Recommendations for a National Ecological Monitoring Program

by

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EXECUTIVE SUMMARY

In this report, the authors express a synthesis of their thoughts and opinions on a framework for a national ecological monitoring program for Canada. The findings also reflect the contributions and feedback of people involved in six regional consultation workshops and meetings held across Canada in 1991-1992. The proposed national ecological monitoring program would support the capability of the federal government and its partners to report on changes in the environment and to understand the causes and consequences of monitored changes.

Ecological monitoring and reporting address issues and concerns related to changes in:

(1) those aspects of the environment that reflect the health and integrity of ecosystems and their component parts—for example water, air, soil, and biota;

(2) the abundance and productivity of economically important biological resources, such as forests, fish, game animals, and agricultural products; and

(3) biota and ecosystems that are not conventionally perceived as having economic value but that are nevertheless of great intrinsic worth and ecological importance. Examples are nongame animals, wildflowers, and the "invisible" biodiversity of microbes and other small wildlife.

Ecological monitoring and reporting has an inter-disciplinary, systems-oriented perspective, and an appreciation is required of linkages among the components and processes within complex systems. Ecological monitoring requires a long-term commitment, because many important changes are subtle and cannot be detected by short-duration monitoring programs.

Wherever possible, the proposed program would build upon existing capabilities and expertise for ecological monitoring and research. Existing programs would be evaluated with respect to providing appropriate information for a national network of ecological monitoring sites. Deficiencies in existing programs would be addressed by integrating present networks and by establishing new sites where necessary. The success of the program would depend upon the cooperation of all agencies that are involved in relevant monitoring activities and the development of partnerships with research groups.

The conceptual design of the program is intended to integrate monitoring and research at the national level. Indicators would be measured at two classes of monitoring sites—intensive and extensive—in each of the 15 terrestrial ecozones of Canada. Within ecozones, potential indicators relevant to the most important regional concerns and issues would be identified. Indicators would be evaluated by expert working groups and a suite of appropriate indicators would be chosen to monitor changes in environmental quality at the regional or national scale. Measurement of indicators would be integrated within and among extensive and intensive monitoring sites.

Intensive monitoring sites would be used for relatively detailed monitoring of indicators relevant to structural and functional ecology and their responses to environmental change. A total of one to three intensive sites is suggested for eventual development in each ecozone, depending upon its size, biogeophysical heterogeneity, and suite of important environmental stressors. Intensive monitoring sites would include:

(1) *reference sites*, located in ecological reserves or other protected areas and used for the study of ecosystem structure and function and for monitoring the effects of regional and global change;

(2) *experimental sites*, where environmental stressors are manipulated under controlled conditions and the ecological responses are studied; and

(3) *stress gradients*, consisting of a series of sites representing a gradient with respect to a particular anthropogenic stressor, such as agriculture or forestry.

The national network of intensive monitoring sites should capitalize on ongoing programs of ecological monitoring and research. However, the new network must deal with deficiencies in the existing programs, including: (1) a lack of intensive sites in some ecozones; (2) insufficient integration of atmospheric, aquatic, and terrestrial components; and (3) a general paucity of standardized biological indicators.

Extensive monitoring sites would be more numerous than intensive monitoring sites. They would be located throughout each ecozone to gain an overview of larger-scale changes in the ecological character of the landscape. In all ecozones, many extensive monitoring data are currently available from existing programs of cooperating sectoral agencies. However, there are two impor-

tant deficiencies with the existing information: (1) biological response indicators are particularly deficient, yet these are the most relevant indicators of ecological integrity; and (2) the spatial designs of current sectoral monitoring programs often do not provide data that are statistically representative of regions or ecozones.

Initial steps in the proposed framework are to:

- (1) identify major sources of environmental stress in particular ecozones;
- (2) identify deficiencies in the available indicators of environmental quality; and
- (3) develop protocols for the selection of ecological indicators and evaluation of data quality.

Monitoring programs should be institutionalized within government and should be integrated with research programs. Related ecological research could be conducted by government and nongovernment (e.g., university and private sector) scientists. The role of research should include: (1) the development of indicators; (2) hypothesis testing relevant to the causes and consequences of environmental change; (3) determination of the compatibility of monitoring techniques; and (4) multidisciplinary study of structural and functional ecology.

For national reporting, the State of the Environment Reporting organization of Environment Canada (SOER) relies on data collected by other institutions. SOER does not have the capability to conduct monitoring activities, nor is such a function planned. The role of SOER in the proposed program would be to:

(1) coordinate and assist working groups composed of experts from government and nongovernment agencies and from all the regions of Canada to undertake various activities (see below);
(2) catalogue and evaluate existing databases for use in state of the environment reporting;
(3) request, obtain, and maintain data for use in state of the environment reports;
(4) coordinate, integrate, map, and analyze the data for the purposes of state of the environment reporting;
(5) prepare reports, fact sheets, and other products that document the state of the environment, and, where possible, forecast environmental trends;
(6) facilitate partnerships with and among sectoral agencies;
(7) coordinate a national network of ecological monitoring sites;
(8) catalogue and maintain a monitoring database that will be accessible to other agencies and the public; and
(9) identify deficiencies in national ecological monitoring and relevant research, and make recommendations to address those deficiencies.

Expert working groups are important in the proposed framework and would assist SOER in some of the functions described above by: (1) identifying the most important sources of environmental stress in particular ecozones; (2) suggesting suitable indicators to monitor the effects of the stressors; (3) identifying deficiencies in the available environmental database that relate to the effects of the stressors, and recommending modifications to sectoral monitoring programs to address those deficiencies; (4) identifying deficiencies in the development of suitable indicators, and directing the development of protocols for the selection and measurement of ecological indicators; (5) directing research to establish protocols for the comparison of different techniques and the evaluation of data quality; and (6) interpreting trends in indicators, and suggesting causal hypotheses.

Important concerns identified during the workshops include the following: (1) financial considerations, including funding requirements and increasing cost effectiveness; (2) fostering cooperation among government agencies, and encouraging partnerships with the academic scientific community, the native community, and volunteers; (3) suggestions regarding the process of data acquisition by SOER, including accessibility of data, benefits to data contributors, and types of information requested; (4) future directions in monitoring and research programs, including issues related to measurements, mandates, adaptability of programs, sample archives, monitoring for unknown stressors, composite indices, and development of biological response indicators (which are especially deficient in current monitoring programs); (5) issues related to state of the environment reporting units; and (6) transfer of information to the public, including notions of environmental quality, interpretation of environmental change, and environmental education in the broad sense.

INTRODUCTION

The ultimate goal of ecological monitoring is to anticipate and prevent deterioration of ecological integrity. This objective is based on the premise that healthy ecosystems are necessary for the sustainable development of healthy societies and economic systems.

PURPOSE OF ECOLOGICAL MONITORING

The purpose of ecological monitoring is to detect or anticipate changes in ecological integrity or ecosystem health by measuring and understanding appropriate indicators. Changes in indicators are evaluated by comparison with their known historical condition or with a reference or control situation.

The consequences of monitored changes in the environment or of predicted future changes are evaluated on the basis of a cumulative knowledge of ecological principles, coupled with research targeted to address emergent questions. For example, changes in the rate at which natural forest is being clearcut and converted to silvicultural plantations can be monitored. The consequences for ecological integrity, however, are interpreted on the basis of ecological principles, gained from scientific knowledge and research. Specific questions include effects of ecological conversion on biodiversity, productivity, soil and streamwater chemistry, watershed hydrology, disease and insect infestation, and global environmental change.

A central problem is the definition of ecological "integrity" or "health." A satisfactory definition must be achieved without invoking judgements or criteria that are too narrow, imprecise, or anthropocentric. Clearly, any changes caused by human activity will benefit some organisms and ecological processes, while being detrimental to others. Nonetheless, at the present stage of development of ecosystem science, enough is known about trends in disturbed or stressed ecosystems to identify those ecosystems with greater integrity as being: (1) relatively resilient and resistant to an intensification of environmental change; (2) relatively biodiverse (i.e., including variety at the genetic, species, and community levels); (3) relatively structurally and functionally complex; and (4) a component of a natural succession that is stable over the long term (Odum 1985; Schindler 1987, 1990; Freedman 1989; Woodley 1990; Karr 1991).

Indicators of ecological integrity can include measures at the metabolic, organismic, population, community, and landscape levels, all of which can respond to

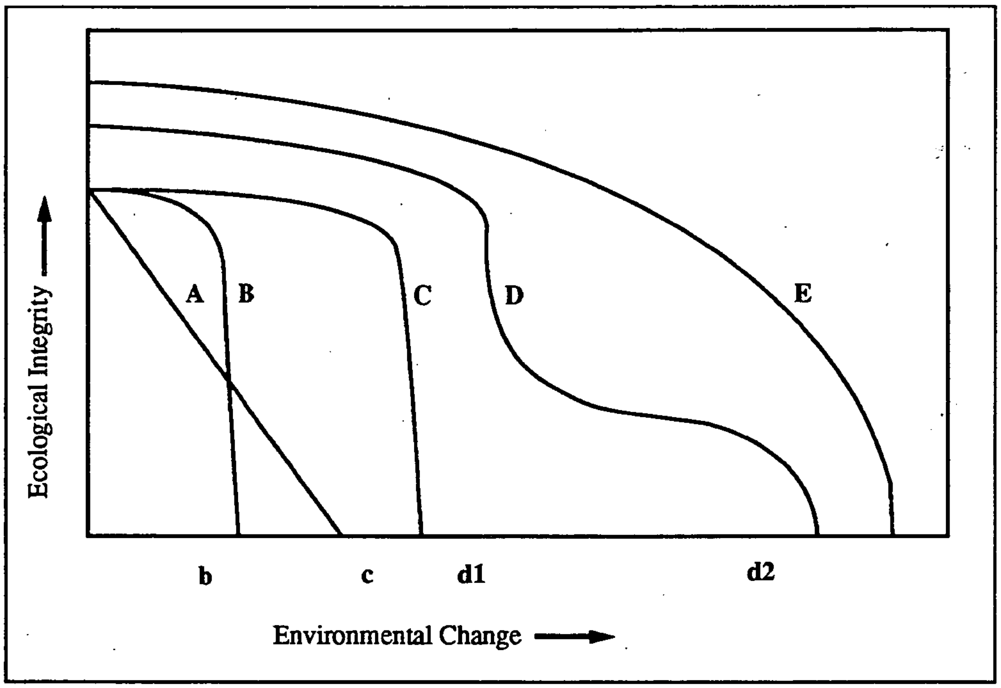


Figure 1
Ecological integrity and resistance to environmental change. The effects of stress on the ecological integrity of various components of the environment (e.g., organisms, communities or landscapes) depend on their resistance to environmental change, or an intensification of stress. The curves depicted above illustrate variation in the ways that components may respond to environmental change. Curve height represents ecological integrity, while slope represents the rate of loss of integrity in response to increasing levels of environmental change. Integrity is initially lower in examples A-C, and higher in examples D-E. Example A responds to increasing environmental change with a steady decline in integrity, but B and C begin to show a notable response only after a threshold of tolerance to environmental change (b and c, respectively) is exceeded, with C having a higher threshold. Example D shows a complex, curvilinear response to environmental change, with rapid loss of integrity at one threshold (d_1), followed by relative stability (resistance), and then rapid response at a second threshold (d_2). Example E has the highest integrity initially, as well as over the longer-term. For the purpose of ecological monitoring, components A and B would be most useful as early indicators of loss of ecological integrity.

changes in environmental conditions. Ecological responses to environmental change can range from simple monotonic responses to complex curvilinear responses. The nature of the change in ecological integrity is partly dependent on the resistance to environmental change and on thresholds of tolerance to stress (Fig. 1). Ideally, to understand what an indicator is measuring, one should determine the shape of the response curve for that indicator when it is exposed to variations of a particular stressing agent (achieved by experiment or by examination of existing gradients). In practice, however, the response curve is rarely known.

Indicators may also take the form of composite indices, which aggregate information of related or disparate types. Composite indices of environmental quality are especially desirable for presentation to the public. Although composite indices of ecological integrity engender scientific controversy, because of difficulties in weighting the "value" of particular variables, progress is being made in their formulation (Steedman and Regier 1990; Karr 1991).

Sometimes important ecological changes are detected, but the causes and consequences of those changes are uncertain. The causes of ecological change may be unclear because: (1) they are part of an undiscovered complex of environmental stressors; (2) they are extrinsic to the monitored ecosystem; or (3) the necessary cause-and-effect experiments have not yet been performed. Once important changes are documented, however, causal hypotheses can be suggested and research can be directed to determine the causes and consequences of the observed changes. At any stage during the process, monitoring and related research can be used to identify important risks to ecological integrity, and to prevent (or less desirably, to mitigate) the hypothesized damages.

Research plays a crucial role in ecological monitoring. Whenever possible, a hypothesis should be identified before monitoring is started, in order to provide a focus to the work. Research is also necessary to understand the possible causes and consequences of change and to develop appropriate indicators for monitoring programs. Sometimes causal factors are obvious (i.e., the research has already been done). Often, however, the particular stressor or combination of stressors is not known. We should be monitoring the general health of ecosystems, and appropriate research is critically needed to develop indicators of ecological integrity.

STATE OF THE ENVIRONMENT REPORTING

Periodic reporting on the state of the environment is prominent among the mandates outlined in Canada's "Green Plan," released by the federal government in 1990 (Government of Canada 1990). To fulfil this requirement, a new branch of Environment Canada, State of the Environment Reporting (hereafter referred to as SOER), was formed to report on the state of the Canadian environment. SOER will play an integral role in the commitment of the federal government to establish a capability for the long-term monitoring and assessment of environmental quality.

SOER has four related initiatives (Government of Canada 1990; Marshall *et al.* 1991):

(1) to provide credible, timely, and accurate reports to the public on the state of the environment in Canada;
(2) to develop and publish environmental indicators for use in guiding routine decision-making by government, business, and the private sector;
(3) to establish a national network of environmental information that will make such information widely available and accessible to the general public; and
(4) to facilitate the establishment of "a long term state of the environment monitoring and assessment capability to study resources at risk, ecosystem response, and the impact of major disruptions to ecosystems" (Government of Canada 1990). A national-scale program of ecological monitoring would ensure that adequate data are available to address issues related to sustainable development, to permit environmental forecasting, and to support periodic reporting of the state of the environment.

CONSULTATIONS ON A NATIONAL ECOLOGICAL MONITORING PROGRAM

The mandate of SOER is "to provide timely, accurate, and accessible information to enable Canadians to make environmentally sensitive decisions" (Government of Canada 1990), but not to actually engage in monitoring activities. Therefore, as an agency, SOER does not conduct monitoring programs, nor does it plan to do so. Information on the environment that is used by SOER for reporting purposes must be obtained from other agencies. The existing monitoring programs, however, have rarely been developed for the purposes of regional- or national-scale monitoring of changes in environmental quality or ecological integrity.

To enhance its capabilities, SOER is attempting to facilitate the development of an integrated, national-scale ecological monitoring network, which would provide the appropriate data for national-scale state of the environment reporting. Through a contract to Dalhousie University, SOER sought recommendations and a regional consultation on issues related to the structure and implementation of a national ecological monitoring program.

Beginning in late 1990, a conceptual framework for a national ecological monitoring program was developed by Dalhousie University, in cooperation with SOER. The framework was initially developed through the authors' expertise, library research, and interviews with professionals involved in monitoring. This initial framework was then progressively modified through feedback obtained at a series of regional workshops held during 1991-1992.

Regional consultations are essential for the development of an ecological monitoring program that is appropriate for national purposes, while still being compatible with regional objectives. During our project, we convened six regional workshops in the Atlantic, Pacific, Northern, Prairie, Ontario, and Quebec regional administrative units of Environment Canada. At each of these consultations, we presented draft versions of our emerging framework for a national ecological monitoring program. This framework served as the background for discussions of ecological monitoring programs, the design of indicators, and other relevant issues. As a result of the feedback and perspectives obtained from each workshop, we progressively modified our draft framework, ultimately preparing the document presented here. Participants in the workshops included persons variously involved in environmental monitoring, ranging from field sampling to design of scientific research and monitoring programs to administration of programs.

The present document describes a conceptual and functional design for a national ecological monitoring program for Canada, including specific recommendations for its implementation. Also contained is an integrated summary of concerns expressed by workshop participants regarding the development of a national ecological monitoring program. Most of these issues were of national concern; however, some were more important in particular regions. The detailed results of the workshops are summarized in Staicer *et al.* 1993.

The opinions, concerns, knowledge, and recommendations herein are an amalgam of those of the authors and the many participants who attended workshops or responded with written commentary. We are grateful to those participants for their time, and for providing many important ideas that have greatly enriched this proposal for a national ecological monitoring program.

CONCEPTUAL DESIGN

The design of a national ecological monitoring program involves a number of concepts, including the nature of environmental indicators, ecological monitoring and reporting units, intensive and extensive monitoring sites, and the integration of ecological monitoring indicators and sites into a national program.

The conceptual design of the present framework for a Canadian ecological monitoring program focuses on monitoring three classes of indicators—stressor, exposure, and response indicators. These would be reported for each of the 15 terrestrial ecozones of Canada and for marine and urban/suburban ecozones, once these are designated. Indicators would be monitored within a network composed of two classes of sampling sites—intensive and extensive—that collectively would achieve an appropriate integration of monitoring and research activities. These concepts are discussed in more detail below.

ENVIRONMENTAL INDICATORS

Environmental indicators are surrogate measurements that are related to important aspects of environmental quality. It is important to note, however, that: (1) the relationships between indicators and environmental quality are often not well defined; and (2) the cause-and-effect relationships among indicators may not be well understood.

For example, there may be concerns over the declining health of forests in some areas. The causes of the forest dieback may not be known, but they might be hypothesized to be related to some combination of stressors, such as air pollution, insect damage, climatic change, and harvesting (Freedman 1989). The degradation of the ecological integrity of the forest is related to a complex of changes, including the species composition and diversity of all components of biodiversity, productivity, biomass, nutrient cycling, soil erosion, age-class structure, etc. However, for the purposes of ecological monitoring, only one or a few key surrogate indicators would actually be measured. Net annual production of trees might be chosen as an indicator of change of the economic forest resource, whereas a species of bird with a specific habitat requirement might be chosen as an indicator of the integrity of old-growth forest.

For the purposes of state of the environment reporting, indicators of change can be generically classified according to the simplistic, widely used stressor-exposure-response (SER) model (after Hunsaker and Carpenter 1990):

In the ecological context, stress is an agent of change and is associated with physical, chemical, or biological constraints on ecological integrity. *Stressor indicators* are mostly associated with human activities, such as the emission of sulphur dioxide and other primary air pollutants, the emission of precursors of secondary pollutants such as ground-level ozone, the use of pesticides and other potentially toxic substances, and the rate of habitat change, (e.g., by forest clearing). Stressor indicators can also be relevant to natural processes, such as wildfire, hurricanes, volcanic eruption, and climatic change.

Exposure indicators relate to the intensity of stressors experienced at a point of time, as well as the accumulated dose over time. Examples of exposure indicators are concentrations or accumulations of toxic substances and specific habitat changes associated with forest fire, clearcutting, or urbanization.

Response indicators reflect the effects on organisms, communities, processes, or ecosystems that are caused by exposure to stressors. Examples of response indicators include changes in the physiology, productivity, or mortality of organisms, in species diversity within communities, or in the rates of nutrient cycling.

The SER model is useful because it suggests a reasonable, intuitive, cause-and-effect linkage, with ecological change occurring as a response to exposure to an environmental stressor. It must be borne in mind, however, that SER is a simplistic conceptual model. It has important drawbacks: in many cases, the cause-and-effect linkages of stressor-exposure-response are not understood or quantified, and the seemingly linear SER model does not deal effectively with cascades and webs of stressors and effects (see below).

Some alternative conceptual variants of stressor-exposure-response models include the following:

1. As described above, the simple linear SER model (Fig. 2.1) indicates that exposure to a stressor may cause an ecological response. The intensity of exposure is important in determining the ecological effect, but there may be thresholds of tolerance (e.g., Fig. 1). For example, exposure of seabirds to spilled petroleum will cause acute toxicity if a physiologically related threshold of dose is exceeded.

2. The web model (Fig. 2.2) incorporates complexes of stressors and/or responses. Exposure to a complex of interacting stressors can cause an ecological response (Fig. 2.2.a). For example, as noted above, some forest diebacks are thought to be caused by an as yet undescribed complex of environmental influences (Freedman 1989). Analogously, a complex of ecological responses can be caused by exposure to a relatively simple stressor (Fig. 2.2.b). For example, acidification of a lake can cause a large number of ecological responses, including changes in water chemistry and clarity and direct toxic effects on phytoplankton, invertebrates, fish, and other biota (Freedman 1989). Of course, there can also be simultaneous webs of stressors and responses (Fig. 2.2.c).

3. The cascade model (Fig. 2.3) acknowledges that ecological responses can become secondary (and higher-order) stressors, causing subsequent ecological changes. For example, consider an extension of the acidification example described above: Direct toxic effects of acidification on certain biota can result in secondary and tertiary effects on other biota as a result of changes in trophic structure and dynamics of the ecosystem. A change in phytoplankton occurring in response to the direct toxicity of acidification can secondarily be a stressor that affects the herbivorous zooplankton, resulting in tertiary influences on planktivorous fish and quaternary effects on piscivorous fish and birds (Freedman 1989).

4. The feedback model (Fig. 2.4) suggests that some ecological responses can result in a modification of the intensity of the stressor. For example, wetlands might become drier as an ecological response to a climatic change that may be substantially forced by increased concentrations of carbon dioxide in the atmosphere (Freedman 1989). Much of the organic carbon accumulated over the long term in the wetland would become oxidized under the drier conditions, resulting in a large flux of carbon dioxide to the atmosphere and representing a positive feedback loop of stressor-response.

Of course, these alternative conceptual models of stressor-exposure-response are all simplistic in view of the complexity of the real ecological world. When designing indicators for environmental monitoring programs, simplicity can be an important operational asset. However, during interpretation of monitored changes in simple indicators, it must always be borne in mind that they represent very complex ecological changes that are occurring in the real world.

MONITORING AND REPORTING UNITS

A goal of national state of the environment reporting is to describe and interpret changes in indicators within the larger context. Ecological issues of more local concern, and any lack of appropriate regional-scale indicators, may not be addressed at the national level. Most appropriate to national state of the environment reporting are broader-scale questions that relate to basic ecological principles—for example, whether biodiversity has been affected by changes in the agricultural or silvicultural use of pesticides.

A national-scale reporting program must necessarily focus on relatively large, ecosystem-based units. Current sectoral monitoring programs, however, are being conducted at various scales, ranging from small sites to large regions encompassing one or more provinces or territories, depending upon the mandate, interests, and resources of the sectoral agency. Moreover, different components (e.g., aquatic, terrestrial, atmospheric) of ecosystems are typically measured at different spatial scales and in different ecological communities.

The choice of an appropriate spatial scale for national environmental reporting is thus a complex issue. Depending upon the question or issue, different spatial scales might be used to monitor the effects of particular regional-scale stressors. For example, climatic change affects all ecozones, whereas acidic fog is important only in a few maritime locations. Below, we discuss an approach to the selection of monitoring and reporting units for the proposed national program.

Ecological Land Classification

The Canadian system of ecological land classification characterizes terrain on the basis of geology, soil, landform, climate, fauna, and flora. This system is hierarchical, in that the smaller spatial units are aggregated into larger units, ultimately into ecozones. Such a system allows the input of monitoring data into a database organized by a geographical information system (GIS). Monitoring data could be mapped at whatever spatial scale they were collected or at a smaller map scale. At the present time, SOER has the GIS capability of inputting monitoring or other data at the ecodistrict level, which corresponds to a map scale of 1:250 000 to 1:500 000. Canada has recently been characterized on the basis of approximately 5400 ecodistricts, 177 ecoregions, 45 ecoprovinces, and 15 ecozones (Wiken 1986; Fig. 3).

The terrestrial ecozone is the largest, most generalized ecological unit in the Canadian system of ecological land classification. It is characterized by interactive and adjusting abiotic and biotic factors. The ecozone is under consideration by SOER as an all-purpose unit for state of the environment reporting. Ecozones are attractive for national reporting because the 15 ecozones largely correspond to ecologists' general impressions of major ecological systems and are easily distinguished on a map of Canada. (The latter is important for practical processes of environmental reporting). Limitations of ecozones (and of other units in the Canadian system of ecological land classification system) as reporting units are discussed below, as are several alternative systems for reporting.

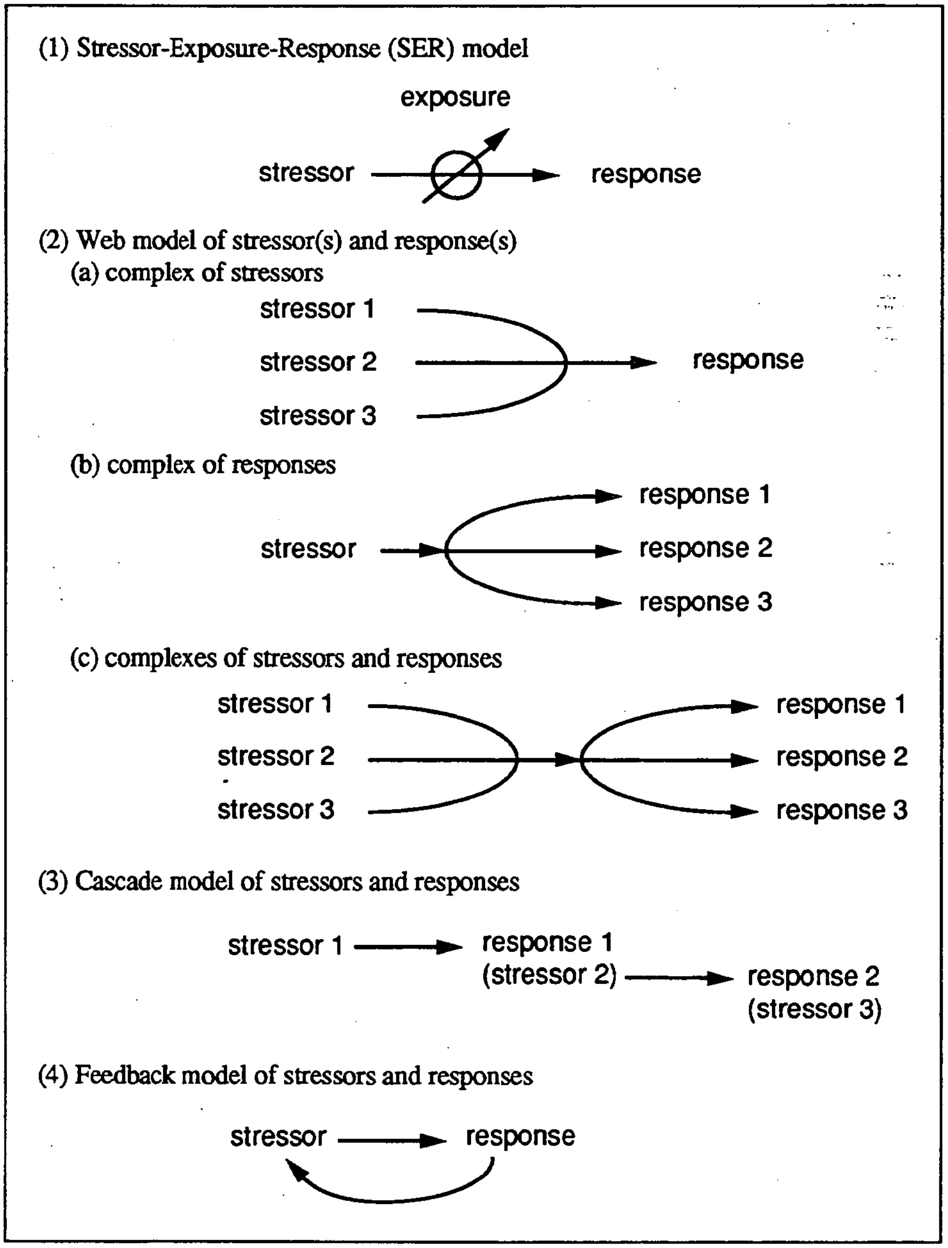


Figure 2
Conceptual variants of stressor and response models.

Concerns over the use of ecozones as reporting units

A number of major concerns regarding national reporting by terrestrial ecozone were expressed by workshop participants:

Rivers and their watersheds can transcend ecozone boundaries. It is unclear how indicator data for major aquatic systems can be integrated into a framework for terrestrial ecozones. If ecozones are used as the basis for national reporting, SOER may have to report separately on particularly important river systems, such as the St. Lawrence, Fraser, and Mackenzie rivers, and on large lake systems, such as the Great Lakes, Lake Winnipeg, and Great Bear and Great Slave lakes. In addition, an ecozone-based framework would have to be developed for the coastal marine zones of Canada. These issues are well known to SOER and are already being addressed (e.g., for large lakes).

Trends and conditions often affect ecozones in a very heterogeneous manner, making it difficult to generalize across this national reporting unit. The Boreal Shield ecozone extends from northern Saskatchewan to Newfoundland. The importance of many stressors varies markedly within this ecozone, because of large differences in human population density, industrialization, and inherent ecological characteristics across this wide distribution. In such cases, variations in stressors within ecozones could be portrayed using maps of isopleths. For some spatially heterogeneous indicators, it might even be useful to report the indicators nationally as isopleths but put them into an ecological perspective by colour coding the map for the 15 ecozones.

Point source effects can be important, but they do not fit clearly into an ecozone framework. Will these be aggregated on the basis of common activities, such as smelting, electricity generation, or pulp manufacturing? Or will case studies be developed?

Mesoscale biophysiographic variations are not well reflected within ecozones. This is an especially important consideration in mountainous areas. In British Columbia the great biophysiographic variation related to topography, climate, and biodiversity (Meidinger and Pojar 1991) is not well reflected within a mapped framework of only four major ecozones, a fact that was stressed during the Vancouver workshop. However, it must be borne in mind that ecozones are proposed here as units for the reporting of the state of the environment only at the national scale. Because ecological land classifications are hierarchical, it is always possible to report data at smaller scales for particular purposes, such as provincial, regional, county, or municipal state of the environment reporting (assuming, of course, that the original monitoring data were measured at a suitable spatial scale). This latter consideration is especially relevant to extensive monitoring indicators, which are derived from data from a relatively large number of sites. In British Columbia, the provincial Ministry of the Environment will be using an ecoprovince/ecoregion spatial framework for its upcoming state of the environment report, a system that is compatible with the proposed ecozone framework for federal reporting.

Units appropriate to stressors

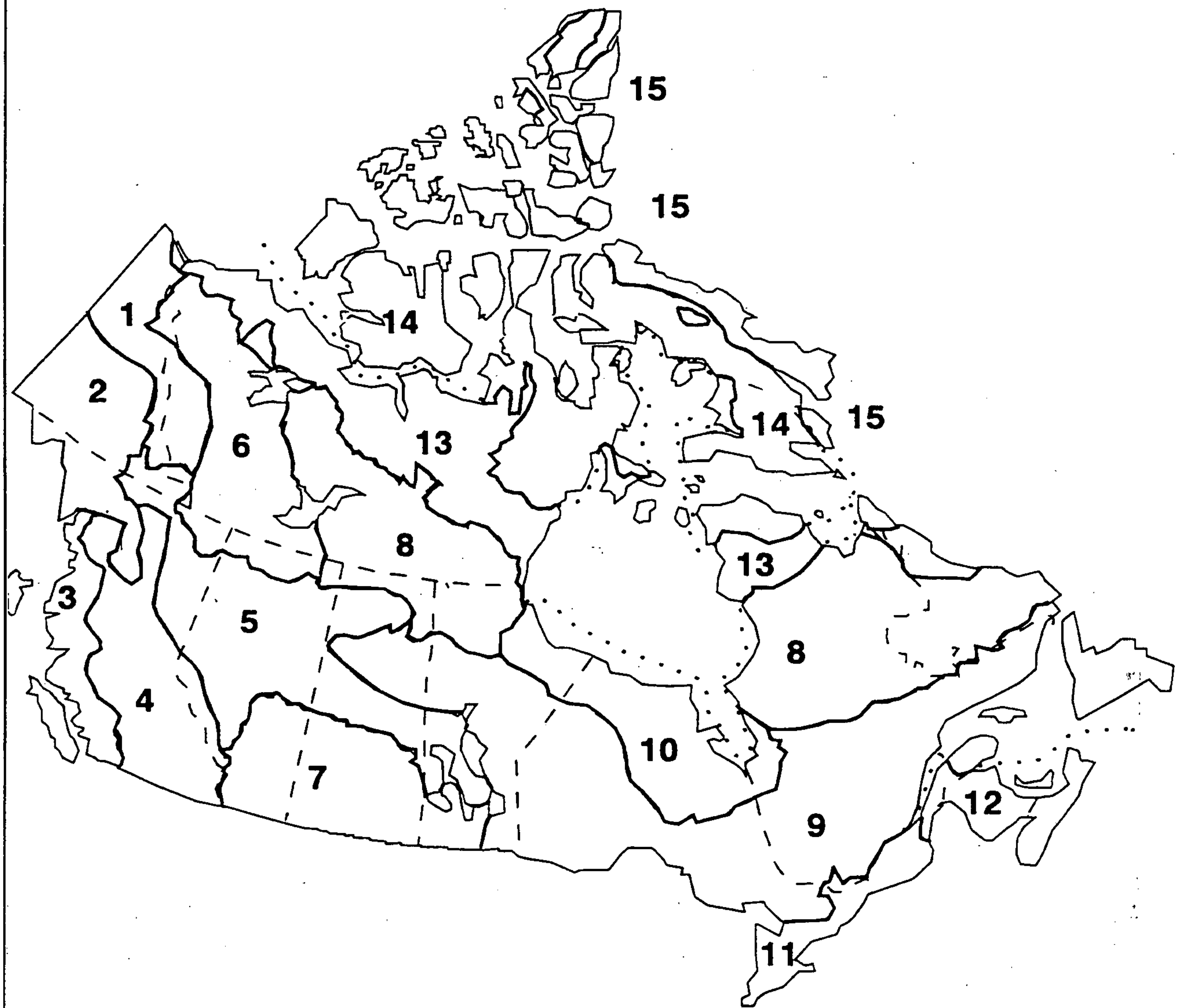
The preceding discussion highlights some of problems with the use of ecozones as the reporting unit. There is no scientifically defensible, *a priori* reason why all indicators in a national program must be reported at the same spatial unit. Rather, monitoring and reporting units should be chosen as being most appropriate to the particular stressors and indicators of interest. Expert working groups, focused on particular issues and concerns, could determine the most appropriate scale for monitoring and reporting for selected indicators.

It is desirable that the monitoring framework allows a degree of flexibility in the types of units used for reporting purposes. For example, the system should have a capability for environmental reporting in smaller-scale units for provincial purposes, as well as in larger-scale units for federal purposes. This sort of flexibility can be readily achieved using a framework based on the Canadian system of ecological land classification, because of its hierarchical nature (depending, of course, on the spatial scale at which the indicators are measured). Similarly, for the sectoral purposes of the Ecosystem Sciences and Evaluation Directorate of Environment Canada, a capability of reporting on the basis of small or large watersheds may be required, but the data should also be capable of integration to an ecozone scale for the development of indicators suitable for national state of the environment reporting.

CLASSES OF MONITORING SITES

In the proposed national ecological monitoring program, indicators would be measured in two classes of monitoring sites in each of the 15 terrestrial ecozones of Canada:

Intensive sites would be used for relatively detailed ecological monitoring of structural and functional ecology. A relatively small number (1-3) of intensive sites would be located in each ecozone in: (a) ecological reserves or other protected areas for monitoring the effects of regional or global stressors; (b) experimental sites at which stressors are manipulated and the responses are studied; and (c) operational situations consisting of a series of sites that represent a gradient with respect to a particular anthropogenic stressor.



Legend

1. Tundra Cordillera
2. Boreal Cordillera
3. Pacific Maritime
4. Montane Cordillera
5. Boreal Plains
6. Taiga Plains
7. Prairie
8. Taiga Shield
9. Boreal Shield
10. Hudson Plains
11. Mixed Wood Plains
12. Atlantic Maritime
13. Southern Arctic
14. Northern Arctic
15. Arctic Cordillera

Figure 3
The 15 terrestrial ecozones of Canada (from Wiken 1986).

Extensive sites would be more numerous and located throughout each ecozone to gain an overview of changes in the ecological character of landscapes and to detect regional trends in selected indicators. Extensive monitoring data would build upon and be largely obtained from existing and emerging programs of cooperating sectoral agencies.

The purposes and characteristics of the two classes of sites are discussed in more detail in the following sections.

Intensive monitoring sites

At intensive monitoring sites, ecological monitoring and intensive interdisciplinary studies would be conducted. The main purposes of intensive monitoring sites would be the following:

1. *Increase our understanding of the dynamics of ecosystem structure and function.* Research at intensive monitoring sites would allow the understanding of relationships and the development of predictive models of ecosystem dynamics. Models are important because they enhance the possibilities of: (a) distinguishing between natural and anthropogenic causes of change; and (b) more accurately predicting the trajectory of future changes.

2. *Develop indicators.* An important function of research activities at intensive monitoring sites would be to refine currently used indicators and to develop new or better indicators if necessary. Indicators suitable for monitoring extensively, as well as at intensive sites, would be developed and studied.

3. *Study the Effects of Stressors by Experiment and Gradient Analysis.* By studying sites that have been experimentally or operationally perturbed, the long-term effects of particular anthropogenic stressors (e.g., agriculture, forestry, acidification) can be understood, in comparison with the reference condition (see below). Experimental perturbations can be continuous or episodic. Continuous perturbation is useful for the study of long-term ecological adjustments to intensified stress. Episodic perturbations are useful for study of ecosystem changes during both the initiation and the alleviation of stress.

4. *Reference Monitoring.* The effects of regional or global concerns, such as climatic change and acidic deposition, would be monitored to provide baseline reference information about change in relatively mature and unstressed ecosystems. This information could be compared with information from intensive studies of anthropogenic stressors (see below) and with extensive monitoring information (see below).

Types of Intensive Monitoring Sites

To serve the purposes of national ecological monitoring, we recommend the following three types of intensive monitoring sites or groups of sites:

1. *Reference sites.* To properly serve the needs of regional reference monitoring, reference sites should allow the detection of changes in situations that are relatively unstressed by direct human activities. The only important stressors should be regional or global in scope—for example, climatic change, ground-level ozone, stratospheric ozone and ultraviolet-B, and the deposition of acidifying substances from the atmosphere. Candidate sites would include protected areas such as national parks. Preference should be given to monitoring relatively mature ecosystems, so that successional dynamics do not overwhelm the reference signal of environmental change caused by regional or global stressors.

2. *Experimental sites.* Long-term experimental work at intensive sites is suggested for controlled, integrated examination of the effects of particular stressors, such as forestry, agriculture, acidification, and urbanization. In general, intensive sites designed for experimental manipulation should be chosen to minimize natural environmental gradients related to the issue or stressor involved, because these could interfere with the interpretation of experiments.

Controlled experimental perturbations, followed by long-term ecological monitoring of the dynamics of ecosystem structure and function, have been crucial to understanding the effects of particular stressors. Examples include long-term monitoring of changes caused by experimental eutrophication or acidification of whole lakes in northwestern Ontario (Schindler 1990) and the effects of forestry practices implemented over an entire watershed (Hartman and Scrivener 1990). Critical to the success of this type of research is the incorporation of a reference comparison into the experimental design. Wherever possible, these experimental sites should be located peripherally to intensive monitoring reference sites.

3. *Stress gradients.* Intensive study of anthropogenic stressors can also be accomplished by monitoring situations along a stress gradient created by some human activity (again, compared with a reference situation) or some natural gradient. For example, changes in ecosystem structure and function could be examined at sites at various distances from a large point source emitting toxic gases and particulates, such as the Coppercliff smelter at Sudbury

(Freedman 1989). Another example could involve monitoring the effects of forestry on a selection of sites that comprise a gradient with respect to the intensity of forest harvesting (e.g., clear-cut, strip-cut, selection-cut, and unharvested) and silviculture (e.g., site preparation, natural regeneration versus planted, use of herbicides). An example of a potentially useful natural stress gradient is the latitudinal tree line, which would be a sensible ecotone to monitor an important ecological change associated with climatic change. Monitoring activities at a stress gradient would be question oriented, focusing on indicators relevant to the particular stressors represented by the gradient.

Network of Intensive Sites.

A national network of intensive sites is envisioned eventually, with one to three sites in each of the 15 terrestrial ecozones. The number of reference intensive sites in a given ecozone would depend upon the areal extent of the ecozone, its biogeoclimatic heterogeneity, and the nature and intensity of its anthropogenic influences. The Boreal Shield ecozone extends from northern Saskatchewan through northern Ontario and Quebec and eastward to Newfoundland (see Fig. 3). Because this large ecozone is affected by a different suite of stressors throughout its range, a relatively large number of reference monitoring sites would be appropriate. Having as large a number of intensive monitoring sites as possible is also important because it confers redundancy. This provides a measure of protection against catastrophic loss of the reference monitoring function (e.g., through wildfire).

Experimental intensive sites should also be established in all ecozones if possible. Reference monitoring and experimental research of particular stressors could potentially be undertaken at the same site. For example, reference monitoring could be undertaken in an ecological reserve, such as a national park, while experimental work is carried out in its adjacent peripheral area. For monitoring of operational gradients, a reference site could comprise the "undisturbed" end of the gradient. Operational gradients are most appropriate to ecozones with landscapes that have been substantially altered by anthropogenic activities (e.g., forestry or agriculture), especially in southern Canada.

Considerations for the selection and development of reference sites.

Ideally, the choice of an intensive monitoring site, including its size, shape, and other characteristics, would depend upon the desired degree of regional extrapolation. It may not be necessary to extrapolate everything to a regional scale, however. Some existing ecological monitoring and research sites may require enlargement, and new sites may need to be developed to meet the goals of regional extrapolation, which must be clearly formulated before sites are chosen.

Considerations for the selection of intensive sites that would be suitable for reference monitoring include the following:

1. The area should be representative of the region or ecozone in terms of climate, topography, soil, flora, fauna, and the types and relative proportions of habitats. However, it must be borne in mind that no particular intensive monitoring site can be truly representative of an ecozone, in the statistical sense. It will be most realistic to consider the intensive monitoring site itself as being an indicator of the ecological structure and function of the larger ecozone.

2. The site should be relatively undisturbed by human activities that would constitute important localized stressors and should be sufficiently large to retain its integrity in the face of activities occurring in its peripheral area.

3. The site should be assured of long-term protection.

4. There must be agreements to provide the funding necessary to maintain the research and monitoring program into the future.

5. Proximity to localized stressors, direction of the prevailing wind, and direction of stream and river flow should be considered to determine the extent to which the site may be affected by local stressors situated outside its boundaries.

6. The area and shape of the site and its spatial configuration (i.e, a single large or several smaller areas) should be appropriate to the local topography, vegetation communities, watersheds, animal movement patterns, etc.

7. The cost of developing and maintaining the site and accessibility for conducting research and monitoring activities may be overriding factors and may result in a strong bias towards the selection of already established monitoring sites. Wherever possible, intensive (and extensive) sites would be located near existing locations within monitoring networks of air or water quality (e.g., CAPMoN, LRTAP) to facilitate the determination of cause-and-effect relationships among indicators.

8. Current and historical human uses of the area should be considered, as should the status of aboriginal land claims.

9. Selection of the site should be subject to the consultation and approval of people living nearby.

10. The site (particularly in remote areas of northern Canada) should be located near a community that can provide local knowledge, information, advice, and labour.

11. The site should have a capability for year-round use for monitoring and research and should have a site manager or managing office to ensure protection of the site and to coordinate activities and logistics.

12. The site should be chosen to maximize the potential for partnerships among government agencies, universities, and other research groups.

Comparison with LTER in the United States.

The purpose and design of the proposed network of intensive monitoring and research sites for Canada are different in some important respects from the already established network of long-term ecological research (LTER) sites in the United States (Franklin et al. 1990; Van Cleve and Martin 1991). The LTER program is funded by the National Science Foundation, with an aim towards the support of long-term studies in ecology. Such research is essential to an understanding of gradual and transient ecological changes and responses and the population biology of long-lived species, and for the formulation and testing of ecological theory (Franklin 1989; Likens 1989; Risser 1991). The LTER program does not, however, have a strategic focus on monitoring and research directed towards an understanding of changes in the environment, although particular projects in the LTER network may have such a focus. In addition, the research and monitoring effort in the LTER network is not integrated with the more extensive Environmental Monitoring and Assessment Program (EMAP) of the U.S. Environmental Protection Agency (Hunsaker and Carpenter 1990). Moreover, while the LTER program is designed to support long-term, integrated ecological research, the focus is on academic scientists, although these may work in close cooperation with government and other researchers. In essence, each site in the LTER network is examining unique hypotheses and therefore has its own design of ecological research and monitoring, although there is also an effort to foster networking relationships within the LTER program, and comparative studies and analyses have some priority.

In contrast, the proposed Canadian network of intensive monitoring sites would have a strategic focus on monitoring and research that is relevant to the description and understanding of changes in the environment. In addition, the network of intensive monitoring sites would be closely integrated with an extensive monitoring network. As described above, the functions of the proposed intensive monitoring program would be to provide a reference monitoring baseline, to study the long-term effects of important stressors by experiment and by gradient analysis, to develop indicators for monitoring programs, and to increase our fundamental understanding of the dynamics of ecosystem structure and function. All of these are important for distinguishing natural and anthropogenic changes, for the prediction of future changes, and for a deeper appreciation of the consequences of monitored changes.

Stressor identification

Stressors should be identified on a site- or region-specific basis, in accordance with the magnitude of their anticipated effect on the intensive site. This presents a problem, in that intensive sites will not be statistically representative of an entire ecozone, so that the extent to which results could be interpreted or linked to extensive sites would have to be judged on a case-by-case basis.

Indicator selection.

A major objective of intensive monitoring is to determine the dynamics of ecosystem structure and function. Attributes appropriate to the ecosystem (i.e., watershed, biogeoclimatic zone, or ecoregion) must be selected for monitoring, but in most instances it is initially uncertain what those attributes should be. In cases where there is insufficient knowledge of ecosystem-level processes, there would initially have to be a comprehensive biophysical program, with monitoring being either periodic (e.g., species composition) or continuous (e.g., temperature). As knowledge of the system accumulates, a reduced set of the most appropriate indicators can be selected for long-term monitoring. In the initial stages of an intensive monitoring program, a team of research specialists would assess whether there was sufficient knowledge to select a reduced set of indicators.

Deficiencies in indicator data.

In general, workshop participants felt that although many potential indicators of abiotic conditions were available, these were not always being thoroughly measured. In particular, there is little information on, or understanding of, the threshold values of abiotic indicators that represent important threats to ecosystems. Furthermore, biotic indicators and data are very deficient. This is especially true of biological resources that are not conventionally considered to have economic value. At the present time, our insufficient knowledge of the links among biological and physico-chemical attributes of most ecosystems prevents an informed choice of appropriate indicators.

Clearly, research is needed on the interpretation of biological indicators and whether changes in intensively monitored biological indicators are reflected in changes in more easily extensively monitored chemical indicators. Of course, this sort of research would have to be done within the context of prominent stressors within ecozones—for example acidification, deforestation, global climate change, ground-level ozone.

As noted above, important deficiencies in state of the environment monitoring are related to incomplete baseline inventories of fauna, flora, and the "invisible" biodiversity of microbes and other very small wildlife, and to an incomplete understanding of the functioning of ecosystems. A synoptic list of some missing, underrepresented, or potential response indicators discussed by workshop participants is presented below. These indicators are variously relevant to extensive and/or intensive monitoring:

1. *Habitat diversity.* Ecosystem changes affect wildlife diversity by affecting the diversity and quality of habitats. Ultimately, management for diversity of habitats of differing successional ages may be easier than trying to attain population goals for all species. For example, intensive forest management affects habitats greatly, and this could be extensively monitored through succession across forest types. Beyond forestry, the loss of specific habitats over time could be measured using data from the Canada Land Inventory.

2. *Ecological reserves.* Ecological reserves are important for the conservation of: (a) rare and endangered species and their habitat; (b) endangered or unusual ecosystems; and (c) representative types of ecosystems for use as reference sites. Changes in the number, area, conservational "integrity," and "completeness" of the system of designated ecological reserves within ecozones could be monitored.

3. *Rare and endangered species and their habitats.* The status of rare and endangered species is an indicator of threats to regional and national biodiversity. The Committee on the Status of Endangered Wildlife in Canada (COSEWIC), a unit of the Canadian Wildlife Service, working in conjunction with the Canadian Nature Federation and the World Wildlife Fund, periodically considers the status of endangered species to ensure the protection of such species and their habitats. As of mid-1992, there were 232 species with a designated status under this program (COSEWIC 1991, and 1992 update). These agencies have initiated a program for the Recovery of Nationally Endangered Wildlife (RENEW), but only a fraction of species with a designated status under COSEWIC have recovery plans in place. Endangered reptiles, amphibians, plants, and invertebrates are underrepresented, in part because they have less "charisma" than mammals and birds. Recovery programs and the development of indicators that are appropriate in the broader ecological context can be facilitated by monitoring the status of a comprehensive set of endangered species.

4. *Opportunistic species.* Changes in the status of organisms that are considered to be "pests" (from the human perspective) are an indicator of deterioration of ecological quality. As humans alter the environment, favourable conditions will be created for particular opportunistic species, such as house mouse, starling, carp, dandelion, and *Escherichia coli.*

5. *Species sensitive to change.* Changes in the abundance, vigour, and distribution of widespread species that are known to be sensitive to particular stressors and exposures can be monitored as a bioindication of ecological quality. Examples include: (a) lichens, which can be effective biomonitors of sulphur dioxide, ozone, heavy metals, and other toxic chemicals; and (b) plant species that are close to the limits of their geographic distribution and that might be expected to respond relatively strongly to climatic change.

6. *Structural and functional indicators of response at the community level.* Changes in nutrient loss from watersheds or in rates of nutrient cycling, biological productivity, and species composition and abundance at the community level can be indicators of long-term effects of regional stressors. For example, controversies that have recently been discussed in both the popular media and scientific literature concern the possibilities of serious declines in populations of neotropical migratory birds, of amphibians, and of certain types of forest. Intensive and extensive, community-level monitoring of these and other biota are essential if we are to have a scientifically credible database that is appropriate to defining the intensity and extent of these sorts of ecological problems.

Extensive monitoring sites

The spatial design of an extensive monitoring network should be dependent on the particular effects being considered. Sites and types of ecosystems within an ecozone will vary in their sensitivity to particular stressors. This feature can be mapped to portray risks to particular ecosystems or indicators. The various sampling stations could be located in a range of sites of low to high sensitivity. The fact that response can often be caused by multiple stressors must also be taken into account. Maps of stressor sensitivities could, in turn, be overlain to combine stressors (using GIS). The result could be a portrayal of zones of intensity of exposure and response to a range of stressors.

Extensive sites would be relatively numerous and located throughout each ecozone. The purpose of extensive monitoring is to document regional and national trends in environmental quality. Relatively localized stressors, such as agriculture, forestry, or industrialization, are particularly relevant to extensive monitoring. Extensive sites would be designed to monitor: (1) the effects of human activities that occur at widely spaced locations over the landscape, such as urbanization, agriculture, forestry, and mining; and (2) changes in the ecological character of the region, as a result of changes in patterns of land use.

Scale of sampling.

Indicators should be monitored in permanent sampling sites throughout each ecozone and in various ecosystems (e.g., forests, agroecosystems, wetlands). Different issues and concerns will often require sampling at different spatial scales. The number and distribution of extensive sample sites are also dependent on the question of interest. For example, endangered Piping Plovers as an indicator of rare and endangered species need only be monitored on sandy beaches and other appropriate habitat, whereas monitoring the effects of global warming on vegetation requires a much more extensive sampling design.

Important information may be missed if sampling occurs at too large a scale (e.g., ecodistrict or ecoregion). At the minimum, each ecozone should contain a network of extensive monitoring sites at which a suite of indicators is monitored in an integrated manner.

An appropriate sampling unit could be established by combining the spatial scale of ecodistrict and watershed, based on their sensitivity to stressors. If too many sample sites are proposed at the scale of ecodistrict and watershed for the practical interests of national monitoring, the number can be reduced by grouping similar sites with respect to elevation, age, soil series, slope, proximity to urban areas or pollutant sources, sensitivity to stressors, etc. Once in a GIS database, information can always be aggregated at higher levels, such as the ecozone, for the purposes of a national state of the environment report.

Sites for extensive monitoring of ecological indicators should be preferentially chosen to be close to stations for monitoring air and water quality (e.g., LRTAP, ARNEWS). Spatial aggregation of indicator measurements is advantageous, because an integrated monitoring design allows for the mathematical determination of relationships among indicators.

It should also be recognized that remote sensing techniques will have great utility in extensive monitoring of certain indicators. This could be accomplished by, for example, the periodic assessment of indicators of vegetation, large animal abundance, or other variables at particular places or areas, using a standardized, temporal series of aerial photographs or satellite imagery. Remote sensing is a rapidly developing field, with a significant capability for the automation of data collection and interpretation, and it will certainly be an important tool for monitoring certain types of extensive indicators.

Sources of information.

Much extensive monitoring information can be obtained from national and provincial agencies. These routinely collect sectoral data on economically important indicators to calculate allowable forest harvests, hunting and fishing limits, production of agricultural commodities, etc. Such data are already an important source of information for state of the environment reporting. Existing biological indicators focus on the productivity and abundance of species of economic value, whereas nonbiological measurements include chemical quality of soil and water, hydrology, and site capability for forestry and agriculture.

The existing databases are being evaluated with respect to the needs of national environmental monitoring and reporting (Environment Canada 1991, Government of Canada 1991). The deficiencies include the following:

1. There are few long-term databases in sectoral monitoring. To identify trends without an existing long-term database, extensive monitoring data could be compared with a known historical condition or with a long-running intensive monitoring database (if such is available).
2. Currently available sectoral monitoring data are often deficient in terms of: (a) biological response indicators; and (b) spatial and temporal sampling design.

Biological indicators.

Biological response indicators are generally deficient in most sectoral monitoring programs, yet these are the most relevant indicators of ecological integrity. Most indicators currently being measured in sectoral programs are indicators of stressors (e.g., emissions of sulphur dioxide) or exposure (e.g., concentration of sulphur dioxide in air). Where response indicators are measured, they are almost always of direct economic importance (e.g., sulphur dioxide-related damage to forest or agricultural crops). An example of a noneconomic biological indicator that would be suitable for extensive monitoring for this stressor is the toxicity caused to epiphytic lichens.

Spatial and temporal design.

The spatial designs of current sectoral monitoring programs may not provide indicator data that are truly representative of a given region or ecozone. Ideally, locations for sampling indicators should be chosen from a probability sample to statistically represent the region. At great expense, the U.S. Environmental Protection Agency has dealt with this problem with its EMAP design, by imposing a statistical sampling grid over the entire country in order to choose appropriate sampling sites for extensive environmental monitoring (Hunsaker and Carpenter 1990). In existing sectoral monitoring programs in Canada, sampling locations have often been chosen to investigate local problems, to study terrain or particular ecosystems that are sensitive to particular stressors, or to take advantage of local administrative resources. This has been an important consideration in the Canadian context, because most of the population, and most of the economic development, and the greatest intensity of anthropogenic stressors occur in the south of the country. As a result, logistical support is lacking over great expanses of terrain. These features, coupled with the smaller amounts of funding available for environmental monitoring in Canada compared with the United States may make an EMAP-style, grid-sampling design impractical in Canada.

If sampling locations are not statistically representative of a particular region, then subtle trends in environmental quality should not be generalized beyond the sampling locations (although large changes in environmental quality may still be detectable with confidence). Consequently, extrapolation to an entire region should be avoided, or the problem should be explicitly recognized as a constraint to state of the environment reporting and interpretation. As a first step, the degree to which the various databases that are now available actually represent a given region should be objectively evaluated.

Lastly, different spatial and temporal scales are often used to sample different indicators. Where possible, measurement of different indicators should be coordinated both spatially and temporally. Such integration of monitoring activities would facilitate the examination of coincidental patterns of change among indicators.

INTEGRATION OF ECOLOGICAL MONITORING

Integrated monitoring can refer to: (1) the integration of activities that monitor different indicators at a particular site; and (2) the integration of monitoring activities among different sites. Both of these concepts are fundamental to a national ecological monitoring program, in that monitoring activities should be integrated within and among sites, to the extent possible. Furthermore, research must be integrated into the monitoring framework, for the many reasons discussed previously. Achievement of this integration will require a great deal of cooperation among government and nongovernment agencies involved in monitoring and research.

Integration within and among intensive sites.

It is particularly important at intensive sites that the monitoring of different indicators be coordinated spatially and temporally, so that links between stressors and indicators can be discovered. This is especially relevant to the intensive monitoring of indicators of ecosystem structure and function, for reference monitoring, and for long-term experimental research on the effects of particular stressors.

As described previously, we propose a network of intensive monitoring sites that would include one to three sites per ecozone. A national network of ecological monitoring sites does not yet exist but may be developed through an emerging initiative under the Green Plan (Anderson *et al.* 1993). Recent Canadian precedents for ecological monitoring sites include the network of five calibrated watershed sites for acidic deposition research in eastern Canada and the Experimental Lakes Area of northwestern Ontario (Schindler 1990). Once a network of intensive monitoring sites is developed, it will be critical that indicator protocols and design be sensibly integrated among sites.

Integration within and among extensive sites.

As much as possible, monitoring activities should be integrated within extensive sites. The lack of integration of monitoring and interpretation of atmospheric, terrestrial, and aquatic components of ecosystems is a deficiency of most existing programs, which tend to focus on specific components. Different sectoral agencies could coordinate their monitoring activities so that more indicators could be measured at the same sites. Integration at this level would facilitate the determination of relationships among the various indicators measured and identification of the likely causes of environmental changes.

Certain indicators might be integrated into a national extensive monitoring network. For example, in the Northwest Territories, an initiative is developing to integrate extensive monitoring of surface water hydrology and chemistry (Inland Waters Directorate) and climate monitoring (Atmospheric Environment Service), and possibly other extensive monitoring efforts, to achieve a cost-effective sharing of remote facilities and other logistic expenses. The development of integrated programs of extensive ecological monitoring activities will require the encouragement of partnerships and networks and perhaps the provision of seed funding.

Integration of intensive and extensive sites.

Intensive and extensive ecological monitoring programs must also be integrated. The linkages envisioned between activities conducted at intensive and extensive sites are described below.

1. *Understanding relationships among ecosystem components.* The most important value of long-term intensive monitoring is to contribute towards an understanding of cause-and-effect linkages, by conducting research that explores the relationships between stressors and ecological responses. In order to understand the ecological relationships among indicators (i.e., what indicators really show), there should be a close coupling between: (a) the collection, analysis, and interpretation of monitoring data; and (b) research into relationships among indicators. Ultimately, research at intensive sites will establish the framework of indicator design and interpretation used at extensive sites. Without intensive monitoring sites and integrated research, the overall monitoring exercise will be of limited value. An important purpose of intensive monitoring sites is to elucidate ecosystem structure and function, so that relationships among stressor, exposure, and response indicators can be examined and, ultimately, understood.

   Information from intensive monitoring sites could be used to hypothesize relationships at extensive monitoring sites, where many fewer variables are measured. For example, it is much easier to extensively measure a decrease in surface water pH or alkalinity caused by the deposition of acidifying substances from the atmosphere (e.g., acid rain) than it is to monitor changes in fish or invertebrate communities or in other biological variables. However, all relevant variables could be measured at intensive sites, and their relationships with pH and alkalinity could be used to predict effects on fish, for example, at comparable extensive sites where only pH and alkalinity are measured. Rigorous, detailed monitoring at intensive sites, coupled with experimental research, will allow the development of models that can be applied at extensive sites.

2. *Modelling.* One of the links among activities proposed for intensive and extensive monitoring sites is the development of explanatory and predictive models. Modelling is an important aspect of monitoring programs, because it allows the prediction of change. Data from ecological monitoring programs facilitate the development of predictive models by providing initial parameter values and by identifying key variables.

3. *Testing of concepts and causal hypotheses.* Hypotheses about the causes of ecological change may be generated from ecological monitoring data obtained in intensive or extensive monitoring programs. These hypotheses can then be tested at intensive sites through experimental manipulation.

4. *Indicator development.* At intensive sites, some of the research activity would be directed towards the development of response indicators of ecological integrity that might be suitable for monitoring at intensive and extensive sites. Indicator development would determine: (a) responses of indicators to selected stressors, including the detection of specific thresholds of change (see Fig. 1); (b) the specificity of the indicator to particular stressor; (c) the ease with which indicators can be measured accurately; (d) protocols for standardization of techniques; (e) compatibility of different techniques; (f) appropriate spatial and temporal configurations for sampling; and (g) procedures for implementation of monitoring the indicator.

5. *Standardization of techniques.* A foundation of ecological monitoring networks is the standardization of techniques. Research into standardization would be best conducted at intensive sites, and the results could then be applied to the network of extensive monitoring programs. Currently, different monitoring programs often use different techniques to measure similar indicators. Relevant considerations include: (a) sampling scales, both temporal and spatial, that are required to allow for statistically significant detections of change; (b) analytical procedures for measuring chemical indicators; and (c) identification and measurement protocols for biological indicators. Considerable effort will be required to ensure that techniques and spatial frameworks are compatible among the activities of agencies of the provinces, territories, and federal government, as well as the needs of national state of the environment reporting.

6. *Value added of extensive sites.* Intensive monitoring at a few sites and extensive monitoring at many sites are both essential to an integrated monitoring program. A major deficiency in the network of intensive sites will relate to problems of regional interpretation. It is hoped that intensive monitoring sites as a group will represent all important ecosystems, because all 15 terrestrial ecozones would eventually be represented by such sites. Nonetheless, it would not be appropriate to extrapolate from these sites to an entire region. Regional trends in

environmental quality and effects of various human activities will be obtained through extensive monitoring.

The values of extensive monitoring to an intensive monitoring network include the following: (a) provision of indications of wider-ranging trends, assuming that the spatial design of extensive sites ensures a spatially representative sampling network; (b) identification of ecological problems that will require detailed research; and (c) assessment of the results of environmental management (e.g., are mitigations such as pollution emissions control actually having the desired effect?).

FUNCTIONAL DESIGN

In this section, we describe the functional design of the proposed program, including the interrelationships of the different "activities" involved. We also consider the "contributors"—that is, which agency or other type of group would be conducting each activity. The design of this model was achieved by progressively adapting a basic framework established by us, on the basis of feedback and discussions of workshop participants.

One of the important features of this proposed functional design is its adaptability. This is achieved through the cyclic nature of the design and the inclusion of feedback loops. The functional design is summarized in Figure 4. Below are described the major contributors and the activities that together would constitute a national ecological monitoring and reporting program for Canada.

MAJOR CONTRIBUTORS

1. *Sectoral agencies.* To ensure the continuity of data collection, the monitoring function should be institutionalized within government. The various sectoral agencies of government will play the lead role in ecological monitoring. This function has historically been part of the mandate of sectoral agencies, and they are well equipped to conduct monitoring activities, from data collection and handling to analysis, mapping, and synthesis of results. The long-term appointment of many qualified personnel in sectoral government agencies facilitates the continuity of monitoring activities, subject to the constraints of available budgets. In some cases, it may be appropriate and cost-effective to contract monitoring activities to the private sector.

2. *State of the Environment Reporting (SOER).* The activities involved in state of the environment reporting are diverse and complex and require expertise at many levels. As primarily an administrative unit, SOER is well equipped for the acquisition, storage, retrieval, processing, and transfer of information relevant to environmental quality, including its presentation to the public. However, SOER is unlikely to ever house sufficient expertise in monitoring and research to conduct all of the tasks required for reporting. Most importantly, SOER will rely on partnerships with sectoral agencies and other cooperators to provide information relevant to state of the environment reporting. It is also unlikely that SOER will have sufficient in-house capability for the interpretation of the causes and consequences of monitored changes in environmental quality. We recommend that a prime function of SOER should be to coordinate expert working groups (described below) to assist in certain of the proposed activities.

3. *Expert working groups.* Expert working groups should include persons involved in ecological monitoring or research, including specialists at government and nongovernment institutions (e.g., universities), and a representative of SOER. These groups should include persons who are: (a) knowledgeable about ecological relationships; (b) well-qualified to interpret data; (c) familiar with techniques used in sampling; (d) expert in data analysis; and (e) experienced in the design of monitoring and research programs. A somewhat appropriate model for the expert working groups might be the subcommittees on particular environmental issues, formerly convened by the Associate Committee on Scientific Criteria for Environmental Quality of the National Research Council of Canada (NRC 1983). The organization of expert working groups would most appropriately revolve around particular stressors, ecosystem types (e.g., forests, agriculture, wetlands, prairie,), or classes of biota (e.g., avifauna, invertebrates, vegetation,).

4. *Research scientists.* An important role would be played by research scientists, including those working at government laboratories or research stations and at universities (see below). Government scientists could be involved in both monitoring and research. University researchers generally do not have a strategic interest in being involved in long-term monitoring activities. This is due to the relatively

short durations of funding for specific projects and the short tenure of graduate student involvement, and the need of most professors to publish relatively frequently in refereed outlets.

The most appropriate involvement of university researchers in monitoring programs will usually be through short-term (perhaps 1-5 years) research activities focusing on the development of indicators, on understanding the causes and consequences of ecological changes, and on the structure and function of ecosystems. University researchers have been significantly involved with ecological research programs at some long-term experimental sites (e.g., Taiga Biological Station in Manitoba, Schefferville Research Station in Quebec, Bon Portage Island in Nova Scotia). The long-term continuity of the most important sites, however, has occurred because of government commitment (e.g., Experimental Lakes Area and Dorset Research Station in Ontario, Carnation Creek in British Columbia, Truelove Lowland on Devon Island in NWT [along with the Arctic Institute], and Kejimkujik in Nova Scotia).

ACTIVITIES

The activities in the proposed functional design of a national ecological monitoring program are described below (refer also to Fig. 4).

1. *Catalogue databases and map resources.* One of the crucial first steps is to catalogue the available databases of various provincial, federal, and nongovernment agencies. This activity should be conducted by SOER. All regional-scale or integrated study databases should be inventoried, even if SOER may not utilize data from these at the present time. The catalogue of databases would be available as a resource for use by sectoral agencies, researchers, and other interested persons. SOER could maintain this information as a national service, in part to serve as payment-in-kind for data that SOER obtains from cooperating sectoral agencies.

   Another crucial first step should be to map ecological resources, an activity that could be done by SOER. Mapping is important to identify resources at risk, as the area of habitat and vulnerability of ecological indicators must be known to understand the importance of effects of the stressors. For example, to assess the potential effects of the atmospheric deposition of acidifying substances (a stressor) on lake ecosystems in Ontario, information is required on the spatial distribution and density of lakes by vulnerability category (e.g., on the basis of alkalinity or calcite saturation index) and of vulnerable, acidification-intolerant aquatic biota.

   Following the initial steps, two strategies can be adopted: (a) to identify the stressors and then monitor for specific effects; and (b) to monitor for emergent problems or "surprises." Both strategies are important, and they should be utilized in concert. For example, many of the stressors that are currently recognized as important in lake ecosystems were initially "surprises" (e.g., eutrophication and acidification). The best approach to monitoring for surprises is to take comprehensive measurements, and to include biological response indicators that are related to ecological integrity.

2. *Identify issues and concerns.* Expert working groups would be coordinated by SOER to assist in identifying the most important issues and concerns in each ecozone. This step is important, because monitoring should be goal oriented and designed around known problems. Such focus can be achieved by identifying stressors that are potentially important in causing ecological change, by monitoring indicators relevant to those stressors, and by evaluating the importance of the stressors through research. Because not all potential problems are currently recognized, monitoring programs must be adaptive and include provisions for detecting emergent problems.

3. *Recommend indicators for state of the environment reporting.* The same expert working groups would recommend indicators for use in state of the environment reporting. It is essential to establish criteria for the selection of ecological indicators (Hunsaker and Carpenter 1990; Kerr 1991; IJC 1991). The most important criteria for the selection of indicators are a need to be relatively: (a) biologically or ecologically important; (b) sensitive, and correlated to changes in other ecosystem components; (c) diagnostic of particular stressors; (d) representative of the region; (e) capable of being related to other classes of indicators; (f) responsive to mitigative measures; (g) capable of being measured in stable sampling units; (h) cost-effective and technically easy to sample, with little measurement error; (i) available from a pre-existing data series or data base; (j) capable of retrospective analysis; (k) capable of anticipating future change; (l) capable of providing new information and of anticipating surprises; (m) capable of being measured at protected locations that will be available for monitoring purposes over the long-term; (n) capable of being related to target threshold levels; (o) policy oriented; and (p) understandable by or interpretable for the general public. It is unlikely that any particular indicator could satisfy all of these selection criteria, but a suite of environmental indicators could be chosen with attention to satisfying all of these selection criteria.

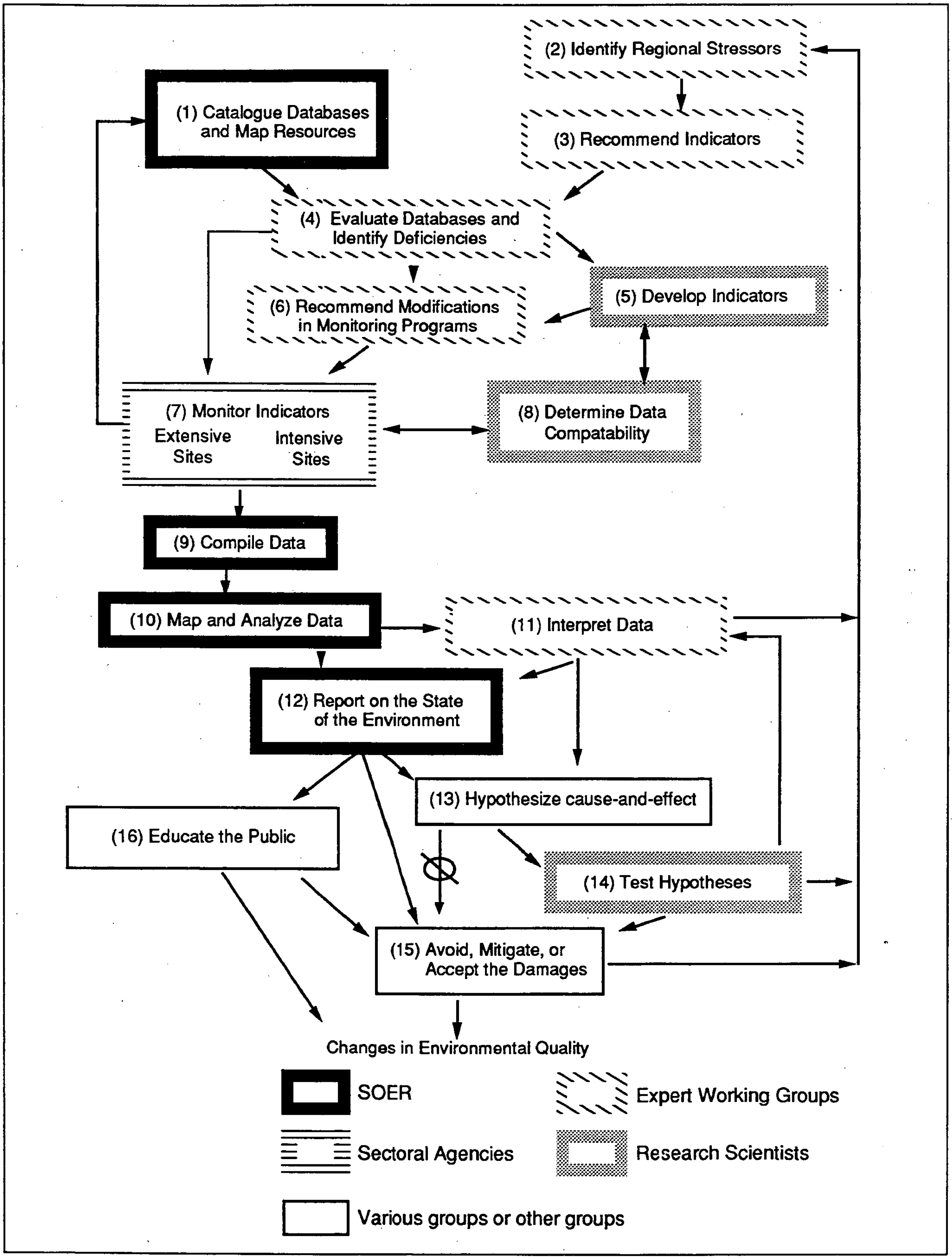


Figure 4
Functional design of the proposed national ecological monitoring program. Each box represents a different activity in the process. Major contributors are indicated by box patterns.

4. *Evaluate databases and identify deficiencies.* The suitability of existing databases for state of the environment reporting should be evaluated by a joint effort of SOER and the expert working groups. The first activity of these groups should be to develop criteria for assessment of the quality of data for state of the environment reporting. Existing databases would then be examined for their deficiencies with regard to national state of the environment reporting. In most cases, this evaluation process will result in the discovery of important deficiencies in the available databases and in fundamental knowledge of the importance of many stressors. The term "deficiency" can refer to: (a) the availability of appropriate databases; or (b) the availability of appropriate indicators. Addressing the former deficiency would require implementation or extension of a monitoring program, whereas addressing the latter would require research into protocol development so that appropriate indicators can be monitored.

5. *Develop indicators.* When indicators of a particular effect are judged to be deficient, research is needed to develop appropriate indicators. One consideration in indicator development is that some indicators integrate information over time, whereas others reflect shorter-term conditions. The development of indicators includes determination of the relationship between the indicator of interest and what it is supposed to reflect. Also involved is the development of protocols for measuring the indicator, including details of spatial and temporal sampling, and techniques for collection and analysis.

6. *Recommend modifications in monitoring programs.* Based on their evaluations of the databases, expert working groups would make recommendations to monitoring agencies to address the deficiencies that have been identified in the available monitoring data.

7. *Monitor indicators.* The activities of monitoring at both intensive and extensive sites should be carried out by appropriate sectoral agencies and should be institutionalized within government. Sectoral agencies would continue to catalogue, analyze, map, report, and interpret their data in accordance with their designated mandate, but those data must also be made available to SOER for the purposes of national state of the environment reporting.

8. *Determine data compatibility.* At the same time that monitoring is being conducted, research should be aimed at standardizing indicator protocols or determining the compatibility of different techniques. This issue is discussed in more detail in a later section.

9. *Compile data.* SOER would compile the relevant data from the various sectoral monitoring agencies. Prior to requesting data, SOER would determine which datasets would have a high likelihood of being used in their reporting products.

10. *Map and analyze data.* SOER would proceed to map and analyze the data for the purposes of national state of the environment reporting. The focus would be on presentation of trends in environmental quality and attempts to statistically or mechanistically link trends among different indicators.

11. *Interpret data.* Expert working groups would assist SOER in the interpretation of changes in the status of ecological indicators. (See also step 13, below.)

12. *SOER reports.* To document changes in environmental quality, SOER would prepare five-year reports, fact sheets, etc. In addition, SOER would engage in forecasting environmental quality (i.e., predict the future effects of environmental stressors) and provide suggestions for further research and monitoring. In these ways, SOER would adaptively influence the monitoring activities of various government agencies.

13. *Hypothesize causes and consequences.* Once changes in environmental quality are reported, various groups are likely to hypothesize the causes and consequences of those changes. The expert working groups, scientists, and the public, including the media, politicians, and special interest groups, will all play a role in this process. Hopefully, once hypotheses are identified, they will be subject to rigorous testing (step 14). There will be cases, however, in which mitigative actions are taken (step 15) before the hypotheses are fully tested.

14. *Test hypotheses.* Expert working groups could define hypotheses and suggest the most appropriate tests. Research groups working at intensive sites and elsewhere, including the laboratory, would conduct experiments to test hypotheses regarding the causes and consequences of ecological change.

15. *Avoid, mitigate, or accept the damages.* The government can utilize SOER reports in its decision-making processes to avoid, mitigate, or accept the damages done to the environment. What government decision-makers do with the data will depend in part upon how the data are presented and interpreted. Socioeconomic and political constraints will also, of course, be important considerations.

SOER reports may also be useful in setting target levels for management purposes. Most response indicators (e.g., biodiversity, fertility of forest or agricultural soils) however, have not yet been studied thoroughly enough to enable management objectives to be set. Nevertheless, where changes are monitored and perceived to be significantly detrimental, remedial measures can be recommended without reference to specific threshold values. In these ways, SOER products can influence changes in environmental quality.

16. *Educate the public.* The products of SOER can help to raise the currently inadequate level of environmental literacy in Canada. A more environmentally educated public may then formulate opinions and make choices that will improve the quality of the environment. Ideally, this important goal could be achieved by the institutionalized incorporation of information on changes in regional, Canadian, and global environmental quality into the educational curriculum, at all levels.

PERSPECTIVES ON THE PROPOSED PROGRAM

In this part of our report, we discuss certain national and regional perspectives that emerged from the regional workshops on the design and implementation of a national ecological monitoring program, held in the Atlantic, Pacific, Northern, Prairie, Ontario, and Quebec regional administrative units of Environment Canada. Other commentary on the conceptual and functional design of the program has been incorporated into the preceding sections of this document. The detailed results of the various workshops and consultations are summarized in Staicer *et al.* 1992.

FINANCIAL CONSIDERATIONS

Not surprisingly, the first questions asked at the workshops dealt with the funding of ecological monitoring programs. The ensuing discussions focused on how the goals of the proposed national-scale program to detect changes in environmental quality could be achieved with limited funds. Concerns and suggestions of workshop participants are summarized below.

1. *Funding.* Among regions, there was a vigorous expression of scepticism that the proposed program could become operational with little or no additional funding for infrastructure, person-years, and operations. Participants felt that, although integrated programs would depend mainly upon coordination of the monitoring activities and goals of different agencies, some initial "seed" funding would be necessary to achieve this coordination.

   Many participants expressed frustration with the establishment and expansion of SOER, which *will not* actually be conducting the monitoring, while agencies that *will* be expected to collect the monitoring data may not be expanded in terms of personnel or funding. Such frustrations were expressed by one participant who stated: "The main problem with state of the environment reporting is that it remains Ottawa-driven. Those in the regions who collect the data, and are in the best position to interpret it, do not share in any SOER funds and so are continually trying to do more with less, while the SOER bureaucracy continues to expand."

2. *Cost-effectiveness.* Monitoring activities can be made more cost-effective through the integration of various programs. At present, there is considerable overlap amongst some monitoring activities within and between agencies in government. In essence, monitoring by government could be run in the fashion of an efficient corporation. SOER could be instrumental in facilitating the integration of monitoring efforts. There are many well-qualified people in government (and in the private sector and universities) who are capable of conducting the necessary work, but operating funds are lacking. To quote a workshop participant: "There's a lot of high-priced talent, but no money to do the work."

   In some cases, consulting agencies are more cost-effective than government in conducting monitoring operations. Although monitoring programs and responsibilities should be institutionalized within government, the actual monitoring could be accomplished, in part, by private consultants. In many cases, contracts should be relatively long term (5-10 years) to facilitate the continuity of data collection and an economically efficient amortization of private sector investments in infrastructure. It is important, however, for government to monitor the consultants' activities, to ensure that operations are conducted according to appropriate protocols and standards.

3. *The Bottom Line.* It is senior administrators, not the persons conducting the monitoring or research, who make decisions about priorities and control budgets.

Strong support at the senior administrative level of various agencies will be crucial to the success of a national ecological monitoring program.

In the workshops, much concern was expressed over the potential effect of political influences on a national ecological monitoring and reporting program. Changes in the political climate can influence the continuity of ecological monitoring programs, the ways that ecological data are interpreted, and the ways that issues are addressed through mitigation or avoidance actions.

FOSTERING COOPERATION

Workshop participants expressed much concern about the potential difficulties of cooperation among federal and provincial agencies in a national ecological monitoring and reporting program. Uncertainties include funding arrangements, the sharing of data, the interpretation of data, interagency conflicts and barriers, and politically inspired conflicts between provincial and federal governments. Considerable discussion focused on suggestions for fostering effective partnerships. These ideas are summarized below.

1. *Organizational considerations for SOER.* Workshop participants were generally wary of an SOER that is nationally centralized, Ottawa-based, and a branch of Environment Canada. To be more effective, at least one SOER official should be based within each region. Only locally-based SOER officials can develop the personal contacts and networking relationships that would be essential in selling a national ecological monitoring program and ensure its success.

   Participants generally agreed that it would be desirable for SOER to be at arm's length from Environment Canada, partly because the monitoring network upon which SOER depends for its information extends well beyond Environment Canada. Also, if interpretation by SOER is to be independent of the political and administrative agendas of line departments, SOER should be independent from other government agencies. The foundation upon which SOER and its expert working groups make decisions and interpretations should be ecological, rather than political.

2. *Partnerships.* SOER will not have its own resources for monitoring. To obtain monitoring data, SOER must rely on partnerships, particularly with national, territorial, and provincial government agencies. Part of the mandate of SOER is to foster partnerships and to network on behalf of the national ecological monitoring and reporting program. Partnerships can be fostered by convening multidisciplinary workshops and by involvement in integrated programs. Potential partners in an integrated network must have sufficient flexibility to allow, where possible, an adaptive shifting of the timing and location of monitoring activities to coincide with the needs of other partners.

3. *Volunteers.* Some participants noted that certain kinds of monitoring data can be collected effectively and inexpensively by volunteers. The Breeding Bird Survey and Christmas Bird Count are examples of extensive monitoring programs for which most of the data are provided by amateur but highly skilled birders. Another example is an extensive program aimed at monitoring the effects of pesticides on bluebirds and Tree Swallows in the Prairie provinces. The public has a vested interest in environmental quality, and the potential contribution of volunteers to monitoring programs should not be overlooked. The longer-term continuity of monitoring programs that are reliant on volunteers could, however, be difficult to maintain.

4. *Native communities.* A particularly important consideration in northern Canada, where native communities are stewards for substantial parcels of land, is the need for an open, bidirectional consultation with local communities. This will be crucial to the successful development of monitoring programs. Native communities and groups should be involved from the beginning of program development. The communities will have to be convinced of the importance of monitoring and its relevance to their own activities and well-being. Native peoples are likely to have vested interests in particular environmental problems, especially those related to the health of game populations, as well as local public health issues. Institutions engaged in monitoring programs should communicate their results to local communities and interpret their significance in an understandable fashion.

   The traditional knowledge of local communities should also be recognized and incorporated into the monitoring program, where possible. In addition, some native organizations are developing their own environmental databases (e.g., hunting, fishing, and trapping activities) in conjunction with their emerging responsibilities under land claims settlements. Local communities may be wary, however, of their data being used against their perceived interests—for example, to lower game quotas.

5. *Conflicts between provincial and federal governments.* This can be important in all of the regions of Canada, but it is a particularly important consideration in Quebec, where cooperation between environmental and other agencies of the federal and provincial governments can be stymied by political

directives related to constitutional uncertainties and other considerations. This regrettable situation can greatly impede the coordinated design and implementation of a national ecological monitoring and reporting network. This is a very difficult problem, for which the solution is political rather than institutional.

DATA ACQUISITION BY SOER

Access to relevant information from various agencies will be crucial to the success of a national state of the environment reporting program. From the start, there must be an agreement that data will be freely available and accessible.

1. *Data accessibility.* Many participants described considerable problems in gaining access to monitoring and research data within and between agencies and other institutions. Government data are not necessarily in the public domain, either because they may be considered to be proprietary or because of considerations for national security. Other barriers to access to information in Canada include a lack of awareness of specific bodies of information (so that a specific request can be made for access to the data) and expenses involved with charges for information by some agencies.

   Some other problems in data acquisition include the following: (a) people (both inside and outside of government) tend to be possessive of their data; (b) government has a history of being secretive about its data (e.g., several Ontario participants described a reluctance of government to release data for precipitation and surface water pH in the mid-1970s); and (c) politicians and administrators have a perception that negative changes in environmental quality will be blamed on them, so they may not want the negative information to be widely publicized.

2. *Mutual benefit.* Concern was expressed over possible problems with the reciprocity of data exchange and analysis between SOER and source agencies. Participants felt that SOER would have to convince outside agencies and individuals that they would benefit from participation in SOER-driven state of the environment reporting. It might be desirable that individual contributors benefit directly—for instance, by making the contribution a significant consideration in terms of career evaluation.

   The activities of SOER can potentially benefit cooperating agencies by: (a) establishing a national database that would be widely accessible; (b) facilitating the development of intensive monitoring sites, which would greatly enhance the value of sectoral monitoring efforts; (c) providing a central administrative structure; (d) facilitating the integration of sectoral monitoring programs; and (e) facilitating the coordination of national efforts to establish standard monitoring protocols and assessment of data quality, possibly using the expert working groups described earlier.

3. *Types of information.* Two related approaches were identified by which SOER can obtain ecological monitoring data for reporting:

   a. Identify monitoring questions, and synthesize published information relevant to the question. A problem with this approach is that the published information will usually be deficient; there is always a much richer and more detailed body of unpublished data compared with what has been published.

   b. Catalogue and acquire unpublished data from various sources that are collecting the information, usually for a different purpose. Three classes of data can be considered: raw, processed (analyzed), and interpreted. SOER must consider which classes of data will be most appropriate to their needs, and also whether the information is freely accessible.

4. *Acquisition procedure.* Workshop participants advocated an organized and specific approach to data acquisition by SOER. Some of the workshop participants have had the negative experience of going to the trouble of providing data to SOER, after which the information did not appear in an SOER report. Wherever possible, SOER should have a clear vision of its data requirements before engaging in data acquisition. Data submitted to SOER should be reasonably expectated to have an effect on SOER products, and contributors of information should be clearly acknowledged in SOER reports.

   When requesting information, SOER should: (a) indicate the ultimate purpose for which the data will be used; (b) determine whether the data are relevant to the intended purpose; (c) determine the most appropriate sources of the information (there will often be redundancies in this respect); (d) consider expenses and logistic constraints for the source agency of the data; and (e) be clear as to whether SOER, the source agency, an expert working group, or some combination of these will have responsibility for analysis and interpretation.

5. *Measurement issues.* In order to predict a future event, we must have confidence in the existing data series (Berkowitz *et al.* 1989). Some important issues to be

considered during the implementation of the proposed program are the accuracy and precision of measurement, and the calculation of confidence limits:

a. *Accuracy* of measurement is the degree to which the data represent true values. Accuracy can be investigated by using different but reliable methodologies and then examining the similarity of the estimates.

b. *Precision* is the repeatability of methodology, or the degree to which the same methodology used in other locations or at other times will yield comparable results. Precision can be addressed by repeated measurements of the same variable, using some accurate methodology.

c. *Confidence limits* are calculated for data sets having replicate measurements, in the proper statistical sense.

6. *Power Analysis.* A statistical technique called power analysis has been little used but is particularly appropriate for ecological data (Peterman 1990). For inference testing, in addition to calculating the probability of making a Type I error (i.e., alpha), the probability of making a Type II error (i.e., beta) or the statistical power (i.e., 1-beta) should also be calculated and reported. For example, a study might report that "no effect" was detected. It is difficult to interpret this result without knowing the statistical power of the data set (i.e., either there truly was no effect or perhaps sample size and design were inadequate to detect a small but potentially important effect). Statistical power analysis should be incorporated into analyses of ecological data, because this procedure provides a measure of the appropriateness of the data for testing a hypothesis.

ENHANCEMENT OF ECOLOGICAL MONITORING

Workshop participants provided a number of useful suggestions that would facilitate the ability of government to detect changes in environmental quality. These suggestions for enhancement of monitoring programs are discussed below.

1. *Periodic Review.* The national ecological monitoring program should include periodic reviews of activities. There will be a continual need to adaptively change monitoring activities to deal with emerging issues, to audit monitoring protocols with respect to quality assurance and control, and to incorporate new information (e.g., on indicators), technologies, and methodologies. Items to be addressed include the following: (a) continued suitability of indicators that are being measured; (b) accuracy and precision of data; and (c) continuity of monitoring activities, so that there are no time lapses.

2. *Data compatibility research.* There is a need for research to determine the compatibility of the various techniques that are currently being used by different agencies or groups to measure particular indicators. This disparity is due to many factors, including differences among agencies or groups in funding, equipment, mandates, hypotheses, and orientation.

   It is unlikely that all monitoring of a given indicator would utilize the same technique at all places and at all times. Much funding, comparative measurement exercises, and workshop activity would be necessary to convince people to adopt particular techniques. Changing methods in midstream would be a major problem for any monitoring program, and the finer the spatial scale, the more serious would be any change in methodology. Depending upon differences in accuracy and precision, changing methods at a site might present a more serious compatibility problem (for that site) than would the use of different protocols among sites (for national reporting).

   In some cases, a more reasonable alternative might be to develop compatibility or correction factors that could be applied to data after their collection. This development would require that research be conducted to make comparisons and identify correction parameters. This alternative would be less expensive than purchasing new equipment and retraining personnel, and it could allow different agencies and groups to maintain their specific focuses and continuity of their data collection. SOER could play an important role in determining the compatibility of techniques by organizing groups of specialists and funding comparability studies.

3. *Appropriate technologies.* Care must be taken to choose appropriate technology for particular monitoring questions. First the most appropriate indicator(s) should be identified, and then the simplest reliable technique should be identified and used to measure the indicator. The use of expensive, high-tech equipment in monitoring programs may be impressive, but it is not always required for ecologically sound monitoring.

4. *Mandates for monitoring.* Many important biological response indicators are not being measured because no agency has had the mandate to do so. The reason that waterfowl are relatively well monitored is that censusing is a legislated requirement under the Migratory Bird Convention between Canada and the United States—that is, there are international

obligations. Purely domestic wildlife issues are addressed much less well. For example, in many jurisdictions there are important deficiencies in the census information used to set bag limits for large mammals and grouse. Another important deficiency in current programs is monitoring songbird and amphibian populations, because concern has been expressed about possible large-scale decreases in the abundance of these wildlife. These should be monitored nationally, but to date no agency has been given or has seized the mandate to do so. Furthermore, the continuity of ecological monitoring activities that are not legally obliged is at the mercy of political and administrative whimsy.

5. *Management decisions*. Participants noted that in many cases, rather than directly deal with important environmental changes, government has tended to stress the need for more monitoring and for additional information. A case in point is the well-known decrease in waterfowl populations in Canada. Much money and effort have gone into censusing ducks in the prairies, and as a result population declines are well documented. However, insufficient action has been taken to deal with the causes of the problem of waterfowl decline. Scientists can, and do, make appropriate recommendations, but these are not always implemented. It is senior administrators and politicians, however, who make the final decisions about whether and how to act, in terms of avoiding or mitigating ecological problems.

6. *Adaptability of monitoring programs*. Environmental change is inevitable, whether it occurs naturally or is driven by the activities of humans. Therefore, ecological monitoring programs must be adaptable and must be continuously rationalized in the face of inexorable change. For example, as climatic change affects the agricultural zones of prairie Canada, there will be important spatial shifts in the use of crops and cropping systems. Where necessary, ecological monitoring programs must adjust to these changes, by adaptive modifications of monitoring protocols and the spatial design of networks. The active role of research scientists will be essential to determine what specific adjustments should be made.

7. *Monitoring for unknown stressors*. The conceptual design of the proposed national program of ecological monitoring focuses on a process by which stressors are identified and indicators are selected based on their relevance to these stressors. However; (a) important stressors are not always recognized; (b) the importance of stressors may change; and (c) a complex of stressors may be contributing to ecological change. A truly comprehensive monitoring program should have the capacity to monitor for unknown stressors or surprises.

The following strategies were identified as useful for monitoring for unknown stressors in freshwater aquatic systems (modified from notes of N. Yan, Dorset Research Centre, Ontario):

a. Determine the most probable routes of delivery of unknown stressors, and locate monitoring sites accordingly. Considerations should include planned urban or industrial developments and movement of air masses.

b. Assess a broad range of contaminants in precipitation.

c. Track changes in the dissipative use of materials in the global marketplace for clues to future chemical stressors.

d. Select response indicators in a multimedia fashion to represent all major habitats, and gather baseline data for these indicators.

e. Select study sites that are representative of all major habitat types.

f. Select some sites that have inherently rapid responses to changes in stressor intensity, such as small lakes and headwater streams.

g. As indicators of ecosystem function, select indicator taxa that are the sole occupants of key niches in the community, as their losses may be especially disruptive to ecosystem function. Schindler (1990) noted that in an experimentally acidified lake at the Experimental Lakes Area of northwestern Ontario, there were no functional analogues of several taxa (*Mysis relicta, Hyalella, Pontoporeia, and Oronectes)*; hence, the losses of these taxa were particularly disruptive in the acidified ecosystem.

h. Closely monitor changes in communities composed of large numbers of rapidly reproducing taxa with great dispersal powers (e.g., phytoplankton, aquatic insects with winged adult life stages). The structure of such communities should respond rapidly to changes in stressor intensity (Schindler 1987).

8. *Sample archives*. Maintenance of sample archives is desirable and would serve several important functions. Archives of material may permit retrospective measurement of the effects of chemical stressors that

are not currently recognized. Also, if monitoring protocols are not consistent over space and time, sample archives can provide a basis for the objective comparison of different methodologies.

9. *Composite indices.* Participants were asked their opinion on the development of composite indices of environmental quality, perhaps for inclusion in daily news reports, as are economic indices. Politicians and the general public would like to see such indices, because they are superficially easy to interpret. Nevertheless, workshop participants were sceptical that scientifically meaningful composite indices could be developed. Composite indices related to economics are relatively easy to formulate, because their components are all measured in a common currency—dollars. Environmental quality is a much more complex issue, and there is no common currency.

   At most, composite environmental indices should focus on particular aspects of environmental quality—for example, forest, fishery, or agricultural resources, air quality, wetland habitats, endangered species, or endangered spaces. Nonetheless, even focused composite indices are problematic in terms of interpretation, because much more information is put into than received from a composite index.

10 *Synthetic indicators.* It can often be expected that coincident stressors will have simultaneous, even synergistic, effects on environmental quality or ecological integrity. Instead of a single important stressor, there may be stressor complexes. Five major stressor complexes have been identified: (a) toxic loading; (b) harvesting of biota; (c) change in ecosystem structure; (d) species loading (e.g., effects of exotic species); (e) material removal (e.g., erosion); and (f) change in ecosystem function (e.g., leaching of nutrients, changes in productivity, nutrient cycling). A synthetic indicator for these stressor complexes in the Great Lakes is the lake trout, for which there is a 200-year record of monitoring and mapping data (H. Regier, University of Toronto, personal communication).

11. *Integrative, biological response indicators.* One of the most important deficiencies in current programs across Canada is the monitoring of integrative biological response indicators. Some biological indicators (e.g., growth of organisms) have the capability of integrating environmental information, temporally and perhaps spatially. Examples of integrative response indicators that could be measured include the following:

    a. Top-level carnivores may be sinks for most of the halogenated hydrocarbons that they ingest with food, so their tissue residue concentrations may represent an integrated measure of exposure over a lifetime.
    b. Lichens may progressively accumulate many trace toxics deposited from the atmosphere over long periods of exposure.
    c. The community structure, abundance, and tissue chemistry of sedentary aquatic macroinvertebrates may integrate temporal variations of water chemistry. Much research is needed to develop monitoring protocols for cumulative response indicators such as these.

INFORMATION TRANSFER TO THE PUBLIC

A major focus of SOER is the transfer of environmental information to the public. In a broad sense, this task includes a description and justification of the spending of public money on environmental protection, as well as the environmental education of the public. SOER could disseminate information to the public through publications (e.g., its five-year, comprehensive state of the environment reports), seminars, workshops, and interactive, kiosk-type displays linked to a database, which would effectively communicate environmental trends and related information.

1. *Environmental goals.* Canadians wish to maintain or enhance their standard of living. Unfortunately, most people, and especially economists and politicians, equate an increase in the amount and intensity of economic development (monitored by indicators such as Gross and Per Capita National Product, stock market indices, etc.) with an increase in the standard of living. Unfortunately, the "conventional" economic indicators do not reflect the profound environmental degradation that usually subsidizes economic growth and development. The notion of "ecologically sustainable development" must replace "sustainable economic growth" as a goal of society.

   In addition, Canadians are increasingly recognizing a responsibility to maintain the integrity of their national ecological heritage. State of the environment reporting will play a very important role in educating the public with regard to this goal. To appropriately influence this function, SOER must resist inappropriate political influences on the selection of indicators for monitoring. In particular, the unbalanced use of "economically interpretable" and "human-focused" criteria could be problematic.

2. *Notions relating to ecological quality.* During workshop discussions, there was no clear consensus of what constitutes "environmental quality," "ecosystem health," or "ecological integrity." Among scientists, there are fundamental disagreements concerning the definitions of these notions. While scientists strive to better understand these notions, the primary and immediate concern of the public is likely to be the effects of stressors on their lifestyle. It is clear that research and discussion are required to better understand the notions of environmental and ecological quality, health, and integrity, and to understand the linkages between stressors and societal goals.

3. *Role of SOER in interpretation.* SOER seeks to bridge the gap between ecological scientists (whose interests focus on understanding ecological integrity) and the public (whose interests focus on environmental quality). The public needs an appropriate, responsible interpretation of environmental data in order to understand their significance. Furthermore, the interpretation of trends in environmental data is an important step that should influence the decision-making activities of government regarding environmental issues.

   There was virtually unanimous support among workshop participants that the interpretation of trends in national environmental data should be a role of SOER. This interpretation may be best achieved through SOER's coordination of expert working groups, thereby utilizing (and not duplicating) the best available ecological expertise in Canada.

   As a "Statistics Canada of environmental accounting," SOER is envisioned as providing the public with information on the status of the environment and emerging trends, without attaching the labels "good" or "bad" to the trends. Workshop participants felt, however, that SOER should also provide sufficient interpretation of the trends. There was a consensus that SOER should discuss (a) potential causal links and (b) whether the state of the environment is getting better or worse, as well as (c) deficiencies in important knowledge with respect to the state of the environment. Some participants also felt that SOER should discuss (d) mitigation or avoidance strategies to address environmental deteriorations and (e) whether such mitigation or avoidance responses (e.g., changes in policy, regulation, acts, guidelines) have affected trends in the state of the environment.

4. *A model for presentation to the public.* The stressor-exposure-response model, which underlies the conceptual design of the proposed national ecological monitoring program, may not be the most useful model for presentation to the public. Although simple and linear, this model may be difficult for the general public to understand, because they may have different interpretations of the terms "stressor," "exposure," and "response." Understanding by the public may be impeded by terminology that they find confusing.

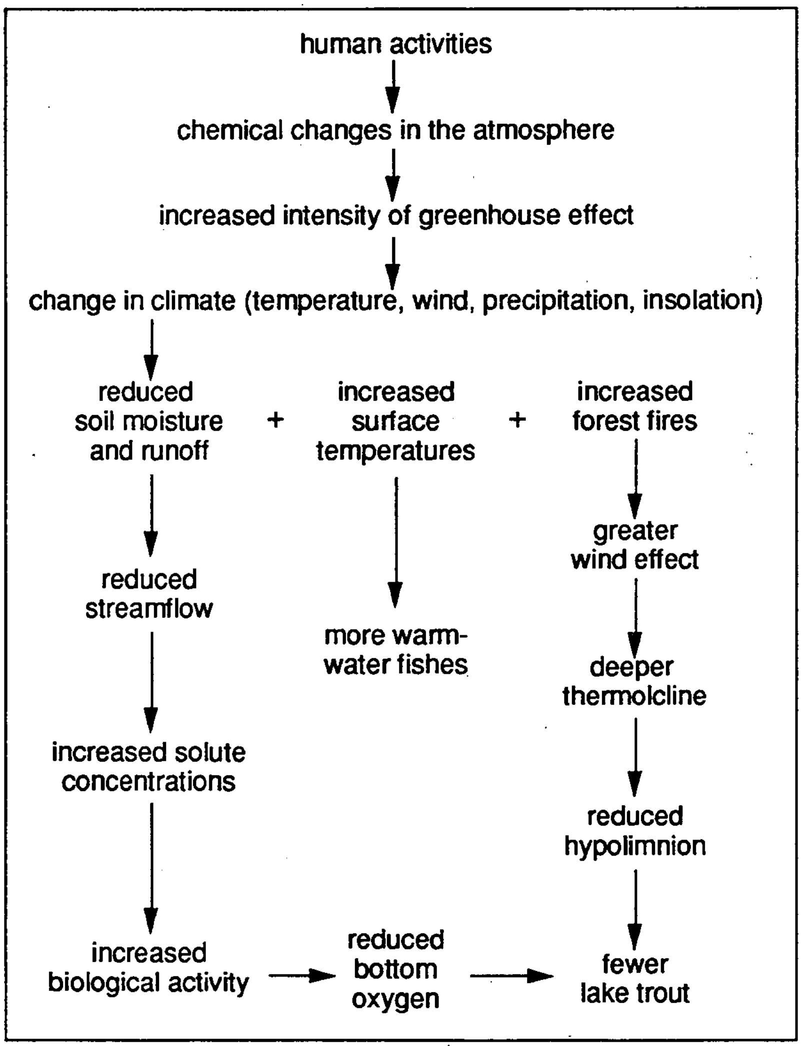


Figure 5
A cascade of effects is a useful way to portray the linkages between stressors and responses in the processes of environmental change. This example explains how human activities may change climate and how this in turn may produce a cascade of effects that ultimately affects fish communities, and specifically, lake trout.

For presentation to the public, a model that focuses on the cascade of effects of stressors may be more useful. In any particular case, stressors could be organized along a sequence, from primary to secondary, etc. This organization is sensible, because the effects of a primary stressor can secondarily become a stressor that affects another component, and so on. The result is a cascade of effects linked by causal relationships. Figure 5 presents an example of such a cascade that explains how climatic change can occur and ultimately affect lake trout, a species of fish used as a key indicator of the ecological integrity of freshwater lakes in some areas. (This example was provided by B. Atkinson and G. Koshinsky of the Freshwater Institute, Winnipeg.)

5. *Environmental education.* Interpretation for the public was considered to be very important by workshop participants, because the environmental education of most Canadians is deficient. In part, this shortcoming exists because the public has relied largely on the media for environmental education. Although the media communicates much environmental information, its presentation may be biased and sometimes inaccurate. The media is in business to make a profit. It therefore may be driven to report what sells and to interpret accordingly. Red herrings can become high-profile issues that dominate the environmental agenda and thereby detract from efforts to solve more important environmental problems.

   For these and other reasons, there is a serious need in Canada for an institutionalized exposure to objective environmental information through the educational system and other programs. This is required to deal with the deficiency in environmental education that was noted to be pervasive throughout the Canadian educational system, from primary school through universities to continuing education for the out-of-school public.

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