that environmental and socioeconomic research and modeling be an integral part of the Framework.

Environmental Modeling

Models - mathematical representations of biological, physical, and chemical processes -are widely used in environmental research and management. Models are one of the fundamental products of scientific research. They range from simple statistical representations estimated directly from data to complex computer simulations whose development requires integrating theory, data from laboratory and field studies, and long-term observations. Models play a number of crucial roles in the scientific management of the environment. They include the following:

(1) *Hypothesis testing*. When the state-of-knowledge advances to the point where quantitative predictions may be made, representing this knowledge base as a model and comparing predictions to observations provide insight into how adequately a given process or set of

processes is known. Models are a key part of gaining adequate understanding and predictive capability for the scientific understanding and management of the environment.

(2) *Extrapolation*. Most environmental observations and experiments are relatively small and short term compared with the areas and time-periods relevant to management. Models are the key mechanism allowing knowledge gained from limited observations to extend to broader scales and longer time-periods. Early examples of this include the use of tabular site index data (based on experimental plots), used widely in forestry; current practice uses computer models of forest growth.

(3) *Experimental design*. When sampling density or replication of measurements is limited by logistics, models can help design environmental observation systems that adequately sample the most critical processes and regions. Models can also help establish required sampling frequencies in order to detect changes over time in environmental variables. This type of application requires that models be adequately tested.

(4) *What if?* Models can be used to simulate the consequences of management alternatives, environmental change and disturbance. This is key when more alternatives are under consideration that can be addressed within the logistical constraints of field studies, the time-scales of interest are very long (decadal forest rotations or climate change are examples), or the spatial scales are too large for direct experimentation.

(5) *Technology transfer*. Models are a tool for allowing users of scientific information access to state-of-the-art knowledge. Increasingly, models are replacing tabular information, nomographs, and other tools that allow land managers, landowners, and other environmental stakeholders to apply the results of scientific research to practical problems. Models, when adequately tested, can be used by practitioners of environmental management to obtain scientific information about their applied problems without requiring that they have complete expert knowledge, specialized equipment, time and facilities for conducting field experiments on their holdings, or other resources not likely to be available to many stakeholders.

Within the area of environmental management, models are widely used in natural ecosystem dynamics; agriculture, soils and erosion; forestry; hydrology; epidemiology and public health; fisheries management; biodiversity; and climate and weather.

How are environmental data used in modeling?

> "No one believes a model save its developer, everyone believes a data set except its collector" (Anonymous).

The relationship between data collection and model development has been the source of continuing confusion in the environmental sciences. Although there are many reasons why the roles of modeling and observation have been misunderstood in the environmental sciences, in reality, they are completely interdependent aspects of environmental science. In the context of the Framework, there are several areas of interdependence:

1. *Model improvements* Modelers require appropriate process studies, experiments, and observations in order to understand nature and to improve models.

2. *Testing*. The continual process of improving the credibility and utility of models requires testing. Data must be available for appropriate tests of models. As environmental models become more sophisticated, the nature of the data required to truly challenge the mechanisms represented in the models may change from data required to test earlier generations of models. Model improvement will mandate an evolving data-collection program.

3. *Experimental design*. When designing measurement programs for "slow" processes (e.g., erosion and forest growth) or large-scale processes (e.g., hydrology of major basins and carbon budgets), models are critical to understanding potential patterns of variability and designing efficient sampling schemes. This technique (targeted observations) is well-developed in atmospheric science and is becoming more and more important in the other environmental sciences.

4. *Inferences about "hidden" variables* Some important variables are difficult, costly, or impossible to measure directly. A simple example is plant growth, which is usually measured by successive harvests of plant mass. Any growth consumed by animals, lost to wind, or otherwise removed from the plant between measurements may be missed. This is a particular problem for root tissue. Models are often used to make inferences about the values of variables that are difficult to determine directly but that depend substantially on processes which can be accurately measured or modeled. This is a crucial application of models, used in hydrology, toxicology, biodiversity, and many other fields.

5. *Application*. Models require data for input, and the quality of the model output is strongly related to the input. For example, models of agricultural yield require as input information: (a) crop and variety-specific physiological parameters, (b) spatial information on climate and soil properties, and (c) details of management practices, such as fertilization. Models of air pollution similarly require kinetic parameters of the chemical species included, distribution of sources, and atmospheric variables influencing transport. If models are to be used to make inferences over large regions from information gained in specific experiments, such as the crop variety or chemical species specific variables mentioned above, then the information required for model input (climate, soils, management practices, etc.) must be obtained by national and regional scale monitoring programs.

Remote sensing can greatly enhance regional estimates of ecosystem characteristics or processes on the basis of in situ sampling. The density of required monitoring and research stations alone would make capital investment and operational costs prohibitive, and there would inevitably be little flexibility to respond to new environmental concerns. Nevertheless, the use of substantial in situ monitoring is clearly necessary because of the intrinsic spatial and temporal variability in the ecological processes and characteristics of concern to regulatory and land management agencies. The problem of interpolating among research and monitoring sites then becomes paramount, as does the issue of attempting to forecast how conditions might change, thus providing additional capability for early warnings. The use of integrative ecosystem models and remote sensing can provide some help in addressing these issues.

The current state of practice in ecosystem process modeling already enables some estimates of environmentally interesting and important parameters, such as net primary productivity, to be estimated with models on continental and even global scales. Two general classes of models have arisen, each of which is potentially useful in a monitoring context - biogeography and biogeochemistry. Extant biogeography models are typically driven by climate data and derive vegetation associations from underlying scientific knowledge of plant-water relations, soil characteristics, solar irradiance, and disturbance frequency, among other parameters. Several of these models are quite good at producing spatial distributions of vegetation that are very similar to extant vegetation by using recent climate records. Extant biogeochemistry models typically use climate, soils, and extant vegetation data to simulate the exchanges of materials, especially carbon and nitrogen, and water within the ecosystem and between the ecosystem and the atmosphere. Analogous to the biogeography models, several biogeochemistry models can provide excellent simulations of current fluxes of materials when forced by current data.

A third family of models has been emerging in recent years - ecosystem process models that are driven by a combination of climatic and remotely sensed data. These models can be quite good at simulating current fluxes of materials and energy budgets, but are generally not structured to operate in a forecast mode. Therefore, at this time, they would appear to be more useful in addressing the interpolation issue and less useful for forecasting.

Model development is occurring rapidly among all these classes of models, and indeed, models that synthesize various features of the current classes are already beginning to appear and be tested. There is every reason to be optimistic about the capability of models to address both interpolation and forecasting issues in the network design.

From an empirical perspective, the uses of remotely sensed data can range from the derivation of geophysical parameters to drive models to the derivation of different kinds of products that describe surface structural and compositional features. Exactly which surface features can be detected and with what accuracy and precision are, in part, functions of the specific characteristics of sensor and orbital characteristics of the platform or the functional capabilities of the aircraft, in the case of airborne remote sensing. Common uses of remote sensing include the characterization of surface landforms, the classification of vegetation and land-cover and land-use features, fire detection, and digital elevation mapping. Remotely sensed data have often been used to create single synoptic maps, but more recent research efforts have also demonstrated their utility for change detection. The degree to which changes in surface features can be reliably detected depends on sensor and orbital characteristics but also on atmospheric properties, such as cloudiness. Newer technologies, such as synthetic aperture radars, offer some relief from the problems of cloudiness, but their application to many ecological monitoring issues is still in a research phase.

As modeling and remote sensing techniques continue to develop, the Framework will also need to take advantage of the ability to use them to validate predictions that arise from other methods. In some ways, this is the reverse of current thinking, which emphasizes the importance of validating the remotely sensed measurements. Models will need to be used, first, for interpretation and, then, for forecasting. The remotely sensed data can then provide a means of evaluating model performance and, ultimately, the confidence associated with forecasts.

Thus, a comprehensive environmental monitoring and related research program needs to reflect, first, the diverse application of models to environmental problems and, second, the needs of models for validation data, data to improve models, and data needed to apply models over time, space, and management practices. The increasing synergism of observations and modeling in the environmental sciences should continue to shape the observing strategy as it evolves.

4. Inventories and Remote Sensing Programs

RECOMMENDATIONS:

€ **Increase the use of remotely sensed information obtained for detecting and evaluating environmental status and change by coordinating these analyses with ongoing in situ monitoring and research efforts.**

€ **Ensure full utilization of the data standards being developed for map and remotely sensed data (by the Federal Geographic Data Committee) to ensure interoperability.**

A resource inventory is a complete description of the resource in question. Inventories typically involve documenting the number and physical features of a resource, such as the number and size of wetlands in a given area. The existing inventories generally do not involve regular, repeated sampling of the resource in question. Remote sensing programs represent the most advanced technology and largest financial investment applied to environmental issues. Remote sensing provides data or measurements collected as a series of contiguous and simultaneous measures across a large area. U.S. Bureau of the Census statistics provide a similarly comprehensive view of the distribution of the human population and many economic activities that interact with the environment.

Remotely sensed surveys provide the capability to monitor a given area for changes in spectral (color) and spatial characteristics and can be conducted over a range of spatial and temporal scales appropriate for specific applications or issues. The most common source of such data is from sensors mounted on fixed-wing aircraft or satellites.

Remotely sensed measurements provide both spatial and temporal integration of ground-based measurements for evaluation of change and for input of driving variables to predictive models. For example, the National Weather Service uses a combination of instantaneous ground-based measurements, radar networks, and satellites to provide continuous monitoring of current weather conditions (retrospective monitoring), as well as predictions of future conditions based on computer simulation models, with continuously updated inputs (predictive monitoring). A variety of other satellite-based systems monitor properties related to both the causes and effects of environmental change. These measurements are made in the atmosphere, on land, and at sea with frequencies ranging from hourly to weekly.

Existing resource inventories and remote sensing programs and their responsible agencies include the following:

Coastal Change Analysis Program (NOAA)
Coastal Ocean Program (NOAA)
Gap Analysis Program (NBS)
Multiple Resolution Land Characterization (EPA/USGS/NBS)
National Weather Service (NOAA)
National Wetlands Inventory (FWS)
National Soil Survey (NRCS)
LANDSAT (NASA)
Total Ozone Monitoring System (NASA)
Defense Meteorological Satellite Program (DOD/Air Force)

These inventories and remote sensing programs are extremely valuable for understanding the distribution and variations in land use, vegetative cover, ocean currents, and other surface properties on Earth, as well as for providing early warning of dangerous weather conditions. However, these programs are capable of focusing on only a small subset of the variables that are important for evaluating environmental conditions and generally require extensive ground-based sampling to interpret the satellite images and to quantify their uncertainty. Remote sensing data have been used primarily to develop static maps of environmental conditions or land uses, such as the National Soil Survey, which uses aerial photography. Programs, such as, GAP use satellite imagery to develop habitat maps to guide conservation and land use decisions, while the Multiple Resolution Land Characterization program is developing a national land cover data set. Many critical independent driving variables, such as air quality and pollution concentrations, as well as dependent variables, such as primary productivity, air and water quality, endangered species, and biological diversity, are simply not being measured with sufficient spatial coverage and frequency to allow evaluation of current and future environmental quality.

An underutilized component in national environmental monitoring is satellite imagery. It has the potential to detect environmental impacts affecting areas of less than 0.5 hectare in size within 2 weeks of the occurrence. Appropriate analysis and use of these data can greatly increase the value of environmental monitoring activities related to specific resources and issues.

The establishment and coordination of survey and monitoring sites around the country can, in principle, yield statistically defensible estimates of some indices of environmental quality. However, additional techniques for interpolating among sites or extrapolating findings made at one site to other places in the United States will continue to be necessary because no one system design can anticipate all the demands that might be placed on it. Remote sensing is an ideal method for these types of interpolation and extrapolation.

The systems by which remotely sensed surveys are obtained represent large capital expenditures. However, once established, operating and data costs are relatively low and provide a cost-effective source of information to supplement in situ monitoring or ground-based surveys. Information derived from remote sensing data can be used to characterize the types, distribution, and temporal changes in features, such as the Earth's surface properties, vegetation, currents, and weather, as well as a variety of variables relevant to the distribution and abundance of resources.

Multiple Resolution Land Characterization (MRLC) Program

At the Federal level, there is a clear need for developing comprehensive and consistent land-cover and land-characteristics information for the United States. To initiate this effort for the Federal Government, four ecological and environmental research and monitoring programs have formed a partnership with the U.S. Geological Survey's (USGS) Earth Resources Observation System (EROS) to design, develop, and test a Multiple Resolution Land Characterization (MRLC) program. The overall objective of the MRLC program is to develop a land-characteristics monitoring system that provides a baseline of multiscale environmental characteristics and mechanisms for monitoring, identifying, and assessing environmental change. In addition, the MRLC program is developing a national land cover data set based on LANDSAT Thematic Mapper satellite imagery (Shaw and Jennings, 1995).

Another potentially valuable contribution of remote sensing technology lies in the capacity to calibrate and validate (quantify uncertainties in predicted response in both the spatial and temporal dimensions) process models developed from research at index areas. Successful attempts have already been made at relating frequency band ratios as estimators of foliar nitrogen, lignin content, and crop production to name a few. As remote sensing technologies improve, the potential exists to develop synoptic measurements of many ecosystem components. As this capability is realized, it will offer the capacity to compare time step analyses from model runs to the actual phenological development of response in the ecosystem. This should prove a powerful tool for the evaluation of model performance.

Current capabilities in ecosystem process modeling already allow some estimates of environmentally important parameters, such as net primary productivity, to be made with models at continental and global scales by using remotely sensed data. Measurements of various parameters associated with the Earth's surface play an important role in several ways - as periodic synoptic surveys of some aspects of land use; as the raw material for detecting changes in surface parameters, especially those changes associated with cover and use; as tools for model parameterization and validation; as tools for extrapolation and interpolation; and, as tools for comparing changes detected in the United States with changes in other parts of the world. Data sets of potential natural vegetation of the conterminous United States at approximately 0.5 degree spatial resolution have been constructed and made available to the research community (Melillo et al, 1995) and have already been used by a variety of biogeographic and biogeochemical models in intercomparison and scenario-based studies.

The major applications of remote sensing in the context of the Framework are as follows:

Site Characterization. The synoptic and extensive data derived from satellites and other sensors can be used to describe both individual index areas and survey regions with regard to identification and distribution of characteristics, such as vegetation, water properties, and land use, as well as measurements of the condition of site-specific variables. These data will be essential for quantifying the relation of the index sites to the regional distribution of surface properties.

Detection of Change. Information derived from remotely sensed imagery provides the basis to detect and describe change in a given area between two or more time periods. This information can greatly improve the interpretation of environmental monitoring activities at the index sites, as well as provide the context for interpretation of the regional surveys.

Definition of Properties. Spectral and spatial measurements from remotely sensed data can be measured directly to provide input to process models or to define structural parameters that have the potential to be related to agricultural and forest productivity, marine resources, biodiversity, and other issues of concern to society (based on Heal et al., 1993).

Increased availability and affordability of remotely sensed data require improved collaboration and communication between agencies and programs that purchase, process, and interpret them. Currently, there are a number of Federal, State, local, and private initiatives that produce products and derive analyses that are based on conflicting definitions, methods, and classifications and on varying levels of accuracy assessment.

Interagency coordination is underway to produce a series of nationally consistent data products and to define a series of standards consistent with the key uses of remotely sensed data. Compliance with these standards will allow Federal, State, and local agencies to collect and process remote sensing data to produce a variety of products that can be interchanged, linked, and compared across regions.

The satellite images that are collected for the entire country at intervals ranging from daily to bimonthly are an underutilized resource. The primary use of remote sensing of the country's land area has been for static classifications of vegetation types and land use patterns. This information represents a large financial investment on the part of society and has the potential to provide nearly real-time detection and monitoring of a variety of environmental conditions. Although remote sensing information on cloud cover and ocean currents is used on an hourly or daily basis, the change detection potential of land-surface properties is not being utilized. This information has the potential to detect short-term significant changes in the condition of forests, grasslands, agricultural lands, and surface waters as they are affected by such factors as droughts, floods, storms, fires, and pollution.

5. National and Regional Resource Surveys

RECOMMENDATIONS:

- **Evaluate existing surveys for coverage of environmental issues, resources, and geographic areas. Determine which surveys should be included in the Framework.**

- **Ensure common definitions, models, data management systems, and areal coverage through cooperation with the Federal Geographic Data Committee.**

- **Identify critical regional and national resources or issues that are not addressed by the current surveys and initiate surveys to address them.**

- **Collect data for various national and regional resource surveys at the same or compatible locations, where appropriate.**

One of the key requirements of a monitoring network that can support environmental assessment and policy decisions is the ability to provide an accurate estimate of the proportion of a particular resource in a specific condition, where that condition is likely to be found, and how that resource has changed through time. Such population characterizations can be determined only by using a complete census of the population or by conducting a survey of a statistically defined sample of the population. Regional information on some resources (e.g., breeding birds and certain aspects of rangeland or cropland health) is currently available from surveys which will be incorporated into the Framework. For other resources, regional survey information is either missing or does not provide sufficient coverage to assess the Nation's environmental problems. In such cases, additional surveys should be undertaken to provide the information needed to integrate the available data with other levels of the Framework.

Policy decisions regarding resources at risk have often been made on the basis of population estimates derived from data collected at a few fixed sites for which there are long-term records. The exclusive use of such preselected sites to estimate regional conditions will almost always result in estimates whose certainty (or uncertainty) is difficult to quantify or, if unknown, will sometimes result in estimates that are so biased as to be misleading or damaging. Surveys must be an essential part of the Framework.

Quantitative surveys are essential for placing data from intensive index sites into a regional or national context. In addition, surveys provide ground-truthing for data collected by remote sensing and detect trends at a resolution or scale not possible by remote sensing or at index sites. They also provide a source for hypothesis development and testing at index sites, and they are the only mechanism available to explore environmental gradients.

These survey programs cover a wide range of resources and use a variety of approaches but generally fall into two broad categories: (1) relatively infrequent surveys of numerous sites without installing fixed-site instrumentation and (2) frequent measurement of specific environmental variables at a few permanently selected and instrumented sites. Surveys are designed, through sampling, to describe quantitatively and statistically characteristics of the entire population of a specific resource (e.g., lakes, birds, and trees) in a given study region without completing a census of the resource.

Renewable natural resources (e.g., timber, agricultural products, and water) and their associated properties (e.g., topography and soils) of greatest economic importance have the most coverage at the survey level, but major deficiencies still exist for assessing the condition of these resources. Major problems of coordination and comparability exist among the survey and monitoring programs, primarily because they were designed independently for specific resources rather than to provide an integrated assessment of multiple resources and related environmental conditions.

Unlike most terrestrial resources, for resources that are fluid and moving, such as the air, oceans, and large lakes, the size of the area that can be sampled from a specific location varies constantly, even within the same geographic region. For these properties, fixed-site monitoring can be used to determine regional conditions and changes. For example, air is taken to be homogeneous under similar climatic conditions except for contaminant concentrations that are determined by measurements, which can be extrapolated from the fixed points to other areas on a map with similar conditions. The scale of interest can be local when process research into the relationship of deposition to aquatic and terrestrial effects is ongoing, or it can be broad when relating deposition changes to source emissions reductions is important. Fixed-site networks should be considered to be an integral component of the Framework with a subset of stations being collocated with index areas.

Fixed-site sampling of surface waters by using a nested watershed approach can provide valuable information about regional status and trends in the environment. The waters draining through a watershed influence are influenced by the vegetation, soils, geology, and human activities within that landscape. Defining hydrologic boundaries and gradients of flux creates a frame of reference within which biotic and abiotic information can be integrated to understand the interwoven temporal trends of ecosystem components. This method is critical to linking ecosystem changes on the continents to changes occurring in the estuarine and near-coastal zones.

Fixed-site monitoring networks are collections of permanent stations that make frequent measurements of a few specific environmental properties at a resolution that is sufficient to determine regional condition. The station density is generally not sufficiently high to accurately predict conditions at points between stations, but these networks serve important functions, such as regionalizing information on environmental parameters (e.g., UV-B radiation and estuary temperature) and forecasting environmental hazards (e.g., SNOTEL, NWS, and National Stream Gaging Network). Other programs sample water properties at fixed stream locations in order to integrate properties of the upstream areas and to achieve some level of predictive understanding (e.g., National Stream Gaging Network).

Existing national and regional surveys and their responsible agencies includethe following:

Breeding Bird Survey (DOI/NBS)
Clean Air Status and Trends Network (Interagency)
Environmental Monitoring and Assessment Program (EPA)
Forest Inventory and Analysis Program (USDA/USFS)
Forest Health Monitoring Program (USDA/USFS)
National Air Monitoring System/State and Local Air Monitoring System (EPA)
National Atmospheric Deposition Program/National Trends Network (Interagency)
National Marine Fisheries Service Stock Assessments (NOAA)
National Resources Inventory (USDA/NRCS)
National Status and Trends Program (NOAA)
National Stream Gaging Network (DOI/USGS)
Photochemical Air Monitoring Stations (EPA)
Remote Automated Weather Stations (USDA/NRCS)
SNOpack TELemetry (USDA/NRCS)

States also have a variety of resource-specific monitoring programs, some driven by Federal regulations and others by State priorities. Federal agencies support regional monitoring and research programs (e.g., Pacific Northwest, South Florida, and Chesapeake Bay), resource-specific monitoring and research programs, (e.g., Forest Health Monitoring, the Breeding Bird Survey, and Mussel Watch). Most of the region-specific programs are designed to address specific needs but are difficult to interpret in a national context because of differences in issues and methods. Programs of this type are designed to characterize spatial and temporal variations in specific environmental conditions and to detect environmental problems when they are still local in extent or modest in development; e.g., novel pollutants, exotic species, and threshold changes.

Quantifying Conditions and Detecting Changes

Environmental issues that must be addressed by regional surveys inevitably will have different properties of spatial and temporal variability and, thus, require different sampling designs. In some cases, spatial variability is relatively low, and a small number of sites can allow characterization of regional conditions and extrapolation to unmeasured sites. Other issues, such as water quality, forest and range condition, and crop production, will require a larger number of sites to characterize changes. Many critical variables, particularly those that have high spatial and temporal variabilities, are impossible to measure adequately at all locations where resource- and issue-specific surveys are conducted. Consequently, information on these variables, which include many of the critical environmental conditions that may cause changes observed in the surveys, is almost never available for interpreting the changes. The lack of this information makes it difficult to determine and to compare the causes of observed changes and changes observed in various surveys.

Regional surveys of both aquatic and terrestrial ecosystems are essential to the Framework. The number of sites needed in such surveys is a function of the precision required for the estimates of regional condition. Because nearly all surveys measure several related variables, the sample size will always represent a compromise between statistical certainty and fiscal reality. The appropriate sample size for regional surveys must be determined as the surveys are designed and implemented.

An inventory or complete census of a given resource population can be prohibitively expensive, particularly in cases where the environmental issues affecting the resource are not clearly understood. The deliberate selection of representative sampling locations may be possible in well-characterized regions with well-studied environmental issues. In the Blue Ridge Physiographic Province, for example, bedrock geology (mapped at high resolution in this region) is a strong determinant of stream-water chemistry (Bricker and Rice, 1989) and may be used to predict the acid-base status of streams. Although useful in the Blue Ridge Province, the applicability of this approach in other areas may be limited by the lack of high-resolution environmental data (Herlihy et al., 1993). When such data are not available, a probability-based sampling regime is the best solution for determining population status.

The fundamental issue in monitoring regional changes is that not all ecosystems nor all components of any given ecosystem will respond identically to a given environmental perturbation. Some sites will inevitably be more sensitive and, therefore, more responsive to any environmental stress. Identifying the sites that are sensitive is, by and large, beyond the state of current environmental science. For example, we know a great deal more about the issue of acidic deposition than we know about most environmental issues. Yet, with the exception of a few regions, such as the Blue Ridge Province, we cannot accurately predict which sites will respond (or how they will respond) to changes in deposition. If our state of science for acidic deposition lacks the certainty necessary to make informed inferences based on hand-picked sites, then we will have even less confidence in extrapolating trends for other environmental issues from specific sites to large regions. The national Framework should, therefore, include selected regional surveys that are repeated through time to make least-biased estimates of regional trends.

As was the case with quantifying regional status, the number of sites needed to assure adequate trend detection can be estimated from data on variability and some idea of the magnitude of trend to be detected. One challenge in the ultimate design of the network is optimizing the estimation of status and trends. There is a fundamental conflict in measuring status and trends, which stems from the need for repeated measurements (through time) to detect trends. The most cost-effective network for determining status would minimize repeated visits because it would allow more sites to be sampled and would increase the reliability of the estimates that result from the sampling. The most cost-effective trend network would involve a smaller number of sites that would be sampled regularly.

6. Intensive Monitoring and Research Sites

RECOMMENDATIONS:

- **Evaluate alternatives for selecting the number and distribution of index sites, including (1) stratification by ecoregion in order to provide the geographical coverage necessary for national assessments, (2) stratification by known and anticipated environmental stresses, (3) location along environmental gradients or transition zones between ecoregions, and (4) unique aspects of terrestrial, freshwater, estuarine, and coastal ecosystems.**

- **Establish a network of "index sites" by integrating existing intensive monitoring and research sites and adding new sites as needed to provide standard information on major independent and dependent environmental variables that are known to influence resource conditions.**

- **Collocate national and regional survey measurements at index sites.**

- **Use data from resource inventories and remote sensing for characterizing and detecting changes at index sites.**

Intensive monitoring and research is currently carried out at a large number of sites, monitoring a range of land- and water-surface scales. The well-developed scientific infrastructure at these sites permits the understanding of specific environmental processes sufficiently to allow prediction across space and time. Research at these sites on basic environmental processes related to hydrology, geology, biogeochemistry, atmospheric chemistry, population dynamics, and ecosystem dynamics has produced many major advances in environmental science. This research addresses the mechanisms of cause and effect through identifying the functional relationships between primarily independent variables (e.g., temperature and precipitation) and the interdependent biotic variables (e.g., crop production and wildlife populations) of concern to society. Process research sites are primarily associated with universities and government research programs and include the USFS Forest Experiment Stations, the USDA Agricultural Research Service Stations, the NSF Long Term Ecological Research and Land Margin Ecosystem Research networks, and other sites associated with USGS, DOE, NOAA, and NPS.

Existing **Intensive Monitoring and Research Networks** and their responsible agencies include the following:

Acid Rain Watersheds (DOI/USGS)
Atmospheric Integrated Research Monitoring Network (NOAA)
ARS Experimental Watersheds (USDA/ARS)
Coastal Ocean Program (NOAA)
Experimental Forests and Ranges (USDA/USFS)
Long-Term Ecological Research (NSF)
Land Margin Ecosystem Research (NSF)
MAB Biosphere Reserves (Interagency)
National Environmental Research Parks (DOE)
National Estuarine Research Reserve System (NOAA)
National Marine Sanctuary Program (NOAA)
National Park Ecosystem Monitoring Program (DOI/NPS and USGS)
National Park Global Change Research Program (DOI/NPS andUSGS)
National Park Watershed Research Program (DOI/NPS and USGS)
National Surface Water Quality Network (DOI/USGS)
National Water Quality Assessment Sites (DOI/USGS)
Research Natural Areas (USDA/USFS)
USGS Benchmark Program
USGS Research Watersheds
WEBB Sites (DOI/USGS)

Most of the national programs that currently conduct intensive research and monitoring were not designed with the objective of environmental monitoring. With regard to monitoring, only three major short-comings of the current set of intensive research programs can be identified (1) a primary focus on research rather than monitoring, (2) the number and locations of sites are not adequate for regional or national assessment purposes, and (3) few, if any, of these sites collect measurements of the full suite of core variables needed for integrated monitoring. These sites should be enhanced, where appropriate, to meet the needs of an environmental monitoring network that includes integration across agencies and regions with regard to the variables measured and connection with resource surveys, inventories, and remote sensing programs.

A monitoring capability for interconnected environmental properties and processes is currently lacking in the national environmental monitoring infrastructure. Such integrated, location-specific monitoring should be carried out at a network of permanent locations (i.e., index sites) where a specific suite of abiotic and biotic variables are routinely measured by using standard methods and used to interpret the results of issue- or resource-specific information collected by inventories and remote sensing or national and regional surveys. The number of variables that must be measured simultaneously to establish cause and effect for environmental change dictates that this type of monitoring must be concentrated at a small fraction of the number of sites covered by current survey, inventory, and monitoring programs.

The purpose of the index site network is to provide high-quality, long-term data on the spatial and temporal variation in major environmental driving variables (e.g., nutrient inputs, climate, and pollutants) that can be directly related to the responses of environmental properties of concern to society (e.g., agricultural, forest, and rangeland productivity; water quality; wildlife; and biodiversity). These areas will provide a coarse resolution network of information that spans the entire country but, more importantly, will link and integrate the broad-based inventories and surveys described earlier to bring a process-level understanding into a regional context. The index sites will serve as integrative "nodes" where inventories, surveys, and other monitoring networks overlap to provide high-quality data on major environmental driving variables of the region. In addition to their integrative value, index sites can become leading candidate locations for process research as various environmental issues arise. Conversely, existing research networks with strong, continuing process research programs contain many logical candidates for index sites. Although these sites generally measure a large number of environmental variables with sufficient frequency to describe fundamental ecological processes, the variables measured or the methods used often differ among sites and networks. Hence, significant enhancements may be needed at intensive research sites to allow the research and modeling products to be generalized with much confidence beyond the site.

The index sites provide a critical missing component in our capacity to conduct an integrated assessment of environmental conditions. These sites will link the broad-based inventories and surveys that provide information on resource status and trends and the research and modeling required to understand and predict the responses of resources to changing environmental conditions. The index site network will serve the following goals in the integrated Framework:

1. Provide data for calibration and interpretation of the results obtained from broad-based inventories, surveys, and remote sensing programs.

2 Provide an ecosystem-based network for understanding the temporal and spatial variability of ecosystem components and their interactions.

3. Provide a long-term environmental data base to address new or poorly understood environmental issues.

4. Provide the data necessary for calibrating and validating ecosystem models.

5. Establish a reference baseline for measuring changes in environmental conditions and ecological processes.

6. Support research to improve the methods for evaluating resource and ecosystem conditions and interpreting and predicting their responses to environmental change.

Core Measurements for Index Sites

All index sites should measure a limited and standard set of the core variables that are scientifically accepted as the major driving forces of ecosystem response (e.g., temperature, moisture, radiation, climate, nutrient inputs, and contaminants) or ecosystem response variables (e.g., net primary productivity, biological diversity components, and bioindicators) that are applicable to multiple environmental issues. In addition, each index site should measure a group of variables that are the focus of regional and national surveys. This will require that the standard measurements made in these ongoing surveys (e.g., Forest Health Monitoring and National Resources Inventory) are also made at the appropriate index sites. In this way, integration among multiple resources and determination of causes and effects can be accomplished. All core measurements at index sites should meet performance-based quality assurance and control criteria. The data and information generated at the index sites should be publicly accessible.

Measurement activities at the index sites will include two key components: (1) collection of data on variables known to be important on the basis of current scientific understanding and (2) archives of selected samples so that unanticipated environmental issues can be evaluated retrospectively in the future. The intent is to create a network, primarily through collaboration of ongoing activities and with a minimum of additional expense, by modification or enhancement of the existing infrastructure of intensive research and

The Unanticipated Value of Archived Samples

The outbreak of the deadly Hanta Virus in the American Southwest in 1993 was a terrifying health issue because it had never occurred before and its sources and extent were initially unknown. Researchers quickly identified the host of the virus as a specific group of rodents, but the reasons for the sudden outbreak were not known. A preexisting long-term monitoring program on the population dynamics of desert rodents, carried out at the NSF-supported Long Term Ecological Research (LTER) program on the Sevilleta National Wildlife Refuge (DOI) in New Mexico, demonstrated that the populations of several rodent species had reached very high levels at the time of the outbreak, as a result of increased availability of food plants caused by El Nino-related weather changes. Retrospective analysis of rodent brains, which had been archived as frozen samples for a different research project, demonstrated that the Hanta Virus had been present in the rodent population for many years, and, thus, did not represent the sudden appearance of a new disease, but rather a climate-induced outbreak of a monitoring sites. A more detailed discussion of index sites is presented in Appendix 4.

Design and Selection Criteria for the Index Site Network

Two considerations in developing the rationale for index site selection include what Earth surface characteristics will define the boundaries of the index areas and what scale of area is appropriate for the range of Earth surfaces and management regimes (e.g., urban, agriculture, forestry, rangelands, wilderness, fisheries, and pristine areas). This section provides the rationale for the recommendations.

Determining the Number and Location of Index Sites. The design of the network must have adequate geographic coverage at both the regional and national scales and must be able to address effectively both current and anticipated environmental issues in order to support integrated resource assessments and policy decisions. The network of index sites must span the range of ecosystem processes and resource types, as well as known gradients of natural and anthropogenic stressors. Accordingly, the number and location of index areas within a given assessment region should be optimized to support integrated assessments of known environmental issues (e.g., acid deposition, air pollution, biodiversity loss, recreational land use, global change, and management regime). The ideal locations for monitoring ecosystem response to a specific issue may change with the issue of concern. For example, the Global Terrestrial Observing System (GTOS) program, which has a clear focus on climate change, calls for a distribution of index areas that focuses on biome representation, ecotones (biome boundaries), and environmental gradients for such driving variables as temperature and moisture (Heal et al., 1993). However, this network may not provide information on many other environmental issues, such as atmospheric deposition or urbanization of the landscape. Any particular stratification scheme may impose limitations on how the data can be used. Site selection presents a critical dilemma for a long-term monitoring network that must address many different issues, including known and unknown problems, and provide geographical coverage.

Index sites should be distributed to achieve geographical representation on an areal basis or on some other subdivision of the Earth's surface, such as physiographic provinces or "ecoregions." By using this criterion, the monitoring network would be based on an analysis of the number and location of distinctly different ecosystem types across the country with areas selected to represent the variability in ecosystem processes observed.

Several approaches are possible, ranging from a uniform distribution across the Nation to picking only existing research and monitoring stations stratified by geographical areas, such as States, hydrologic units, physiographic provinces, major land-resource areas, climate regions, or ecoregions. A proposed method for regionalization of index sites is discussed in detail in Appendix 4.

For the coastal and estuarine zones, index sites should be selected to include locations in the major coastal biotic communities found across the Nation. Sherman (1994) provided a delineation of large marine ecosystems that could be used as a starting point in similar fashion to the terrestrial sites. To assess the range of coastal conditions found in the United States, one or more of the coastal index areas should be located in each of the eight large, marine ecosystems distributed near our coasts and in at least two of the Great Lakes.

The objective of the index site network is not to be "representative" in the sense of representing the typical or average condition of any particular resource type, environmental issue, or geographic region. Given the dramatic variability observable in natural ecosystems, it is not realistic to expect a small number of sites to “represent” the range of conditions found in nature. Probabilistic surveys will provide the information needed to determine the regional context within which the index site results can be interpreted. The regional surveys and networks quantify the variability in specific environmental conditions so that the place of each index site along any continuum can be determined. Consequently, the characteristics of any site can be quantified with regard to any specific poststratification based on current or future environmental issues. Instead of acting as indices of the status of a particular ecosystem, the index sites will provide detailed information on short-duration, and long-term temporal variability of variables and measurements of environmental response to environmental stresses.

The network design should be flexible. Resolution finer than that achieved by covering all Level III ecoregions (Omernik, 1986) can be obtained by adding index sites to address specific environmental issues and policy needs. The total number of sites selected for the initial network is expected to be less than 200. However, any area that meets the protocol and quality-assurance requirements of the network can contribute to and make use of the network data. Additional areas may be recommended in specific locations to address future needs. The eventual implementation of the index site network will have to respond to a variety of scientific and programmatic issues that will influence selection of specific sites. Regardless of the eventual criteria for site selection, the final network design must have the capability to address effectively major environmental issues within defined regions of the country.

The environment covered by the Framework includes all States and territories of the United States and the coastal zone to the extent of the Nation's territorial waters. This area of responsibility can be subdivided into three broad Earth-surface types: (1) terrestrial and freshwater, (2) estuarine, and (3) coastal (including the Great Lakes). Index sites need to accommodate the principal differences among these environments.

Terrestrial and Freshwater Index Sites. The ecosystem management plan for the U.S. Forest Service has identified watershed assessments as the best information available for developing a decision support system for managing the National Forests. As described earlier, defining hydrologic boundaries creates a frame of reference within which biotic and abiotic information can be integrated. All data collection within the watershed can then be tied together by monitoring stream- or ground-water yields from the area delineated by the watershed boundary. In some settings, hydrologic boundary conditions may be more difficult to define, but the concept of establishing these boundaries (e.g., by monitoring ground-water flowpaths and estimating input and output budgets by indirect measurements) remains valid.

In spite of their value for biogeochemical monitoring and research, watersheds are arguably not the ideal integrating unit for all ecosystem components. Given the mobility of many animal species, the indistinct limits of many terrestrial plant species' distributions, and the variability of air mass movements, it can be argued that any particular division of the landscape will be arbitrary. Nonetheless, where the ecosystem component influences ecosystem function in the watershed, within-watershed information on that component is still invaluable. For example, monitoring of air quality requires networks of fixed measurement sites. The addition of measurement sites within index sites would augment the quality of data from the regional air monitoring network while providing improved resolution of the deposition of stressors, such as nutrients, oxidants, and acidic and toxic compounds, to the index watersheds. In this way, monitoring air quality according to a watershed approach to account for its "dose" makes sense. Responses to air quality within the index watershed to changing source pollution levels can then be linked to the regional network through empirical and modeled approaches depending on the desired level of certainty in the results.

Unless this flexible concept of index sites based on watersheds that are integrated with other issue-specific networks can be shown to be somehow biased for particular ecosystem components, the clear advantages it presents for aquatic and biogeochemical monitoring make the watershed approach a suitable scheme for defining the boundaries of terrestrial and freshwater index areas.

Estuarine and Coastal Index Sites. Although the estuarine and coastal index sites (including the Great Lakes and major reservoirs) cannot be delineated by watershed boundaries, these index sites will be located downstream from watersheds with major monitoring surveys so that input budgets at the coastal area can be determined. Each coastal index site should be located within an estuarine or other identifiable area along the shore. Each area should also include a series of measurement locations that run offshore from the shoreline across the gradient in depth and salinity. Estuarine and coastal index areas should be located where existing large-basin studies are available for estimating inputs to the estuarine and coastal systems.

Size and Arrangement of Index Sites. The appropriate physical size for an index site will vary according to local surface properties, spatial heterogeneity, and the number of management regimes to be represented by the area. The questions being asked are also an important determinant. Thus, index sites could be expected to range in size from a few square kilometers to a few hundred square kilometers. Within each index site, intensive measurements will be made within one or more subunits, which represent individual Earth-surface types (e.g., vegetation type, geology, land use, and current or tidal regime) and management regimes. The sampling design for each variable within an index area should be determined on the basis of our best understanding of the spatial and temporal variability of that variable.

Using mass balance units to study environmental effects on a single surface type or resource use allows integration of a variety of processes, each operating at different scales and with different sources of variability, across an area large enough that the dominant environmental signal stands out from the noise created by process variability. For example, processes that are influenced by atmospheric deposition operate at the scale of different soil types or even smaller scales; e.g., base saturation, hydrologic flowpath routing, and nitrogen transformations vary over very small areas, depending on soil type. Small watersheds provide a sufficient area to smooth the effect of transient or plot-specific processes and to allow detection of trends and patterns in the overall biogeochemical signature of surface-water discharge and soil loss.

As the monitored area increases, other complicating features of the landscape or seascape (e.g., human land use, floodplain, reservoir, and coastal processes) tend to play a more significant role. Various resource uses may create a need for different criteria for area selection, size, and sampling design. These differences in the scale at which environmental stresses interact with different management regimes create the need to tailor monitoring systems to optimally monitor those interactions. In other words, atmospheric and management regime impacts on ecosystems will require a different scale of measurement and integration area to reduce uncertainty in detecting change.

An effective environmental monitoring program must also take into account the effect of interaction among resource management regimes on ecosystem function. The effect of a mosaic of management regimes on the ecosystem in a given region cannot be determined by a summation of ecosystem changes in each individual management regime parcel. The juxtaposition of different resource uses will have important effects on ecosystem characteristics (e.g., distribution and populations of animal and plant species and changes in the biogeochemistry of surface waters that pass from one management regime to another) that are different from the characteristics of either management regime alone. In regions with steep environmental gradients, such as the alpine to desert transition in the sky islands of southern Arizona, these "edge effects" can also occur within a single management regime. The reality of the modern environment is that there are few areas of the globe that are not significantly influenced by human activities and boundaries between different uses.

Site History and Infrastructure. As much as possible, the index sites should be placed so that they include locations for which long-term data sets describing environmental conditions already exist. Sites that already have programs for educating the public and resource managers will provide added benefit to the Framework. Areas that have been federally designated as focal points for long-term monitoring and research activities will be favored in site selection. Table 1 shows the criteria that should be applied when selecting index sites.

TABLE 1. Operational rules for index site selection (adapted from Heal et al., 1993)

A. Mandatory: An index site must satisfy the following:

1. On currently available evidence, the site must have tenure for monitoring for the next 50 years.
2. The site-operating agency must be willing to accommodate collection of the core set of monitoring variables to the necessary quality standards and in a publicly accessible format. Site operators must agree to the integration aspects of the network, including quality-control procedures and data-collection and presentation requirements.
3. The site must be (or contain an area that is) suitable for making the measurements that are desired.
4. The site must be cost-effective to operate and be likely to remain cost-effective for the next 50 years.

B. Preferential: Candidate index sites will be preferred to the extent that they satisfy the following criteria:

1. Sites will have a set of desired environmental characteristics (e.g, ecoregion representation, climate, soil types, land-use types, and biotic richness) not already represented in the network.
2. Sites will be established and supported already and require minimal additional cost.
3. Sites will have committed institutional support at the local level and that are important to national and regional resource management.
4. Sites will have a long-term record of high-quality observations.
5. Sites will have appropriate on-site technical competence.
6. Sites will be located within a large study basin with high-quality data for integrating the index site to the larger watershed and region.
7. Sites will have established programs for education of the public, students, and resource managers.
8. Sites will contain locations or have adjacent areas that can be used for manipulative research.

These considerations can be repeated as part of ongoing Framework adaptation to determine (1) how many sites are needed to address specific known issues, (2) what issues would not be adequately addressed by any specific site configuration, and (3) what compromises are necessary to implement a national network in the context of budgetary constraints. These criteria should enable creation of a network that allows the biome, ecotone, and gradient stratifications recommended by the GTOS designers for monitoring the effects of global change (Heal et al., 1993) while also having the capability to address other environmental issues.

7. Selecting Variables of Environmental Change

RECOMMENDATIONS:

€ **Select a common set of core variables to be measured at all index sites.**

€ **Select variables that are responsive to policy needs.**

€ **Ensure that the variables being measured and the locations where they are measured are sensitive to environmental change.**

€ **Ensure that the measurements are comparable with those of appropriate international monitoring programs.**

Ecosystem processes respond to complex spatial and temporal combinations of environmental properties; e.g., climate, soils, topography, vegetation, and trophic structure. The utility of a monitoring and research approach will depend upon its capacity for identifying major resources of concern, suggesting research priorities, defining attainable conditions given prescribed management objectives (e.g., extractive, aesthetic, water purification, and preservation), and evaluating achievement of the desired objectives.

The Framework must provide quantitative information about the condition of resources or properties of the environment that can subsequently be used in any valuation scenario deemed relevant to a particular policy analysis. The Framework is designed to facilitate the interpretation of information within the context of multiple models; e.g., conceptual, empirical, process, statistical, economic, and social. It provides guidelines for characterizing uncertainty in measurement, information aggregation, value assignment, interpretation, and projections of ecosystem response. A key component of the Framework will be the inclusion of sensitivity analyses to ensure that the variables being measured and the locations at which they are measured are sensitive to environmental change.

The following discussion is presented largely as written for the GTOS workshop report on detecting and monitoring change in terrestrial ecosystems by Heal et al. (1993). Adaptations were made to accommodate variables for the coastal and estuarine environments and for the specific requirements of a national program. By adopting the GTOS concept of variable selection, the data base created with the Framework should be fully compatible with the global data base created by the GTOS and related international programs.

A preliminary list of variables is presented (Appendix 2) for consideration at index sites. These variables can be used to characterize the sites, to monitor change, and to test and validate models. The list includes many variables that have been used to address such issues as water quality, the effects of acid precipitation, and the effects and detection of climate change. Most of these variables are relevant to more than one environmental issue and should provide currently missing information about known environmental issues while providing some capability to address future environmental problems that are currently unknown. A separate selection process is needed to decide upon the common set of variables measured at all index sites.

Site-Characterization Variables

A primary set of standard information is necessary to locate each site and to define its basic physical and resource-use characteristics. Some of these variables can be measured from remote sensing and will help define the regional context of the index sites. These variables are measured initially and infrequently afterwards. A further set of variables is needed to document the factors that have historically affected the status of the ecosystem. The historical variables are identified because they should be measured repeatedly. Similarly, climatic and other variables that assist in basic characterization are included in Appendix 2.

Core variables

A core set of variables should be selected to:

1. Allow for detection of changes in structure and performance of priority environmental properties and processes;

2. Support cause and effect evaluation for the results of regional surveys;

3. Provide a minimum set of input data needed at the index site level for a broad array of terrestrial, aquatic, and oceanic models;

4. Contribute to validation of models and remote sensing observations;

5. Facilitate long-term comparability between sites;

6. Be as free as possible from observer bias;

7. Use standard methods (automated if possible); and

8. Be applicable over a 50-year period.

Landscape composition is identified for core measurement. The spatial variability that is found at each index area needs to be described in order to assess the range in measured values within the landscape for model extrapolation and for interpretation of remote sensing observations. Remote sensing provides a tool to develop maps of ecosystem distribution, as well as overlays representing our best conceptual models of ecosystem organization for interpretive analyses. However, these measurements are also necessary to construct the spatial integration necessary to tie together all components of the Framework. The resolution capabilities offered by remote sensing technologies allow index areas to be placed in at least some context of regional representativeness (i.e.,vegetation cover, elevation, aspect, and proximity to urban or industrial areas) as compared with the regional survey sites.

Variables describing site history and disturbance regime are needed to define the factors that affect the current status of the ecosystem. Historical documentation is required for naturally occurring events (e.g., fires, storms, and floods) and human-induced events (e.g., cropping, logging, and grazing). In addition, changes in management or disturbance events need to be documented, and their spatial extent, quantified. Climate variables include a number of basic meteorological variables needed to run various terrestrial models as well as to relate to responses within the ecosystem.

Soil variables will be used to detect change in the quality and quantity of the soil ecosystem and for model inputs and validation. Many of these features will change gradually over time, except when events relate to soil disturbance, such as storm damage causing tree throw; alternative cropping sequences; or changes in land use. A five-year sampling interval will usually capture changes in the stable variables. However, a number of dynamic soil-related variables will need to be measured to assess ecosystem dynamics. Hydrological and hydrochemical measurements in soil, ground water, and streamflow represent a set of variables needed to develop and evaluate models, but they also indicate system responses to climate or land-use changes.

Vegetation variables are used for change detection and model validation. Annual measurements of dominant plant components will be adequate for most of the variables. However, the ability to measure the short-term dynamics of certain vegetation components to assess changes in production from alternative management practices and to validate terrestrial models and remote sensing observations are also needed. These may include changes in intercepted radiation, precipitation, phenological stages of leaf onset, flower initiation, and dispersal of propagules.

Variables related to biodiversity of flora and fauna should be made at frequencies appropriate to anticipated or observed rates of change. Use of permanently marked plants and quadrats will be used to monitor long-term persistence and performance. Other variables, such as bird counts, will be included in this component. The definition of biodiversity variables and methods requires further research.

Marine core variables

Because the spatial and temporal dynamics of marine systems differ significantly from those of terrestrial systems, a separate core set of measurements should be obtained on a continuing basis at each of the coastal index areas. Each area should include several locations where measurements of certain properties, such as temperature, salinity, dissolved oxygen, ambient light conditions, turbidity, and chlorophyll concentrations, can be measured on a nearly continuous basis by placement of in situ sensors at several depths. Other properties should be measured on a weekly to monthly frequency to follow the seasonal progression of the levels of these properties and to allow the separation of annual and longer term anthropogenically influenced trends from seasonal and other shorter term sources of variability.

Methods for the collection of core variables should be standardized and applied at all index sites, where scientifically justified. Some measurements may have to be varied for technical reasons, but this should be kept to the minimum so that data can be compared and aggregated as much as possible. The selection of the final suite of variables and the methods to be used will have to be done by a separate process, drawing on experience from existing monitoring networks and agricultural and ecological research organizations. The final selection of variables will be based on various technical criteria. However, it is essential that individual core variables have a clear functional relationship with others to have an effective, integrated program.

Additional variables

In addition to the measurement of core variables, an important role of index sites in the national Framework is to serve as "nodes" where all relevant environmental monitoring programs will take collocated measurements. Probability surveys, such as the Forest Inventory and Analysis, Forest Health Monitoring, the National Resource Inventory, the Breeding Bird Survey, and other spatially sampled surveys or monitoring programs should establish standard measurements at index sites. Because of the regional nature of some resource issues, index sites in different parts of the country may have different suites of supplemental variables.

8. Achieving Integration

RECOMMENDATIONS:

€ **Integration of environmental monitoring and research networks and programs across temporal and spatial scales and among resources should be the highest priority of the Framework.**

€ **The integrated monitoring and research program proposed by the Framework should establish and maintain strong linkages to similar international programs.**

The proposed multilevel monitoring and research Framework is a strategy for uniting the measurement methodologies of different disciplines and addressing environmental questions of complexity beyond the scope of many existing activities. The underlying integrated monitoring concept involves a hierarchical “nesting” of networks, with each level comprised of networks selected from specific missions or purposes arranged to maximize the number of common locations where more multidisciplinary questions can be addressed.

A distinguishing feature of integrated monitoring is that it involves a closely coupled analysis and interpretation component designed to reveal not only details of what environmental changes occur but also the reasons. In this regard, integrated monitoring needs to be anticipatory. By integrating monitoring at index areas with research at special process-study locations, it extends the conventional Framework of "status and trends" to "status, trends, and causes." For example, if the goal is to focus on some specific resource or part of an ecosystem that is affected by stresses from atmospheric, as well as terrestrial sources, then deducing why changes occur requires consideration of both atmospheric and terrestrial factors. A difficulty immediately arises when the spatial and time scales involved are substantially different. The central operational question becomes- how do we use infrequent measurements made at sites that may not be representative to describe the exposure and stress continuum that threatens particular resource populations? Without this linkage, the main predictive goal of integrated monitoring would be unattainable. We would only have an expanded traditional monitoring program, in which we would wait patiently for measurements to reveal statistically significant changes and then we would initiate studies to examine why these changes occurred. The Framework is designed to emphasize integration by ensuring that the necessary research, analysis, and interpretation are continuous, exploratory, and closely coupled with the consolidated monitoring program. Significant categories for integration include time, space, resources, and international programs.

Integration through time. Regional surveys have the potential to answer a variety of important policy questions that fit into the general category of "relative importance." Examples might be: How important is eutrophication as an impact on northeastern U.S. lakes? How important is acidification? How important are toxics? How important is forest harvesting? Regional surveys, however, are by necessity focused on a single sampling period. This time period cannot be guaranteed to capture information on the annual worst-case condition. Such information will more likely be provided by index areas. A monitoring program that integrates extensive and intensive sampling could use intensive data to model the annual worst-case exposure or effect and to extrapolate these measures to the regional or national level. Models that are developed at the index site level can estimate the renewable natural resources of a region that would be difficult or prohibitively expensive to sample regionally.

The TIME Project: Integration Through Time

In the case of acidic deposition, a combination of intensive site monitoring and regional surveys has been used to extend the site-specific knowledge about the occurrence of episodic events (acute, worst-case acidification) to the regional level by way of models. The TIME (Temporally Integrated Monitoring of Ecosystems) project includes chemical monitoring of both specific acid-sensitive sites, which are small in number and frequently sampled (4-18 times per year) and a probability survey of sites, which includes many sampled once per year. Data from the more intensive sites (analogous to index sites in the proposed Framework) are used to create models that predict spring chemistry (the worst-case annual condition, which has significant biological effects) from summer chemistry and watershed characteristics. These models are then applied to the survey data, yielding estimates of both chronic condition (i.e., the percentage of lakes that are acidic during summer baseflow) and episodic condition (i.e., the percentage of lakes that are acidic during spring snowmelt). The first of these estimates comes directly from the survey results, while the second is the result of modeling the intensive sites and applying the models to the extensive survey data.

Integration across space. One limitation of regional surveys is that the suite of measurements that can be taken must be limited. We simply cannot afford to measure every possible variable at every site. Part of the justification for monitoring at fixed sites is the ability to measure a wider variety and complexity of variables; e.g., measurements of ecosystem processes and their driving variables. However, if the variables are measured at only a few fixed sites, then there will be insufficient information to determine their regional distribution. One solution is to include a core set of variables at both extensive and intensive sites in a hybrid monitoring program, such as the integration of regional surveys and index sites proposed here. Models, using the data from regional surveys, link through the core variables and can then be applied across the region.

The essence of this type of integration is to develop correlative or, process-based, models from intensively studied areas and to apply them at the regional scale. The only requirement is that the data necessary to run the models be available from regional surveys or other sources. Sometimes, this requirement may lead to simplification or calibration of the models to more readily available data, but a key characteristic of the Framework is that it allows the iterative improvement and modification of models that can confirm the linkages between cause and effect and be used for prediction and evaluation.

Nitrogen Saturation Modeling: Integration Across Space

The value of integrating information collected at different spatial scales is demonstrated by the results of integrating the intensive plot-scale monitoring of the Integrated Forest Study (IFS) (Johnson and Lindberg, 1992) with regional soils data from the Direct/Delayed Response Project (DDRP) (Church, 1989; Church et al., 1989). The spatial distribution of soil nitrogen saturation, based on data collected as part of the probability-based DDRP, showed a complex and uninterpretable pattern. However, analysis of IFS data, collected through intensive sampling of vegetation, soils, soil water, and atmospheric deposition at 17 intensive sites, led to a simple model that predicted nitrogen saturation on the basis of forest age. A combination of the IFS-based model with the regional survey data from DDRP revealed clear and interpretable patterns in the spatial distribution of nitrogen export from forested watersheds in the Eastern United States.

The mass balance (input-output) paradigm provides a mechanism by which linkage of process and trends information developed at the index areas can be scaled up to larger regions. In the "nested watershed" approach, large-basin monitoring stations will include index areas within their drainage boundaries. Exports from these large basins can then be used to create estimates of inputs into important large water bodies; e.g., estuaries, Great Lakes, and coastal zones. The same conceptual approach can be used for scaling up process and trends information on air quality to broad regions, given secondary stratification along source and pollutant concentration gradients. Statistical modeling and, in particular, mass balance

methods can be used in nested basins to measure the effect of various upstream regions on the larger basin downstream.

Integration among resources. Index sites provide locations where a variety of media or resources (e.g., surface water, wetlands, forests, soils, and the atmosphere) can be monitored simultaneously. In many cases, understanding the linkages between these components of the ecosystem will be crucial to understanding environmental problems. As in the case of spatial and temporal integration, an integrated monitoring design allows us to extrapolate exposures and effects from the site specific to the regional level and to understand and predict the interactions between linked resources and environmental changes.

Environmental effects span a broad range of scales and intensities, ranging from diffuse and extensive (e.g., those caused by chemical inputs in deposition, weather, and climatic effects) to concentrated and intensive (e.g., forest harvest, grazing, agriculture, fires, and hurricanes). One of the fundamental differences between these two categories is the scale at which the processes controlling them operate and, therefore, the scale of the variability that might confound our interpretations of monitoring results. To assess the ecosystem response to both these categories of effects requires information at a range of scales. The hierarchical approach of the Framework is critical to track ecosystem trends relative to both extensive and intensive factors.

The Everglades and South Florida: Integration Among Resources

Dramatic decreases in the number of the wading bird species (for which Everglades National Park was originally created), along with invasions of exotic plant species and other indications of environmental deterioration, focused local, State, and Federal attention on water distribution in South Florida. A Federal interagency task force was created to coordinate research and monitoring activities among the major stakeholders and to evaluate alternative approaches to solving the problem. The issue of Everglades biodiversity is being addressed by an integrated monitoring, research, and modeling program with the objective of using the output of hydrologic models to predict the responses of the major groups of plants and animals. Because of the complex interactions among organisms, particularly predation, multiple levels of ecological processes are being modeled in the Across Trophic Level System Simulation project. The computer models will be used to help evaluate which alternative restoration plan will ultimately be implemented by the U.S. Army Corps of Engineers.

Effects of extensive forcing variables, such as atmospheric deposition, tend to blanket whole regions and are, therefore, best understood by comparing an index area with sites that have differing deposition levels or different capacities to resist change from deposition. This can be generally achieved by locating stations along a gradient of moisture, temperature, or deposition conditions or by having a cluster of stations representing a range of sensitivities to environmental change within each index site. Process information from either configuration of index areas must then be compared with regional survey data to determine the lateral extent of the conditions observed and to determine if regional scale processes are at work.

Integration with international programs. Many countries are designing and implementing environmental monitoring programs in response to increasing recognition of environmental problems such as global warming, acid deposition, atmospheric ozone depletion, air and water pollution, loss of biodiversity, and crop production. Improved and expanded monitoring at the national and international levels is necessary to collect better information on the extent and severity of these problems and to identify new problems before they reach crisis proportions. National scale programs with goals similar to those outlined in this report are being developed by Canada, the United Kingdom, Germany, the Netherlands, China, Mexico, the European Economic Community (EEC) countries, as well as others. A few examples of well-developed, ongoing programs are the United Nations Economic Commission for Europe's (UNECE) Integrated Monitoring Program (IMP), the United Kingdom's Environmental Change Network (ECN), the Canadian Environmental Monitoring and Assessment Network (EMAN), and the Wadden Sea Trilateral Monitoring and Assessment Program (TMAP).

The UNECE's Integrated Monitoring Program (United Nations Economic Commission for Europe, 1993) was originally designed to address the problem of long-range transboundary air pollution on the Continent and to assess the effects of air pollutants on the environment. The network currently consists of 58 monitoring sites distributed across 30 countries with the expectation that more will be added in the future. Sweden is the lead country for coordination of the network, and Finland has the responsibility for management of data from the network. Although the original goal of the program was focused on air pollution and atmospheric deposition, it has developed into a much more comprehensive environmental monitoring program. The monitoring sites are small watersheds, less than a few square kilometers in size. Parameters measured include atmospheric deposition inputs and outputs through surface- water runoff, evapotranspiration, and ground-water recharge. The central approach is to monitor the mass balance of major chemical components within the site. In addition to the physical and chemical measurements, extensive biological monitoring is being conducted. A major strength of this program is the ability to relate biological and ecological parameters to a wide group of physical and chemical variables that are measured simultaneously at the same site. This provides the basic information needed as inputs for ecosystem modeling. The IMP has modeling components that address deposition, hydrology, hydrochemistry, and biology. These models establish links between individual ecosystem components and provide a powerful tool for the assessment of ecosystem response to future environmental change. The models also provide a feedback mechanism to the monitoring program so that measurements can be adjusted to changing conditions and information needs. The coordinating board of this program has been active in promoting cooperation with other countries, including the United States and Canada, to link environmental monitoring programs and ultimately to build a monitoring network for the global environment.

The Canadian Environmental Monitoring and Assessment Network (Royal Society of Canada, 1995) is, in many ways, similar to the European Economic Community's IMP. Instead of beginning with a single issue, however, it was designed as a broad multimedia program. It focused on increasing the understanding of ecosystem function to provide information for improving the management of natural resources. The program is establishing a network of stations across Canada by building on existing facilities and programs. This approach is similar to that being proposed in this report for establishing a U.S. integrated monitoring network. EMAN sites have been chosen to (1) show sensitivity to global influences, (2) have a high specificity to stress-producing factors, and (3) be representative of larger ecological areas. The EMAN sites span a range of environments from terrestrial to marine and represent land uses from wilderness to managed and degraded areas. Each terrestrial site contains a small calibrated watershed to provide basic information on hydrological and biogeochemical cycling. The EMAN network has been designed to be long term, from decades to a century, and because unprecedented change is possible in the 21st century, priority is being given to the development of early-warning indicators of change.

The United Kingdom’s Environmental Change Network (National Environmental Research Council, 1994), begun in 1972, is an integrated environmental monitoring network being used to (1) identify and quantify natural and human-induced environmental factors, (2) distinguish short-term fluctuations from long-term trends, and (3) predict future changes. The network presently consists of 50 sites across England, Scotland, Wales, and Northern Ireland. The sites, terrestrial and freshwater, range from upland to lowland, and from moorland to chalk grassland and include small and large lakes and rivers. Variables measured are those expected to be important in driving environmental change and the ecosystem variables likely to respond or be sensitive to such changes, including climate, air quality, water flow and quality, soil development and chemistry, vegetation, vertebrates, and invertebrates. The goals of the integrated network are to (1) obtain comparable long-term data sets for major environmental variables that can be used to distinguish human-induced change from natural variation; (2) identify and quantify environmental changes associated with human activities; and (3) give warning of undesirable effects. The network stresses measurement of a wide range of variables in the terrestrial and aquatic environments to allow relationships among variables to be examined in depth at individual sites and across the network.

ECN sites are operated by a consortium of more than 15 sponsoring organizations, and the network is managed by the National Environmental Research Council. The ECN provides researchers with a range of representative sites where there is good instrumentation and reliable environmental information to use as a platform for environmental research. The ECN is linked to integrated surveys combining remote sensing and ground-based sampling that will be repeated at the decadal time scale. In this respect, the United Kingdom’s multiagency, multiresource ECN with its linked surveys is similar to the proposed Framework. It currently has linkages to the European Economic Community's IMP and the Canadian EMAN Program.

The Wadden Sea Trilateral Monitoring and Assessment Program (Common Wadden Sea Secretariat, 1995) is a cooperative effort involving Denmark, Germany, and the Netherlands. In the early 1990's, Quality Status Reports of the Wadden Sea identified large gaps in understanding basic features of the Wadden Sea ecosystem and a lack of environmental data. Major problems were identified in the collection and management of data; the sampling methods being used for data collection were not the same, and data were being stored in different locations and in different formats. In 1994 this led to the establishment of the TMAP. This monitoring program combines a comprehensive set of physical, chemical, biological, and socioeconomic parameters, which provide information about the development of the ecosystem in time and space, with concomitant ecosystem research. The major issues being addressed are (1) climate change, (2) input of nutrients, heavy metals, organic pollutants, and solid wastes, (3) commercial fisheries, (4) recreation, and (5) the response of salt marsh communities to agricultural practices. All parts of the monitoring and research program are integrated in a common structure for the collection, processing, and exchange of data. The monitoring is integrated across media and includes measurements of the drivers of environmental change and the ecological systems that respond to those driving variables.

In addition to the programs described above, international efforts, such as the Global Terrestrial Observing System (GTOS) and the related Global Ocean Observing System (GOOS), are being designed as part of the International Geosphere-Biosphere Programme (IGBP). GTOS and GOOS have addressed many of the issues discussed in this report, including developing criteria for site location and characterization and assembling lists of the cote variables that serve as indicators of important environmental and biological properties (Turgeon, 1995; Heal et al., 1993).

Within the United States, the U.S. Global Change Research Program (USGCRP) provides coordination for all Federal programs related to global change. In addition to establishing budget priorities related to assessment needs, the USGCRP coordinates U.S. activities with international programs and compiles and updates the latest research results to provide a state-of-knowledge assessment each year.

The common threads connecting all these international monitoring and research programs are the integration across all facets of the environment (from the driving variables to the responding systems and across temporal and spatial scales) and the commitment to developing long-term data bases (decades to centuries). Each of the programs discussed recognizes the necessity for using methods that provide interoperable data and the need for an information management system that provides easy access to the data by all users. In developing and implementing a national environmental monitoring program for the United States, we need to take advantage of the experience of the existing programs.

The United States is a member of the global community and national activities affect the global environment. Likewise, the Nation's environment is affected by global activities. It is no longer sufficient for a nation to look only at its own environmental conditions. Human activities have reached proportions that they now exert an impact at the global scale. To begin to understand global environmental change and the forces that drive it, particularly the effects of human activities over which we may have some control, it will ultimately be necessary to establish a global monitoring network. Some of the pieces are already in place, and linkages are being established; e.g., Canada, Europe, and the United Kingdom. As the U.S. national monitoring program is being implemented, close contact should be maintained with the monitoring programs in other countries so that data collected in all these programs is interoperable. Linking existing and planned environmental monitoring programs across nations by using comparable methods for collecting and processing data will lead to a monitoring network that will be capable of addressing global issues. The President's Council on Sustainable Development's recent report, "Sustainable America: A New Consensus for Prosperity, Opportunity, and a Healthy Environment for the Future," recommends the following as an action item for international leadership:

> The Federal government, assisted by nongovernmental organizations and private industry, should maintain scientific research and data collection related to global environmental challenges. Credible, complete, and peer-reviewed research and data are central to guiding U.S. policy and international deliberations (President's Council on Sustainable Development, 1996).

9. Data Comparability and Information Management

RECOMMENDATIONS:

€ Support the efforts of the Federal Geographic Data Committee to develop a National Geospatial Data Clearinghouse to promote information access and data sharing.

€ Establish a georeferenced data base of ongoing environmental monitoring programs on the INTERNET.

€ Establish standards and protocols for data comparability and quality as integral components of the Framework.

€ Disseminate all Framework information and data in a timely manner by employing a range of communication strategies.

€ Establish policies for data confidentiality, ownership, and accessibility.

Screening for data comparability can be used to define and provide the infrastructure necessary to combine individual networks and monitoring programs into a integrated information structure. A key component of comparability is the development of standards for terms and definitions, naming conventions, communication, performance measurement, quality control, and data management. Development of such standards is already underway through several interagency initiatives.

An accompanying archival strategy should be developed and implemented that provides for stewardship and long-term responsibility of data and samples. The Framework will rely on offices and interagency initiatives, such as NIST and FGDC (pursuant to Executive Order 12906), to provide these standards where available and relevant. Gaps in existing standards should be identified and addressed as high priority. Standards should be identified and in place before monitoring begins.

A rigorous and relevant quality-assurance and quality-control program that includes training, site visits, performance evaluation, and instrument and procedure calibration is critical. The strategy must also identify and address relevant degrees of accuracy, precision, and uncertainty. Development and coordination of these activities is a primary function of the administrative structure established to implement the Framework at all scales.

The Framework may incorporate existing monitoring programs that are affected by changes in monitoring protocols, measures, or standards. Care must be given that concurrent measurements, using both protocols or methods, should be undertaken for a time to evaluate comparability and potential need for dual strategies.

An information and data-management infrastructure is required to support data from field and laboratory collection through access and analysis to final reporting and archiving. The data management approach should build on current Federal and local efforts, such as the Global Change Data and Information System, the National Spatial Data Infrastructure, the National Environmental Data Index, and the National Biological Information Infrastructure (NRC, 1995). A georeferenced data base containing metadata about ongoing environmental monitoring networks and programs should be established on the INTERNET. This data base can allow the user to determine quickly the monitoring networks or programs that have relevant information for a given application.

Framework interoperability will provide the ability to perform analyses, retrievals, and other operations with data from different sources on separate hardware and software systems. The Framework will also attempt to optimize interoperability across geographic, temporal, and thematic scales. Interoperability requires that data exist in a common environment. The environment includes definitions, performance methods, quality assurance, and meta-data. The information management strategy for the Framework should follow the recommendations proposed by the NRC (1995) that include articulation of definitions, performance methods, quality assurance, and suitable meta-data.

Research efforts that focus on strategies for scaling information and data across temporal, spatial, and thematic resolutions are required. The use of modeling and geographical information systems (GIS) will be critical in this development.

Policies regarding data confidentiality and ownership and intellectual property rights need to be developed and addressed within the context of the Framework. These policies should include incentives that reward the timely and efficient reporting of monitoring data.

10. Administration of the Framework

RECOMMENDATIONS:

€ **Establish a national interagency coordinating body to implement the Framework and to oversee recommended actions.**

€ **Establish an independent panel to provide scientific and technical reviews of activities within the Framework.**

€ **Adopt performance-based protocols for quality control and data and information management that apply to all components of the Framework and establish a national quality-control program.**

Successful implementation of this Framework requires a strategy that will guarantee interagency cooperation, planning, and action. The strategy outlined here does not propose to alter agencies' basic legislative mandates or missions, but does require unprecedented interagency coordination among Federal, State, academic, local, and private interests. Although a fully integrated national monitoring program has never been implemented, numerous monitoring and research networks and programs have been created to address environmental issues and agency missions (see Appendix 5). Each of these programs uses methods or addresses issues relevant to the Framework. Although these programs can provide the "backbone" of the integrated Framework, they should not be modified without a comprehensive assessment of how change would affect the delivery of information necessary to agency mandates. Moreover, any changes that are proposed, even following an in-depth assessment, should be implemented gradually. Such a phased modification of Framework components is likely to require a decade or more but will ensure the continued delivery of high-quality policy-relevant information while moving towards an ecosystem-based approach to evaluating the status of our natural and managed resources.

As implementation proceeds, attention must be paid to linkages with the users of monitoring information, including responsiveness to decision makers' information needs, interpretation of results, integration of environmental and resource data with social and economic considerations in assessments, dissemination of information to decision makers and the public, and prediction. In addition, to achieve integration of monitoring programs, there is a need for driving hypotheses and models, more inclusion of monitoring of conditions that directly affect human health and well-being, development of methods that link space- and site-based measurements; and more aggressive inclusion of non-Federal participants. Finally, the integration between research and monitoring must address such difficult issues as quality control of research and monitoring performed within all sectors, detectability of change, and the development of human resources needed for effectively integrated monitoring and assessment over the long term.

The National Science and Technology Council's Committee on Environment and Natural Resources (CENR) should function as the Steering Committee for this Framework. The Steering Committee will assure interagency cooperation and assist with the identification and resolution of priority issues. The Steering Committee should pursue the inclusion of agencies not currently involved with the development of this Framework, such as the U.S. Departments of State and Defense. The Office of Management and Budget should be directly involved with the Steering Committee and the implementation process to assure coordination of agency budgeting for the Framework. The Steering Committee should establish immediately an interagency coordinating body to assist it in using the Framework to coordinate the development of a detailed design and implementation plan for a National Integrated Environmental Monitoring and Research program. An independent scientific panel should provide scientific and technical advice throughout development and implementation of the program. Additional mechanisms should be included to ensure full involvement of non-Federal partners in the design, implementation, and operation of the program.

The following activities are currently underway and can contribute directly to the development of the proposed Framework:

The **User Needs Working Group of the CENR Task Force on Observations and Data Management** is tasked to identify the needs of various user groups for environmental observations, monitoring systems, and data management, particularly at national and regional scale, and to determine the specific measurements or variables most needed by various users.

The **Council on Environmental Quality (CEQ)** seeks to use monitoring to improve the effectiveness of National Environmenatl Policy Act (NEPA) implementation. As part of the requirements of NEPA, agencies evaluate the potential impacts of their program actions on ecosystems. The CEQ is working on new approaches that will allow better monitoring needed to detect and predict ecological changes, including developing corrective changes over the lifetime of project or mitigation plans.

The **Interagency Working Group on Sustainable Development Indicators** has been tasked to identify ways to measure progress toward sustainable development. Their objectives include (1) developing a framework to identify, organize, and integrate the indicators,
(2) developing an information system to provide low-cost access to information about indicators, (3) releasing regular reports on progress toward sustainable development, and
(4) recommending an organizational strategy for collaboration on development of sustainable development indicators.

The **Interagency Committee on Environmental Trends** advises the Council on Environmental Quality on environmental data and assessment issues, including preparation of the required annual report on environmental quality. It also provides a forum for interagency coordination on data and assessments, and develops interagency assessments; e.g., environmental indicator bulletins.

The **Federal Geographic Data Committee (FGDC)** coordinates many activities relevant to the Framework objectives, including the following:

- Development of a Coordinated National Spatial Data Infrastructure. The objective is to develop a consensus on standards to be used for geographical data on computers and the standardization of classifications of vegetation and land-use information derived from both satellites and ground-based observations.

- Development of the National Biological Information Infrastructure (coordinated the by USGS/Biological Resources Division).

- The Working Group on Sample Inventory and Monitoring of Natural Resources and the Environment is conducting the "Northern Oregon Pilot"in which the National Resource Inventory (USDA/NRCS), the Forest Inventory and Analysis (USDA/USFS), and the Forest Health Monitoring Survey (USDA/USFS) are being evaluated for the potential to use joint survey teams to implement combined surveys of multiple resources and to increase coordination between related natural resource surveys.

The **Intergovernmental Task Force on Monitoring Water Quality** (ITFM) has been a highly successful Federal and State interagency collaboration group since 1992. The effort is carried out under the authority of Office of Management and Budget (OMB) Memorandum 92-01, which gives the U.S. Geological Survey (USGS) the lead in water-information coordination. The ITFM, with multiple rounds of public participation, and an interorganizational advisory group, adopted a nationwide strategy for water-quality monitoring (surface, ground, and coastal), which addressed institutional collaboration, environmental indicators, comparable monitoring methods and quality assurance/quality control, information management and sharing, and water-quality assessment and reporting. The ITFM has completed a series of goals to help revitalize monitoring, including a publishing final report, "The Strategy for Improving Water-Quality Monitoring in the United States" (Intergovernmental Task Force on Monitoring Water Quality, 1995).

To assist in implementing the Framework, the ITFM will facilitate implementation of the strategy for water resources information and will work in cooperation with the Federal Geographic Data Committee. The ITFM will be responsible for efforts concerning (1) consensus about sets of widely useful key physical, chemical, and biological indicators for water to support information for decision-making across many scales, (2) joint development and adoption of common water-use indicator and data-element names, definitions, and formats, (3) implementation of a performance-based monitoring methods system and quality assurance/quality control to achieve comparable water data, more flexible use of monitoring methods, and more cost-effective monitoring, (4) joint establishment of reference conditions or sites for shared use in biological and ecological assessments and comparisons for water, and (5) design of water-quality monitoring programs and selection of indicators to measure progress in meeting clearly stated goals for aquatic resources, including State standards for designated uses. ITFM will work with CENR to implement any associated pilot studies.

11. Program Design and Implementation

This Framework proposes a strategy for uniting the environmental monitoring and research capabilities of the Federal agencies and the measurement methodologies of different disciplines to build a National Integrated Environmental Monitoring and Research program. Integration of environmental monitoring and research networks through time, across space, and among resources is the primary distinction between the proposed national Framework and the existing array of single-issue or single-resource monitoring programs. This integrated approach will allow us to answer complex environmental questions that are beyond the scope of most existing programs and activities. It will also provide the scientific information needed to support policies related to ecosystem management and sustainable development. It must involve a full partnership among Federal, State, Tribal, private, and nongovernmental entities. Network integration should remain the primary focus to guide program implementation.

Activities related to collection of environmental monitoring data in the United States must be coordinated at local, regional, national, and international levels. Congress has intended that many Federal environmental programs be administered and implemented at the State and local level (General Accounting Office, 1994). The implementation plan should reflect the concerns of State, Tribal, local, private, and international entities and foster partnerships for sharing data among their environmental monitoring programs.

The initial steps for implementing the vision of the Framework include the near-term activities and products described below.

This conceptual framework was reviewed and discussed at a Mid-Atlantic Regional Workshop of Federal and non-Federal stakeholders in April 1996. On the basis of that workshop, a Regional Pilot Demonstration Project of the framework in the Mid-Atlantic Region is planned. This Regional Pilot, and others if possible, will be used to evaluate the specific requirements for and demonstrate the added value and benefits of program integration at the regional level.

A National Stakeholders Workshop was held in September 1996 to continue refining the overall vision and questions for a well-integrated national monitoring effort in order to build the broadest foundation for cooperation as possible. The workshop examined the fundamental questions that need to be addressed when assessing multiple resources at regional and national scales, explored how well current assessments address cause and effect relationships, and discussed a national vision for the design of a monitoring framework.

An INTERNET Home Page that includes maps and other information about major Federal monitoring and related research networks and programs will be introduced. Managers of other networks, Federal and non-Federal, will be invited to link their environmental monitoring network or program data bases to the home page.

An interagency Integrated Environmental Monitoring Team, under the direction of

CENR, will be established to coordinate program development and implementation. This Team will work closely with the Federal Geographic Data Committee (FGDC), the Interagency Task Force on Monitoring of Water Quality (ITFM), and other appropriate interagency committees.

Agencies should collaborate also through the Integrated Environmental Monitoring Team to support research in areas identified as key to the Framework. Some examples of possible collaborative research topics follow:

1. Integration of information across temporal and spatial scales to link understanding of ecological processes to regional assessments.

2. Improvements in monitoring design, measurements, and statistical methods.

3. Integration of social and economic models and variables into the Framework.

4. Use of Framework data for making policy.

5. Comparability of spatial scales in data collection and interpretation.

6. Development of conceptual models to drive the Framework design at different levels.

7. Quantification of uncertainty for monitoring protocols, sampling designs, and models operating at different spatial or temporal scales.

8. A statistical framework for linking networks and programs at similar and different Framework levels.

12. Conclusions

A fundamental improvement in the way that the Nation monitors its environment is required if we are to meet the challenges facing us during the next several decades. Current monitoring programs do not provide the integrated data across multiple natural resources at the various temporal and spatial scales needed to develop policies based on current scientific understanding of ecosystem processes. New developments in science and technology provide new opportunities for collecting and organizing data that could greatly expand our capabilities for meeting agency missions. With the current fiscal limitations facing all levels of government, cooperation among environmental agencies will be essential to the long-term success of any individual program. The time is right for the integration of monitoring programs, even where aimed at specific resources, in order to create a vision of the environment as a whole.

The combined Federal environmental and natural resources research budget totaled more than $5 billion in fiscal year 1995 (National Science and Technology Council, 1995b). About $650 million of this amount was provided for about 30 major Federal environmental monitoring and research networks and programs. Although the associated programs, activities, and networks were established in response to specific legislation about specific resources and issues, they can be better integrated to provide information needed for effective ecosystem management. Similarly, the networks can be better integrated to provide information synthesis across a range of spatial scales.

The Nation needs a framework for environmental monitoring and research that will enable comprehensive assessments of its renewable natural resources at national and regional scales. Such a framework for environmental monitoring and related research is essential if we are to differentiate between actual and perceived environmental issues and to address them appropriately to avoid both unnecessary regulation and serious environmental problems.

Four distinct activities are required to develop the types of data needed for improving assessment and planning capabilities with the proposed Framework. National capabilities in each area should be upgraded through more efficient use of existing facilities and programs and by supplementing those programs where critical gaps in monitoring are observed. These activities are summarized as follows:

1. Integrate data and programs across resources, agencies, and temporal and spatial scales through research and modeling. Integration is the primary difference between existing monitoring programs and the proposed national Framework. This integration concept should be the highest priority of the Framework program.

2. Develop data standards and methods for interoperability to increase the utility of information obtained from inventories and remote sensing programs and to coordinate research activities with the needs of ongoing monitoring and survey programs.

3. Coordinate and enhance existing national and regional surveys by agreeing upon common definitions, methods, data management systems, and areal coverage for similar resources. This will require identification of critical regional or national resources or problems that are not being effectively addressed by the current set of inventories, surveys, and fixed-site networks and enhancing or supplementing those programs to fill the information gaps. It will also require that existing and new survey and monitoring programs collect data at the same locations, where appropriate, and specifically at sites in the national network of index areas.

4. Establish a network of index sites that will provide standardized information on major independent and dependent environmental variables that are known to affect ecosystem processes. This network should be built from existing intensive research and monitoring sites and networks where possible.

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Appendix 1. Explanations of Abbreviations and Acronyms Used

AIRMON - Atmospheric Integrated Research Monitoring Network

ARS - Agriculture Research Service

BBS - Breeding Bird Survey

BIA - Bureau of Indian Affairs

BLM - Bureau of Land Management

BOR - Bureau of Reclamation

BRD - USGS/Biological Resources Division

C-CAP - Coastal Change Analysis Program

CASTNET - Clean Air Status and Trends Network

CENR - Committee on Environment and Natural Resources

COP - Coastal Ocean Program

CSRS - Cooperative State Research Service

DDRP - Direct/Delayed Response Project

DOC - Department of Commerce

DOD - Department of Defense

DOE - Department of Energy

DOI - Department of the Interior

ECN - Environmental Change Network

EMAN - Environmental Monitoring and Assessment Network

EMAP - Environmental Monitoring and Assessment Program

EPA - Environmental Protection Agency

EROS - Earth Resources Observing System

FGDC - Federal Geographic Data Committee

FHM - Forest Health Monitoring

FIA - Forest Inventory and Assessment

FWS - Fish and Wildlife Service

GAP - Gap Analysis Program

GIS - geographic information system

GOOS - Global Oceanic Observing System

GTOS - Global Terrestrial Observing System

IFS - Integrated Forest Study

IGBP - International Geosphere Biosphere Program

IMP - Integrated Monitoring Program (UNECE)

ITFM - Interagency Task Force for Monitoring of Water Quality

LMER - Land Margin Ecosystem Research

LTER - Long Term Ecological Research

MAB - Man and the Biosphere

MRLC - Multi-Resolution Land Characteristics

NADP/NTN - National Atmospheric Deposition Program/National Trends Network

NAMS - National Air Monitoring System

NAPAP - National Acid Precipitation

Assessment Program

NASA - National Aeronautics and Space Administration

NASQAN - National Stream Quality Accounting Network

NAWQA - National Water Quality Assessment

NBS - National Biological Service

NERRS - National Estuarine Research Reserve System

NIST - National Institute of Standards and Technology

NMFS - National Marine Fisheries Service

NOAA - National Oceanic and Atmospheric Administration

NPS - National Park Service

NRC - National Research Council

NRCS - Natural Resources Conservation Service (formerly the Soil Conservation Service)

NRI - National Resources Inventory

NS&T - National Status and Trends

NSF - National Science Foundation

NWI - National Wetlands Inventory

NWS - National Weather Service

PAMS - Photochemical Air Monitoring System

PCSD - President's Council on Sustainable Development

RAWS - Remote Automated Weather System

SLAMS - State and Local Air Monitoring System

SNOTEL - SNOpack TELemetry

TIME - Temporally Integrated Monitoring Experiment

TMAP - Trilateral Monitoring and Assessment Program

TVA - Tennessee Valley Authority

UNECE - United Nations Economic Commission for Europe

UNESCO - United Nations Educational, Scientific, and Cultural Organization

USACE - U. S. Army Corps of Engineers

USAID - U.S. Agency for International Development

USDA - U. S. Department of Agriculture

USFS - U. S. Forest Service

USGCRP - United States Global Change Research Program

USGS - U. S. Geological Survey

WEBB - Water, Energy, and Biogeochemical Budgets

Appendix 2. Preliminary List of Descriptors and Variables To Be Considered Within the Monitoring Framework.

Site descriptors:
Site name
Latitude
Longitude
Elevation
Landscape position
Slope
Aspect
Land use history
Natural disturbance history (storm, fire, pest, etc.)
Soil profile and classification

Soils:
%Organic Matter
Water holding capacity
Water retention curve
Sat. hydraulic conductivity
Infiltration parameters
Soil Moisture
%Litter
Total N
Available N
Denitrification rate
N fixation rate
$^{13}C/^{12}C$ in SOM
$^{15}N/^{14}N$ in SOM
% Water-stable aggregates (< 100 um, 100-250 um,> 250 um)
Total N (by aggregate size)
Total C (by aggregate size)
Major cations (Ca^{++}, Mg^{++}, K^+, Na^+, NH_4^+)
Major anions (SO_4^{--}, PO_4^{---}, Cl^-)
pH in water 1:2.5
CEC
Soil temperature (by horizon)
Exchangeable acidity
Toxic contaminants

Ground water:
Depth to water table
Total C
DOC
Total NO_3^{--} and NH_4^+
Toxic contaminants

Streams:
Discharge
Major cations (Ca^{++}, Mg^{++}, K^+, Na^+, NH_4^+)
Major anions (SO_4^{--}, PO_4^{---} NO_3^{--}, Cl^-, F^-) pH
DOC
DON
Sediment load
Metals (Al, Hg, Cd)
Toxic contaminants

Lakes:
Major anions (PO_4^{---} , NO_2^{--}/NO_3^{--},)
Major cations (H^+, NH_4^+)
Temperature profile

Climate:
Rainfall
Snowfall
Photosynthetically Active Radiation
UV–B
Wind run
Humidity
Air temperature

Vegetation:
% cover (by species)
Demography (by species)
Size (DBH, height)
Leaf Area Index
Leaf % N, P
Leaf % lignin
Leaf $^{13}C/^{12}C$
Leaf $^{15}N/^{1}$

Vegetation (continued):
Litter fall
Establishment (by species)
Flowering
Leaf budbreak
Phenological stages
Above–ground NPP
Below–ground NPP
Necromass
Leaf and stem lesions
Leaf wilt
Chlorosis
Animals:
Species presence/absence, density, diversity
Breeding demography
Insect herbivores (by group)
Landscape:
Patch size
Patch distribution
Edge area/length
Atmospheric Fluxes:
CO_2 flux
CH_4 flux
N_2O flux
Wet Deposition
Dry Deposition

Marine/Estuarine:

Water Temperature
Salinity
Ambient Light
Turbidity
Water Movement
Water Depth
Nutrient Dissolved Oxygen
Dry and Wet Deposition
Sediment Grain Size
Sediment Total Organics
Sediment Toxic Contaminants
Sedimentary Oxygen Demand
Net and Gross Primary Production
Chlorophylls
Phytoplankton Biomass/Composition
Zooplankton Biomass/Composition
Benthos Biomass/Composition
Nekton Biomass/Composition
Decomposer Biomass/Composition
Resource Harvest

Appendix 3. Glossary of Terms

abiotic: Nonliving characteristic of the environment; the physical and chemical components that relate to the state of ecological resources.

accuracy: The degree to which a calculation, a measurement, or set of measurements agree with a true value or an accepted reference value.

aquatic ecosystem: A water-based ecosystem (See ecosystem); an interacting system of water with aquatic organisms (plants and animals).

assessment: Interpretation and evaluation of monitoring results for the purpose of answering policy-relevant questions about ecological resources.

biodiversity: The variety and variability among living organisms and the ecosystems in which they occur.

biomass: All the living material in a given area, often refers to vegetation.

biome: Entire community of living organisms in a single major ecological area.

bioregion: A territory defined by a combination of biological, social, and geographic criteria, rather than geopolitical considerations; generally, a system of related, interconnected ecosystems.

biota: The living components of an ecosystem or community

biotic: Of or pertaining to living organisms.

biotic community: Any assemblage of populations living in a prescribed area or physical habitat; an aggregate of organisms that form a distinct ecological unit.

characterization: Determination of the attributes of resource units, populations, or sampling units.

cropland: Land devoted to the production of cultivated crops.

community: An aggregation of living organisms having mutual relationships among themselves and to their environment.

comparability: The degree to which different methods, data sets, or decisions agree or can be represented as similar.

condition: The distribution of scores describing resource attributes without respect to any societal value or desired use; i.e., a state of being.

data quality: The totality of features and characteristics of data that bear on their ability to satisfy a given purpose; the sum of the degrees of excellence for factors related to data.

directory: Set of summarized documentation about data sets.

ecological site: A specific location on the land that is representative of an ecological type.

ecological unit: A mapped landscape unit designed to meet management objectives, comprising one or more ecological types.

ecology: The relationship of living things to one another and their environment, or the study of such relationships.

ecoregion: A relatively homogeneous geographic area perceived by simultaneously analyzing a combination of causal and integrative factors, including land-surface form, soils, land uses, and potential natural vegetation.

ecosystem: The biotic community and its abiotic environment.

ecosystem management: Use of ecosystem concepts to predict effects of management actions on the ecosystem and to guide management planning and actions.

ecotone: A transition between two or more biotic communities (junction zone or tension belt); a transition area of vegetation between two communities having characteristics of both kinds of neighboring vegetation, as well as characteristics of its own.

environment: The sum of all external conditions affecting the life, development, and survival of an organism.

estuary: Regions of interaction between rivers and near-shore ocean waters where tidal action and river flow mix freshwater and saltwater.

fragmentation: Breaking up of contiguous areas into progressively smaller patches that are increasingly isolated.

habitat: The place where a population (e.g., human, animal, plant, microorganism) lives and its surroundings, both living and nonliving.

index: Mathematical aggregation of indicators or metrics.

indicator: Characteristics of the environment, both abiotic and biotic, that can provide quantitative information on ecological resources.

integration: The formation, coordination, or blending of units or components into a functioning or unified whole.

landscape: The set of traits, patterns, and structure of a specific geographic area, including its biological composition, physical environment, and anthropogenic patterns.

landscape: The set of traits, patterns, and structure of a specific geographic area, including its biological composition, its physical environment, and its anthropogenic patterns.

landscape ecology: The study of distribution patterns of communities and ecosystems, the ecological processes that affect those patterns and changes in pattern and process over time.

meta-data: Descriptive or qualifying data that describes primary data elements.

model: Mathematical or physical representation of data or a system that accounts for all or some of its known properties.

observation: A fact or occurrence that is recognized and recorded.

parameter: Any quantity, such as a mean or a standard deviation, characterizing a population.

population: A group of interbreeding organisms occupying a particular space; the number of humans or other living creatures in a designated area.

precision: The degree to which a set of observations or measurements of the same property, usually obtained under similar conditions, conform to themselves.

quality: The sum of features and properties/characteristics of a product or service that bears on its ability to satisfy stated needs.

quality assurance: An integrated system of activities involving planning, quality control, quality assessment, reporting, and quality improvement to ensure that a product or service meets defined standards of quality with a stated level of confidence.

range: Land supporting indigenous vegetation that is grazed or has the potential to be grazed and that is managed as a natural ecosystem.

rangeland: Land on which the indigenous vegetation (climax or natural potential) is predominately grasses, grasslike plants, forbs, or shrubs and is managed as a natural ecosystem. Where plants are introduced intentionally, they are managed as indigenous species.

region: Any explicitly defined geographic area.

risk: A measure of the probability that damage to life, health, property, or the environment will occur as a result of a given hazard.

species: A population or series of populations of organisms that are capable of interbreeding freely with each other, but not with members of other species.

standard method: An assemblage of techniques and procedures that is based on consensus or other criteria, often evaluated for its reliability by collaborative testing and receiving organizational approval.

stressor: Any physical, chemical, or biological entity that can induce an adverse response.

suitability: The appropriateness of applying certain resource management practices to a particular area of land, as determined by an analysis of the economic and environmental consequences and the alternative uses foregone.

sustainability: The ability to sustain diversity, productivity, resilience to stress, health, renewability, or yields of desired values, resource uses, products, or services from an ecosystem while maintaining the integrity of the ecosystem over time.

trends: The changes in the distribution of scores for condition indicators over multiple time periods.

validation: The process of substantiating specified performance criteria.

watershed: The terrestrial area of the landscape contributing to flow at a given stream location.

APPENDIX 4. Building an Index Site Network from Existing Programs

During the discussions on Framework design that were conducted both within the Environmental Monitoring Team and with others in of the natural resource management and scientific community, the emerging Framework concept has created both enthusiasm and concern. The concerns can be summarized as follows:

Where do specific programs fit? The Framework diagram provides broad categories of monitoring, but does not clarify where different types of existing programs fit relative to each other within the index site level.

What issues will the Framework address? The framework was deliberately designed to be useful to a range of environmental issues. Although this design ensured that any environmental issue could be addressed through the Framework, it also created a concern that a generic network would replace our current issue-specific networks and significantly reduce our ability to address specific issues, or that costly measurements would be added to existing programs that were not needed to meet their objectives.

How should the Framework get started? Some wished to start the program by immediately picking index sites others, by determining the major issues to be addressed, designing the entire frame, and then integrating existing programs. Some wished to move quickly, while others wanted to take a slow, methodical approach that included involvement of stakeholders in the Framework development.

The following discussion attempts to further refine the index site level of the Framework in order to clarify how existing programs could be integrated to provide whole-ecosystem data across a range of scales. It also proposes a phased approach to integrating existing programs and identifying future monitoring needs.

Creating a frame of reference for comparing existing index sites

The concept of index sites. Index sites are defined in the Framework as places for monitoring an ecosystem at a scale and intensity adequate to develop an understanding of the processes controlling ecosystem change. These sites will measure, among other things, a common set of core variables by using performance-based protocols and standardized quality control procedures and will be linked to the region by including measurements of ecosystem status that are also made as part of regional surveys. Because the Framework is not intended as a mechanism for creating a new monitoring program and the cost involved in equipping and operating intensive monitoring sites is beyond the scope of available funds, the first set of index sites will be developed through improved communication, data comparisons, and development of common core variables among existing programs. The intent is for monitoring at these initial sites to make up the backbone of a long-term index site monitoring network for the Nation. It is important to stress that the proposed framework is not a new monitoring program that will supersede existing activities. The framework will be, in essence, a "virtual" network established through enhanced collaboration among existing monitoring programs.

Index site levels based on watershed or habitat scale. There are several "vectors" of regional integration that are implied in the Framework. The integration over time is achieved through linking relatively continuous intensive monitoring in index sites to regional survey databases. The integration from the few areas where we can afford to do process-level monitoring to the regional scale where management and policy decisions are made is implemented through linkage among index sites and regional probability surveys. Integration across media (air, soil, water, etc.) is achieved by having selected areas where all media are monitored in a way that allows us to see the intermedia processes that control ecosystem function and which are, in turn, linked to regional surveys that bring that whole-ecosystem understanding to the regional scale. Integration among State, local, Tribal, and Federal agencies is essential to fill adequately the different levels of monitoring for the spatial and temporal integration we hope to achieve.

There is another key type of integration that is not as clearly delineated in the original Framework structure-the integration from the small plot, watershed, or local habitat scale where a few major processes control ecosystem function to the larger river basin or landscape where different or multiple processes are in effect. In fact, existing programs in the United States, although not commonly integrated or compared, are monitoring the environment at each of these environmental scales. This integration is needed to detect differences in important processes across the range of landscape scales and to understand the combined effect of multiple land uses on the ecosystem. Our understanding of the effect of landscape scale on ecosystem processes is limited and will require monitoring data at locations where scale issues can be addressed. The Framework, therefore, must integrate an array of index sites at different scales, from ecosystems in small headwater watersheds to the large river basins and coastal zone downstream, with different measurements and intensities of sampling that are appropriate to understanding and tracking processes at each scale. For water- and land-use issues, the small to large integration we are seeking requires that the index site level of the Framework comprise a hierarchy of plot-scale to large watershed and coastal-zone-scale monitoring programs. For animals (wildlife, insects, etc.) and some characteristics of plant populations, the watershed paradigm might not be appropriate for effective monitoring. Instead, index site levels could range from the local habitat to maximum- and migration-range scales. Data from those levels could then be indexed to a watershed within the habitat boundaries in order to integrate biological data with data from other components for the ecosystem. A diagram of the Framework concept with the proposed hierarchy of index sites is presented in Figure 4.

Data from all these index sites can be related to the regional surveys where sampling is done over the whole region and is, therefore, independent of the small-to-large scale issue. By combining these index site levels with the larger Framework structure (surveys,

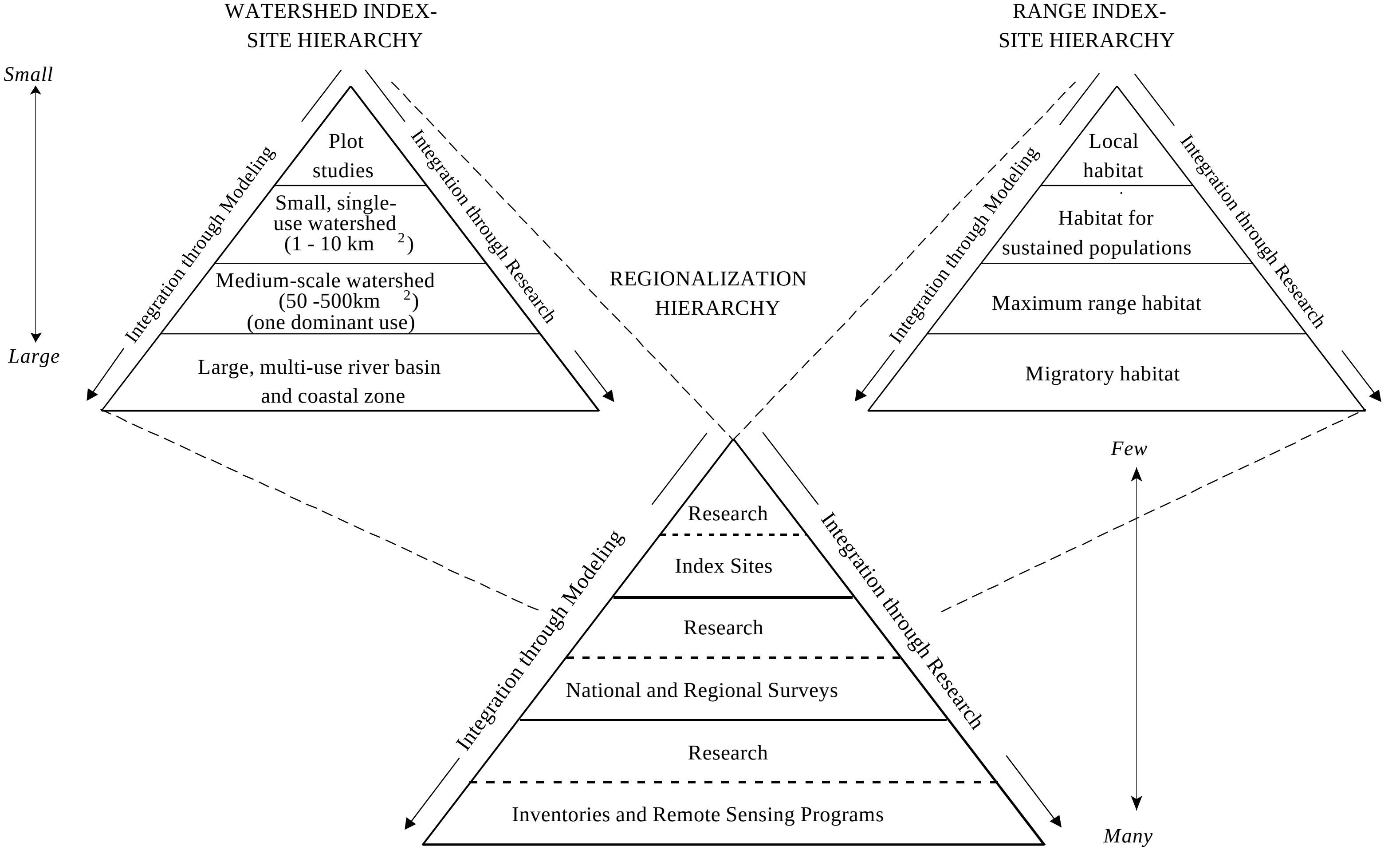

Figure 4. Proposed refinement of index sites within the intensive monitoring level.

inventories, and remote sensing), we can begin to illustrate the possible relationships among existing programs and eventually determine points of integration and gaps in monitoring capability.

Nesting of index sites. Nesting or clustering index sites is a tested technique of addressing the scale question for water resources issues (Lawrence et al., 1994). Besides the obvious advantage for linking process understanding across scales, an effective environmental monitoring program must take into account the effect on ecosystem function of the interaction among land- and water-use types. The effect of a mosaic of management regimes on the ecosystem in a given region cannot be determined by merely a summation of ecosystem changes in each management parcel. The juxtaposition of different resource uses will have important effects on ecosystem characteristics (e.g., animal and plant populations and species distribution and changes in the biogeochemistry of surface waters that pass from one management regime to another) that are different from the characteristics of either management regime alone. In regions with steep environmental gradients, such as the alpine to prairie transition in the headwaters of the Platte River in Colorado, these "edge effects" can also occur within a single management regime; i.e., minimally-developed landscapes. The reality of the modern environment is that there are few areas of the globe that are not significantly influenced by human activities and the edge effect of adjacent uses. Nesting index watersheds, such that mass balances can be calculated at the boundaries between different land uses, can be an effective way of tracking the influence of that land use over time on water quality and will thus set boundary conditions for looking at other issues related to the edge effect between the adjoining land uses.

Addressing environmental issues by using the Framework

Creating subnetworks of index sites. The initiation of the framework should focus on small, clearly achievable integration steps that are undertaken in the context of a design framework that will eventually expedite the full integration desired. Integration of programs that address similar issues, but at different scales or sampling intensities, should, therefore, be the first order of business.

Research and monitoring programs at existing potential index sites are focused on specific land- and water-use environments (nondeveloped, agricultural, and urban suburban landscapes, coastal zones, etc.) or specific media (air, water, soil, vegetation, and wildlife). Because our ultimate goal is to have long-term, integrated data for whole ecosystems (i.e., all media) within a given landscape, creation of an ecosystem monitoring network should begin with the parallel development of subnetworks that pull together programs that already have a common landscape of focus. This strategy will make the initial integration possible without drastic alteration of existing program plans and protocols and would ease development of a set of common assessment goals and measurement protocols, quality-assurance guidelines, and reporting requirements for intercomparison of data. The combined set of subnetworks should then be reviewed to ensure that our ability to address within-media issues that are the focus of many of our existing programs has not been compromised. This review can be achieved by using the sites and programs selected for the subnetworks to populate a framework diagram for a specific media or issue and then by assessing gaps in the monitoring network that results. Separate framework diagrams should, therefore, be drawn for air, water, soil, vegetation, and wildlife, and gaps in the framework for addressing issues in each medium should be determined.

Initially, we recommend integrating plot scale, small watershed, and medium-scale watershed monitoring programs to create subnetworks for whole-ecosystem monitoring in the following land-use categories:

(1) Watersheds with minimal direct human impact (principally parks and wilderness areas): These areas and survey sites are essential to determine, model, and monitor processes controlling ecosystem function in our nondeveloped lands and waters and to serve in coordination with the regional surveys as an early-warning system for detecting subtle ecosystem changes before they would be observable in more managed or manipulated environments. These areas will be most suitable for addressing such issues as the effects on natural ecosystems of atmospheric deposition, UV-B, climate change. This type of landscape also makes up a large portion of the watersheds feeding municipal water supplies and, therefore, is important to human water-use issues.

(2) Agricultural watersheds (crop, range, and managed forest land uses): These areas and survey sites will provide long-term monitoring data for agricultural ecosystems. These sites should include research watersheds, but should also be large enough to serve as good indicators of regional agricultural trends and not be significantly influenced by the fluctuation of individual farm activities. These areas will address the effects of those issues listed above in agricultural settings, as well as be most suitable for addressing such issues as nonpoint source pollution, pesticide contamination, and soil erosion.

(3) Urban/suburban watersheds: The urban/suburban environment represents the most dynamic land use currently affecting ecosystems in the Nation. Expansion of suburban development and the effects of that expansion on biodiversity, water quality and quantity, and other values are increasing rapidly throughout the world. These index sites will provide trends and process information on human environments and key environmental data for the linkage of environmental change to human health. How to design an effective long-term index site for this environment, however, is still poorly defined. This type of index site should, therefore, be established slowly with significant up-front research on methodology. These "single dominant use" areas will be nested within larger watersheds that will form the next tier of index sites.

(4) Landscape mosaic index sites: These sites are specifically chosen for integrated process monitoring of the landscape mosaic created by all index site types listed above. These sites will generally be large river basins. They will be the unit at which the mosaic of nondeveloped, suburban, urban, and agricultural land-use change can be tracked and the effect of those changes on the ecosystem can be described. These large watersheds will also be the principal source of data for computing load estimates to coastal regions.

(5) Coastal/marine index sites: These areas will be specifically designed for monitoring ecosystem change in coastal and estuarine ecosystems, including the perimeter of the United States and the Great Lakes. A major driver of ecosystem change in the coastal zone is water, nutrient, and chemical loading from the continent to coastal areas. Therefore, a network for deposition, river, and ground water monitoring sites operated specifically for computing loading to the coastal zone will need to be maintained for these index sites (see category 4 above). These sites will provide cause and effect information on issues such as fisheries decline, marine pollution, coastal erosion.

Linkage of index sites to the larger Framework

Linkage to regional surveys. Each subnetwork of index sites must also be coupled with a larger population of similar land- or water-use areas that are periodically sampled as a subset of broad regional surveys, inventories, and remotely sensed data to put the information from the index sites into a regional context. The linkage between the index sites and periodic surveys will be essential to bringing process-level understanding to the regional scale. The purpose of each index site/survey subnetwork is to ensure that we can at least characterize ecosystems within each subpopulation over time and understand the processes controlling the changes observed. However, the ultimate goal will be to find ways to understand better the ecosystems within each subnetwork through integrated analysis of the entire network of index sites and surveys.

Linkage to fixed-site distributed monitoring networks. Monitoring of the air environment, especially for estimating wet and dry deposition to land and water surfaces, is most effectively done through maintaining an array of fixed-site monitoring stations. When effectively designed, these networks provide a map of conditions in the entire monitoring area and thus are most appropriately placed in the inventory level of the framework. The land or water surfaces that are well-suited for monitoring Earth-surface characteristics are not always suitable for accurate measurement of air-quality parameters, especially dry deposition. Interpolation between stations to provide estimates of deposition and air quality in a particular watershed, however, is a scientifically accepted practice. It is, therefore, important that air-quality and deposition stations be maintained in an array that maximizes data quality for regional mapping of the air and deposition conditions, with additional stations added if needed to increase accuracy in the index sites. Besides providing estimates for inputs to the index sites, these networks will also allow us to track trends in national and regional air quality and deposition and to contrast air and deposition quality in our urban and nonurban environments.

The challenge of defining a reference or baseline condition

One of the common methods being considered for assessing the impact of specific land uses on ecosystems is the "reference watershed approach”, in which a watershed with minimal human influence and with similar site characteristics to a watershed with large human influence, is selected to provide comparison data for the impacted watershed. Unfortunately, true reference watersheds have been fairly elusive for research projects that have tried this to date. The reality of nature is that there are too many environmental factors that vary radically across small distances in a landscape to ever achieve an adequate watershed-to-watershed paired comparisons. A method with a greater potential for success and cost effectiveness in determining a reference condition is the "gradient approach," in which numerous watersheds representing a range of states of influence are sampled and compared (Murdoch and Stoddard, 1992). Regression can then be used to determine the watershed characteristics with the strongest relation to the issue in question and can suggest a regional baseline condition by back-calculating the regression to a zero-stress condition. Results from these studies argue for a network that tracks land-use effects through monitoring of a continuum of land-use conditions. Budgets for environmental monitoring will never be sufficient, however, to fund the number of sites needed to address many environmental issues with intensive-monitoring methods alone. Defining reference conditions, therefore, will require a careful linkage of the index sites we can fund with regional surveys that have lower cost per station and, therefore, allow better regional coverage. The EPA Long-Term Monitoring network is a recent example of this model of monitoring that has been successfully applied to determining the regional effects of acidic deposition on the landscape (Newell, 1992).

The selection of index sites can be tailored over time to quantify the uncertainty in larger surveys and to test the utility of survey variables. The resulting combination of index site and survey information developed from one subnetwork will then be used to compare with and contrast the combination of index site and survey information from another, thus providing a form of "reference" information that is more robust than can be achieved with the individual reference watershed.

The rationale for the index site/survey/inventory integrated program is, therefore, fairly simple. To meet the demands of ecosystem-based management of the Nation's resources, we have to integrate the kind of regional information that can be gathered from surveys, inventories, and remote sensing with data from areas of intensive monitoring programs designed to help us understand process. In many cases, this will require frequent sampling of the environment in small "index sites," such as small watersheds and plot studies. In other cases, the important ecosystem processes are taking place on a larger scale and will require more of a regionally intensive monitoring approach, such as tracking changes in land use within large watersheds. Our current monitoring programs that support site-intensive measurements, although effective for the specific issue they address, are inadequate on their own for bringing process understanding to the regional scale. Linking surveys and intensive-site monitoring programs is, therefore, the obvious next step in the evolution of an effective environmental monitoring program for the United States.

Getting started

Determining the number and location of index sites and survey points. The number of index and survey sites should be sufficient to represent the gradients of ecosystem condition relative to the issues those subnetworks address (see reference condition discussion above). The number of sampling stations needed to characterize a subpopulation and the spatial distribution of areas across the Nation will vary from issue to issue and from media to media. Initially, the number of sites will be small, and analysis of existing site-specific and survey data will be used to determine the optimum number of sites needed to characterize that population. The subnetwork could then be expanded or reduced to meet that need over time. Assessments focused on developing index site criteria from available data collected by EMAP, NRI, NAWQA, and other regional programs would be valuable in determining the optimum number and distribution of index sites in the initial phase of network development. We have the capability now to use several landscape characteristics for computer generated clustering of landscape types.

Fine tuning the index site networks by using a regional focus. Environmental issues and landscape characteristics vary across the United States according to local climate, land use, and political conditions. Any network that will ultimately provide useful information to resource managers must be flexible enough to address region-specific issues, as well as national trends. Further, monitoring of the environment is more developed in some areas of the country than in others, and even national programs have an uneven distribution of data collection activities across the country. An analysis of the current status of our monitoring capability and determining the gaps that need to be filled must, therefore, occur at the regional or smaller scale. As a starting point for the index-site network, we should break the country into 10 or fewer regions on the basis of a logical distribution to address the major regional and national issues. For example, we could strive for adequate coverage of 10 major climate/deposition effects regions of the United States. A rigorous assessment will then be necessary for that region to determine optimum site and survey density. This concept is essentially a compromise between original considerations to distribute index sites based on ecoregions and distributing sites based strictly on major issues. Distribution by ecoregion placed a primary emphasis on geographical coverage while distribution by issue could leave large areas of the continent without an index site. By dividing the Nation into 10 or fewer regions, some regional or geographical representation can be achieved while still focusing most of our resources on effectively addressing known environmental issues.

A phased strategy for integrating existing programs. Creating a truly integrated ecosystem monitoring network is a large and complex proposition that, at best, will take several years to achieve. Trying to do too much too soon will jeopardize achieving this goal in the long run. Much of what has been proposed as part of the Framework has been proposed before. The difference is the focus on integrating information across scales and media to bring process understanding to scales where it is useful to resource managers. Just to integrate ecosystem data across spatial scales for individual land- or water-use types (e.g., undeveloped headwater watersheds, agricultural plots, and estuaries) or media (e.g., air, water, soil, and forests) would be a great step forward in our capabilities. The first steps toward integration should, therefore, be to link those existing programs that are most easily integrated--programs that focus on a specific land and water use--thus creating a set of parallel subnetworks that can be further integrated over time. On the basis of the above discussion, we propose that the following phases in framework development take place:

Phase I: Update of national data base. Compile a list of major Federal programs and where they fit the Framework and determine major endangered or missing capabilities. Each agency with environmental monitoring programs should be asked to report to CENR where those programs fit in the Framework as shown in Figure 4. Once completed, the database should be used to build a virtual national framework as illustrated in Figure 4, and apparent gaps in monitoring coverage should be noted for expediting the region by region analysis (see below). National programs that would obviously benefit from greater collaboration should be encouraged to initiate discussions on how to integrate their data.

Estimated time for completion: 1 year.

Phase II: Analysis of pilot regions. The national analysis can tell us what national monitoring programs exist, but not whether those programs are effective in any given region of the country. For an effective assessment of current monitoring capabilities, we need to study existing programs at the regional and local scales. Western and eastern pilot regions should, therefore, be selected to create a virtual integration of monitoring programs within those regions. The pilot exercise should be used to determine what questions should be asked in the region, what programs and data can be integrated to answer those questions, and what changes in monitoring need to be made. This will involve compiling all Federal, State, local, and tribal monitoring capabilities in the pilot region; analyzing the types of data collected; and determining if integration would lead to more effective environmental monitoring. Once completed, the data base of programs should be used to build a virtual regional framework as illustrated in figure 4, and a gap analysis should be performed. It is critical that this activity include involvement of the stakeholders in the environmental issues being addressed.

Estimated time for completion: 2 to 3 years.

Phase IIIa: Development of the national Framework. Export the experience from the phase two pilot studies and begin development of the national Framework region by region.

Estimated time for completion: 2 to 3 years per region, conducted in parallel.

Phase IIIb: National integration of regional frameworks. This phase should occur incrementally as Phase IIIa develops to facilitate interaction among the regions during framework development and to ensure that critical national issues are addressed. The national integration must also include regional stakeholders in planning and implementation activities. Such a phased implementation will allow a systematic development of the Framework and can ensure a fair selection process for index sites that is based on scientific analysis of available data.

Appendix 5. Description of Major Federal Environmental Monitoring and Research Networks and Programs

MAJOR FEDERAL ENVIRONMENTAL MONITORING & RESEARCH NETWORKS & PROGRAMS

Inventories and Remote Sensing Programs

Program Name (Acronym)	C-CAP	GAP	MRLC	NWI
Program Name (Full)	Coastal Change Anal Pr.	Gap Analysis Program	Multi Resol.Land Charact.	Natl Wetlands Inventory
Agency	NOAA	NBS	EPA/USGS/NOAA/NBS	DOI,Fish & Wildlife Serv.
Year Initiated	1990	1988,1994 funded	1992	1978
Measures	Land cover change	4 basic data layers	Electromag,radia,lnd cov	Determine extent & type...
Collection Source				
Point	-	x	-	x
Source	-	x	x	x
Transect	-	x	-	x
Other area	Satellt.imag. & aerial ph.	Satellite imagery	TM image	Color infrared photography
Locations for Data Collection	In 16 states, coastal US	40 states involved	540 scenes all over U.S.	Done 85%/US land cover
Temporal Interval	Every 1-5 years	Optimal-every 5 years	1992-95 (every 10 yrs)	10 year intervals
Sampling Design				
Random	-	-		x
Selected	-	-	-	-
Synoptic	x	x	x	-
Data Available	Yes	Some	Yes	Yes
Accessible	CD ROM	INTERNET	USGS EROS data center	Maps, INTERNET
Extent for Reporting	Estuarine drainage area	US (starting in Hawaii)	Continental U.S.	50 states,4 sq.mi .plots
Partners				
International	-	-	-	-
Agency	Numerous Federal	EPA, Dept.of Defense	EMAP,GAP,NAWQA,C-CAP	Federal Resource Agen
State	State cooperators	State agencies	-	All 50 states
Local	Local cooperators	Local agencies	-	Private sector, local govt.
Authorities/Reason for Running Prg.	Study cov.change & eff.	Fish & Wild. Coord. A.	Land cover data required	Emerg Wetland Resour.A
Users of Data per Year	Hundreds	800/ mo. on INTERNET	200	1.6 million paper NWI maps
Program Meets Metadata Standards	Yes	Yes	Partly	Yes
Expansion of Prog (Needed/Not)	Needed	Needed	Needed	Needed
Contact Person	Don Field	Michael Jennings	Denice Shaw	Bill Wilen
Phone #	803-974-6233	208-885-3565	919-541-2698	703-358-2161

MAJOR FEDERAL ENVIRONMENTAL MONITORING & RESEARCH NETWORKS & PROGRAMS

National and Regional Surveys - Part 1

Program Name (Acronym)	BBS	CASTNET	EMAP	FHM
Program Name (Full)	Breeding Bird Survey	Clean Air S&T Network	Envir.Mon & Assess. Prog.	Forest Health Monitoring
Agency	NBS	EPA mainly,multiagency	EPA	Multi-ag.,EPA & USDA
Year Initiated	1966	1988-lst data, 1991-formed	1988	1990
Measures	Bird species	Sulfate,nitrate,cations	Multi-resource eco-ind.	Data on trees, plants
Collection Source				
Point	-	x	-	-
Source	-	-	x	x
Transect	-	-	-	-
Other area	Route	-	-	Radiation,remote sensing
Locations for Data Collection	3000 routes-50 points	55 sites in U.S.	12,600 sites in U.S.	4,000 forested plots
Temporal Interval	Yearly	Weekly	Annual	
Sampling Design				
Random	x	-	x	
Selected	-	x	-	Annual (June 15-Sept 15)
Synoptic	-	-	-	-
Data Available	Yes	Yes	Yes	x
Accessible	INTERNET, CD ROM, disk	Data Clearinghouse	INTERNET, CDROM	Developing on INTERNET
Extent for Reporting	24.5 mile routes	1-10 sq km	640 square km	1 ha. plot & 4 subplots
Partners				
International	Mexico,Canada	Canadian government	Russis, Canada, Czech	-
Agency	Wildlife agencies	Federal agencies	Federal agencies	Bureau Land Mgt.,NRC's
State	Priv. org. state govt.	State agencies	State universities	State forestry
Local	Universities	Universities	-	-
Authorities/Reason for Running Program	Migratory Bird Treaty Act	Clean Air Act, Can. AQ Agr.	Clean Air Act, NEPA	88 For. Ec & Atm Re Act
Users of Data per Year	Thousands	150	Thousands	Hundreds
Program Meets Metadata Standards	No	No	Yes	In progress
Expansion of Program (Needed/Not Needed)	Needed	Needed	Needed	Needed
Contact Person	Bruce Peterjohn	Jim Vickery	Laura Jackson	Robert Loomis
Phone #	301-497-5841	919-541-2184	919-541-3088	919-549-4020

MAJOR FEDERAL ENVIRONMENTAL MONITORING & RESEARCH NETWORKS & PROGRAMS

National and Regional Surveys - Part 2

Program Name (Acronym)	FIA	NADP/NTN	NAMS/SLAMS	NASQAN
Program Name (Full)	Forest Inventory Analysis	Natl Atmos Dep Pr/Trends	Nat Air Mon sta/st. & loc	Nat Stream Qu Acct Net
Agency	USDA Forest Service	USGS	EPA,State &loc agen ow	USGS
Year Initiated	1930	1978	1979	1973
Measures	Forest attribts,type,size	Precip.chem.cation,anions	Criteria pollutnts,metallic	Major ions,nutr.,DOC
Collection Source				
Point	x	x	x	x
Source	x	-	-	-
Transect	-	-	-	-
Other area	-	-	-	-
Locations for Data Collection	1 plot per 1500-7500 ac.	192 sites in U.S., 1 in Can.	5000 samplrs,3150 sites	1996 35 sites
Temporal Interval	7-12 years	Weekly	Hourly,Pb&PM10 variable	Pres to future,18 t. Yrly.
Sampling Design				
Random	x	-	-	-
Selected	-	-	x	x
Synoptic	-	x	-	-
Data Available	Yes	Yes	Yes	Yes
Accessible	Disc,see attachment	Pub.yrly in data summary	EPA reg offices	NWIS
Extent for Reporting	1/6 to 2.5 acres	Points create isopleths	Primarily urban,some rura	Trend anal. at rivr flx pt.
Partners				
International	-	-	-	Mexico, Rio Grande...
Agency	Federal agencies	EPA, USDA, NPS, NOAA	EPA Regions	USGS
State	State resource agencies	State govt.,wildlife service	State agencies	-
Local	Citz.,envir grps,fores.ind	Private utilities,universities	Local agencies,contrctrs	-
Authorities/Reason for Running Program	Organic Act 1897,PL93	Clean Air Act of 1990	40CFR58	basic water data
Users of Data per Year	Thousands	Hundreds	450	Thousands
Program Meets Metadata Standards	In progress	Yes	No	Will meet ITFM standards
Expansion of Program (Needed/Not Needed)	Needed	Not needed	Not needed	Needed
Contact Person	Brad Smith	Mark Nilles	David Lutz	Rick Hooper
Phone #	202-205-0841	303-236-1870 x307	919-541-5476	770-903-9146

MAJOR FEDERAL ENVIRONMENTAL MONITORING & RESEARCH NETWORKS & PROGRAMS

National and Regional Surveys - Part 3

Program Name (Acronym)	-	NRI	NS&T	-
Program Name (Full)	Natl Stream Gaging Network	Natl Resources Inventory	National Status & Trends	NMFS Stock Assessment
Agency	USGS	USDA-NRCS	NOAA	NOAA/NMFS
Year Initiated	1888	1956-CNI,1977-now TRI	1984	1871
Measures	Water discharge, levels, temp.	Status & trendsof soils, etc.	Chem.contam.in mussels...	Fisheries catch and effort...
Collection Source				
Point	x	x	x	x
Source	-	x	-	x
Transect	-	x	-	x
Other area	-	-	-	-
Locations for Data Collection	7200 stations	800,000 samp sites US/Car	260 sites in U.S.	200 naut mile zone off coast
Temporal Interval	Continuous	Every 5 years	Annual	Annual
Sampling Design				
Random	-	x	-	-
Selected	-	-	x	x
Synoptic	x	-	-	-
Data Available	Yes	Yes	Yes	Yes
Accessible	WATSTORE,NAWDEX	CD ROM,INTERNET ,offices	INTERNET,, diskette	Reports, INTERNET,, CD, disk
Extent for Reporting	Puerto Rico,Guam,U.S.	Any geographic unit	20 km between sites	Multiple scales
Partners				
International	U.S.Territories	-	United Nations	Univ, Commissions, Agencies
Agency	Fed.Ener.Reg licensees	Agencies,Nat.Resour grps	EPA...	13 federal
State	State agencies	Forest Serv.,Iowa State U.	State governments	66 State & Territorial agencies
Local	Local agencies	Local convervation districts	Local municipalities	-
Authorities/Reason for Running Program	Organic Act.Sundry Civil	Rural Devel Act.Security A	Marine Prot.,R & S Act	4 Federal statutes
Users of Data per Year	Don’t know	Don’t know	1,000	1,000s
Program Meets Metadata Standards	No	No	Yes	Yes
Expansion of Program (Needed/Not Needed)	Needed	Needed	Needed	Needed
Contact Person	Ernest F. Hubbard	Jeff Goebel	Tom O’Connor	Carolyn Brown
Phone #	703-648-5312	202-720-9032	301-713-3028 ext 151	301-713-2363

MAJOR FEDERAL ENVIRONMENTAL MONITORING & RESEARCH NETWORKS & PROGRAMS

National and Regional Surveys - Part 4

Program Name (Acronym)	PAMS	RAWS	SNOTEL	
Program Name (Full)	Photoch.Asses.Mon Stat.	Remote Auto Weather Stat.	Snowpack Telemetry	
Agency	EPA,State& loc agen ow	Multiagency	NRCS	
Year Initiated	1994	Late 70's,early 80's	1978	
Measures	Bckgrnd conc,hydrocarb	Fire danger, wind, air...	Snow water content, precip.	
Collection Source				
Point	x	x	x	
Source	-	-	-	
Transect	-	-	-	
Other area	-	-	-	
Locations for Data Collection	57 sites in US,grow rapid	500 weather stations	560 sites/West of 100mer.	
Temporal Interval	Continuous	Generally hourly	Daily-hourly	
Sampling Design				
Random	-	-	-	
Selected	x	x	x	
Synoptic	-	-	-	
Data Available	Yes	Yes	Yes	
Accessible	EPA reg.offices,AIRS	West Region Climate Ctr.	Working towards internet	
Extent for Reporting	4 types of monitors	-	100 square miles	
Partners				
International	-	-	Canada,Mexico	
Agency	EPA Regional Offices	USDA,USDI/BLM,NPS,BIA	BOR, USACE, NWS	
State	State agencies	Fire Protection Agencies	Water Resour, state eng.	
Local	Local agency,Contractors	Fire Protection Agencies	Municipalities, tribes	
Authorities/Reason for Running Program	Clean Air A.Amen-1990	To protect public lands	PL46, Mem. 870, USDA	
Users of Data per Year	450	2000	3000	
Program Meets Metadata Standards	No	Yes	No	
Expansion of Program (Needed/Not Needed)	Needed	Needed	Needed	
Contact Person	Nash Gerald	Kolleen Shelley	Garry Schaefer	
Phone #	919-541-5652	208-476-8362	503-541-3068	

MAJOR FEDERAL ENVIRONMENTAL MONITORING & RESEARCH NETWORKS & PROGRAMS

Intensive Monitoring & Research Sites - Part I

Program Name (Acronym)		ARS Water Database	Forest Serv Experimental	LMER
Program Name (Full)	Acid Rain Watersheds	Agric. Research Service	Forest & Rangeland Sites	Land Margin Eco Res.
Agency	USGS	USDA	USDA	NSF
Year Initiated	1982	1937	1909	1988
Measures	Ca,Mg.pH,K,S,N	Precip,stream flow,air temp	Hydrologic,wildlife,soil	Changes in coastal zone
Collection Source				
Point	x	x	x	x
Source	-	-	x	x
Transect	-	-	x	x
Other area	-	-	Satellite imagery, remote	Watershed
Locations for Data Collection	15 sites U.S.3 still oper.	333 watershed areas/US	83 experimental forests	4 sites
Temporal Interval	Weekly-monthly	Every minute	Varies-some continuous	Variable-Weekly to qurtlly
Sampling Design				
Random	-	-	x	-
Selected	x	x	x	x
Synoptic	-	-	x	-
Data Available	Yes	Yes	Yes	Yes
Accessible	USGS Database	REPHLEX II, Internet	Profess,literature,records	From individual sites
Extent for Reporting	10 square km or less	.2 hect to 12,400 sq km	Puerto Rico, US(Hawaii)	Coastal U.S.
Partners				
International	-	-	Puerto Rico	-
Agency	National Park Service	NRCS, Hydrology Lab	EPA,NBS,USGS,NOAA	none
State	MD Dept.Natural Res.	State cooperative station	State agencies	State agencies
Local	State agencies	Universities	Univ.,priv.ind &landownr	Agen.,conserv.assoc.
Authorities/Reason for Running Program	Nat. Acid Rain Program	Reason for research	Renewable Resource A	Pred.coast resp to chang
Users of Data per Year	-	100	Don’t know	Don’t know
Program Meets Metadata Standards	Yes	Yes	No	Yes
Expansion of Program (Needed/Not Needed)	Needed	Needed	Needed	Needed
Contact Person	Owen Bricker	Jane Thurman	Dick Cline	Phillip Taylor
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MAJOR FEDERAL ENVIRONMENTAL MONITORING & RESEARCH NETWORKS & PROGRAMS

Intensive Monitoring & Research Sites - Part 2

Program Name (Acronym)	LTER	MAB		NOAA COP
Program Name (Full)	L.Term Eco Mon & Resear	Man & Biosphere Prog.	Natl Park Eco Mon Prog	Coastal Ocean Program
Agency	NSF	Voluntary interagen prog	DOI/Natl Park Service	NOAA
Year Initiated	1980	1976	1991	1990
Measures	Around 5 core areas	List of measures on disc	Water quality,veg.,birds	3 major program areas
Collection Source				
Point	-	x	x	x
Source	x	x	x	x
Transect	x	x	x	x
Other area	Grid system & satellite im.	International Network	Remote sensing	Satellite imagery,remote sen
Locations for Data Collection	18 sites in US, Puerto,Ana	47 US, 100 W.Hem, 324	5 funded prog, 11 not yt	9 sites
Temporal Interval	Hourly-annually	Variable	Varies from park to park	Minutes-yearly
Sampling Design				
Random	x	x	x	x
Selected	x	x	x	x
Synoptic	x	x	x	x
Data Available	Yes	Yes	Some	Yes
Accessible	Contact sites, INTERNET	INTERNET	Hard copy & floppy disc	STORET, prog mgr., univ
Extent for Reporting	Varies/plots 1 sq m-.10 hect	World-wide-114 nations	Ecosystem being rep.	Very narrow - infinite
Partners				
International	Yes	Yes	-	-
Agency	USDA-ARS,Nat.Conserv	EPA,NASA,NBS,USAID...	Nat.Con.,NBS,EPA,FWS	EPA,USDA,DOI,USACE
State	Forest Service	-	Universities	State agencies,universities
Local	-	-	Volunteer groups	Private industries
Authorities/Reason for Running Program	-	Voluntary Program	NPS Organic Act 1916	Part of NOAA’s responsib
Users of Data per Year	many	about 1 million	-	Don’t know
Program Meets Metadata Standards	In progress	Yes	In progress	Yes
Expansion of Program (Needed/Not Needed)	Needed	Needed	Needed (250 parks)	Needed
Contact Person	Scott Collins	Roger Soles	Gary Williams	Larry Pugh
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MAJOR FEDERAL ENVIRONMENTAL MONITORING & RESEARCH NETWORKS & PROGRAMS

Intensive Monitoring & Research Sites - Part 3

Program Name (Acronym)		NOAA NERRS	USGS Benchmark	USGS Coop Program
Program Name (Full)	Natl Marine Sanctuary Pr	Natl Estuar Res Reserv Syst	Benchmark Network	Bisc.Brk.Wtrshd,Bnchmrk
Agency	NOAA	NOAA	USGS	USGS
Year Initiated	1972	1972	1965	1983
Measures	Ident desig mgmt areas	Water qual, temp, salinity	Stream disch.,major ions...	Soils,water quality,Al,Si
Collection Source				
Point	x	x	x	x
Source	x	-	-	x
Transect	x	-	x	x
Other area	-	-	-	-
Locations for Data Collection	14 sites in US (& territories)	21 sites, 21 data loggers	50 sites (Decrease in 96)	l watershed/tons stations
Temporal Interval	monthly-annual	Every half hour	Quarterly	15 minutes-monthly
Sampling Design				
Random	-	-	x	-
Selected	x	x	x	x
Synoptic	-	-		x
Data Available	Yes	Yes	Yes	Yes
Accessible	Thru site managers	Thru sites & on internet	District office sites	WATSTORE
Extent for Reporting	US territorial waters	NERRS	Total export of watershed	Watershed scale-66 sq mi
Partners				
International	US territories	Mexico	-	-
Agency	DOI, NPS, Navy	EPA, DOI, DOC	Natl Park Service, Forest	EPA
State	State governments	State agencies	-	Univ. Of N.H., Syracuse U.
Local	Private industry, volunteers	Local agen, landowners	-	NYC Dept of Envir Protect
Authorities/Reason for Running Program	Marine Prot Resource & Sanc	Coastal Zone Mgmt Act	Organic Act	Research & Monitoring
Users of Data per Year	Don't know	.5 mill-prog info/100's-tech	30	Dozens
Program Meets Metadata Standards	In progress	Yes	No	In progress
Expansion of Program (Needed/Not Needed)	Needed	Needed	Needed	Needed
Contact Person	Jim Lawless	Randall Schneider	Kathy Fitzgerald	Pete Murdoch
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MAJOR FEDERAL ENVIRONMENTAL MONITORING & RESEARCH NETWORKS & PROGRAMS

Intensive Monitoring & Research Sites - Part 4

Program Name (Acronym)	USGS NAWQA	USGS WEBB		
Program Name (Full)	Natl Water-Quality Asses	Water,energy,biog.budg		
Agency	USGS	USGS		
Year Initiated	1986 pilot,1991-full prog.	1991		
Measures	Assess qual, H20(stream)	Water & biogeoch process		
Collection Source				
Point	x	x		
Source	x	x		
Transect	x	x		
Other area	-	Satellite imagery		
Locations for Data Collection	60 units(2/3 of U.S. water)	5 sites		
Temporal Interval	3 years of intens, 7 low	Minutes-daily		
Sampling Design				
Random	-	x		
Selected	x	x		
Synoptic	x	x		
Data Available	Yes	Yes		
Accessible	Distributed info system	INTERNET		
Extent for Reporting	Study unit is 52,029 sq km	100's of sqare km		
Partners				
International	Mexico, Canada	Puerto Rico		
Agency	EPA	USACE, NPS		
State	State water agencies	Universities		
Local	Local water agencies	Municipalities, Tribes		
Authorities/Reason for Running Program	Charged by Congress	Global Change Program		
Users of Data per Year	40,000	100		
Program Meets Metadata Standards	Yes	Don’t know		
Expansion of Program (Needed/Not Needed)	Not needed	Needed		
Contact Person	Tim Miller	George Leavesley		
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Abstract

The National Science and Technology Council's (NSTC's) Committee on Environment and Natural Resources (CENR) established an interagency working group in July 1995 and charged it to "recommend a framework for an integrated monitoring and research network that allows evaluation of the Nation's environmental resources (e.g., air, water, soil, plants, animals, and ecosystems)." The resulting Framework will build upon the strengths of the Nation's existing environmental monitoring and related research networks and programs. A fully integrated and coordinated network can provide a better understanding of our environmental resources and produce greater cost-effectiveness while continuing to meet individual agency missions.

A conceptual framework is presented for integrating the Nation's environmental research and monitoring networks that will enable comprehensive and integrated assessments of natural resources. This framework can link inventories and remote sensing, national and regional resources surveys, and intensive-monitoring and research sites with research and modeling to produce an integrated national environmental monitoring program. This integration of the Nation's major environmental monitoring and research networks can allow understanding, assessment, evaluation, and forecasting of its renewable natural resources at national and regional scales. It can also enhance and support our understanding and predictive capability of the causes and consequences of environmental change and ecosystem response, address multiple scales of ecosystem and resource interactions, and allow level syntheses and assessments of data and information. This is the added value that network integration can provide that the current array of fragmented single-purpose networks cannot.

The proposed Framework is envisioned to be a collaborative effort building upon existing networks and programs facilitated by any necessary standardization and data management infrastructure. Most importantly, this Framework and related ecological research will provide both data and understanding of ecosystem condition and sustainability at the scale where policy and management decisions are most effectively made.

The resulting program will produce a sound scientific information base to support natural resource assessment and decision making. Linking the program to those of other nations by compatible data-collection and management protocols can lead to an international monitoring network capable of addressing global scale issues. Such an integrated monitoring system can be used to detect large-scale, long-term environmental changes, such as improvements in response to environmental policies or detection of new, and perhaps unanticipated changes owing to climate and other environmental or anthropogenic changes.

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