Towards a Measurement of Ecological Integrity

Summary Report

Prepared for:

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Towards A Measurement of Ecological Integrity

We are pleased to submit this Summary Report, a shorter version of a 74-page research discussion paper titled *Towards a Measurement of Ecological Integrity* (November 15, 2001). The research paper, commissioned by the National Round Table on the Environment and the Economy as part of the Sustainable Development Indicators (SDI) initiative, explores the theory and practical approaches of measuring the integrity of Canada's ecosystems.

The research report examines the "state of the art" of measuring ecosystem integrity by reviewing literature on the most relevant and practical emerging methods that might guide the work of the NRTEE in the most challenging area of measurement: assessing the health of ecosystems.

We have attempted to find ways to reconcile the more linear "capital approach" posited by Statistics Canada with an ecological-biological perspective that would assess ecosystems for what they are—dynamic, resilient systems that demonstrate pressure-state-response characteristics.

Measuring ecosystem integrity is emerging as a discipline in itself. The recent transdisciplinary publication *Ecological Integrity: Integrating Environment, Conservation, and Health* (D. Pimentel, L. Westra and R. Noss, eds. Island Press, Washington, DC, 2000) is just one example of efforts to understand the complexity of ecosystem integrity. Our discussion paper scratches the surface of the emerging knowledge base, identifying only a fraction of the available Canadian and global information on this intricate subject.

Our expectation is that this discussion paper will provide realistic ideas to help the NRTEE SDI Committee move towards the desired outcome of ecosystem health indicators that meaningfully gauge sustainability for Canadians.

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Contents

List of Figures

List of Tables

1. Introduction

The National Round Table on the Environment and the Economy (NRTEE) was commissioned to produce a framework of national-level indicators for the environment and the state of sustainable development in Canada. A Committee was struck to oversee the development of these indicators and is expected to complete its work by the spring of 2003. A series of cluster groups was established to examine the development a handful of indicators selected from six domains: human capital, non-renewable natural resources, renewable natural resources, land and soils, air quality and atmospheric conditions, and water resources.

The task of measuring and developing indicators of ecological integrity covers most of these domains but is most relevant to the work of the Land and Soils Cluster Group (dealing with non-forested agricultural land and soil productivity, contribution of land to economic activity and terrestrial ecosystem functions, and the health of terrestrial ecosystems) and to the Renewables Cluster Group (dealing with forests). The Land and Soils Cluster Group was charged specifically with examining the feasibility of a national indicator of the health of non-forested terrestrial ecosystems, such as wetlands and grasslands ecotypes, with an emphasis on physical degradation and/or loss (e.g., biological diversity, endangered species, protected areas).[1]

The assessment of ecosystem integrity is undoubtedly the most complex and challenging aspect of the NRTEE SDI Initiative, particularly within the "capital" approach advocated by Statistics Canada (see *A Proposed Framework for the Development of Environment and Sustainable Development Indicators Based on Capital*[2]*)* and supported in the *Technical Guidelines for Indicator Selection.*[3] Measuring the integrity of an ecosystem requires a diagnostic framework that reflects the complex nature of these systems. Such an accounting framework must reflect the dynamic interrelationships that constitute the ecosystem and must provide guidance in assessing their health—that is, their ability to sustain services.

Measuring ecosystem integrity is analogous to measuring the health of the body, and the tools do not necessarily lend themselves to a linear accounting model, which is the norm for traditional natural capital accounting systems now being developed. A unique approach to measurement and accounting, which draws information from various natural capital and environmental quality accounts, may be required to construct a meaningful picture of ecosystem integrity at various scales. This will require a living systems approach to assessing the pressures, state and response (outcomes, in terms of functions) of ecosystems, realizing that the capacity to measure is fundamentally limited by our knowledge and ability to actually assess "health."

Fortunately, there is growing literature and research about measuring ecological integrity, including the recent work by several experts in ecological integrity issues, contained in *Ecological Integrity: Integrating Environment, Conservation, and Health,*[4] and the work by Michelle Boyle (1998)[5] and James Kay (1994)[6] who examined performance indicators for ecosystem management. The most recent benchmark analysis of agriculture, land space and ecosystem indicators by Delaney and Associates[7] for the NRTEE Land and Soils Cluster Group has also provided important insights into the scope of emerging indicators and meaningful metrics for assessing ecosystem integrity. Statistics Canada[8] too has offered guidance about how to measure ecosystem service outcomes, which are useful starting points for an integrated systems approach to measuring ecosystem health.

2. Defining Ecological Integrity

2.1 Ecosystems as Capital

Statistics Canada has acknowledged that "measurement of ecosystems as capital is the most difficult of the three dimensions of the environment. In theory, the correct approach is to measure the services that are provided by ecosystems to the economy and to estimate the value of what these services represent as contributions to production. In practice, even if we can define what these services are, we cannot observe them directly."[9] In terms of natural capital, Statistics Canada has defined three categories: natural resources, land and ecosystems. It is the latter category we are interested in measuring.

Ecosystems are complex living systems that may or may not lend themselves to the definition and measurement of "capital" used by Statistics Canada. Because ecosystems are dynamic, the static, historical and linear accounting of "stocks, flows, and values"—as is currently done in natural capital accounts for forests, agriculture and subsoil assets—makes developing a "living systems" account more challenging and complex. Measuring ecosystem integrity is akin to measuring human health—a complex task that uses common indicators for gauging the conditions of wellness but requires unique interpretation by the "doctors" making the assessment. As Statistics Canada notes, "If the outcomes of ecosystem services are constant over time (e.g., air quality is non-declining), then one can conclude that the natural capital—that is, the ecosystems—that provides the services that leads to these outcomes is being maintained."[10] It is thus most relevant to measure the integrity of ecosystems by using biological assessment and monitoring techniques to do a "physical checkup" of ecosystem health.[11]

2.2 What Is Ecosystem Health?

Webster defines health in terms of physical and mental well-being, vitality, soundness, or being whole.[12] As Karr notes,[13] health is short for "good condition," as it applies equally to assessing our individual or human health and to the health of an ecosystem. Further, "An environment is healthy when the supply of goods and services required by both human and nonhuman residents is sustained" (p. 211). Constanza (1992)[14] defines the health of an ecosystem as follows:

> *Its [the ecosystem's] ability to sustain its structure and function over time in the face of external stress.*

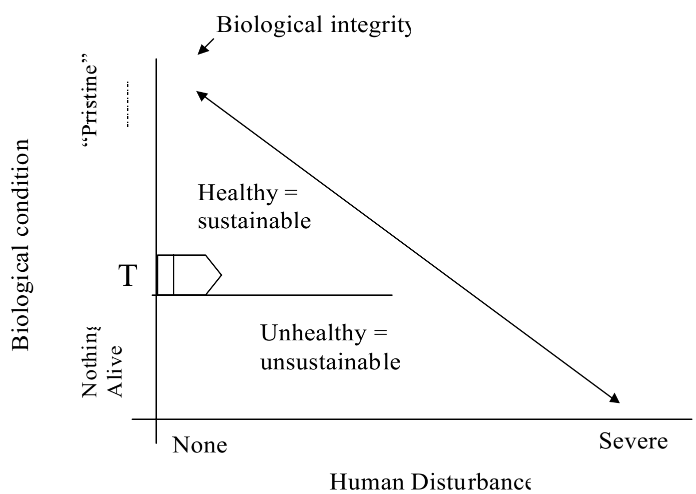
2.3 What Is Ecosystem Integrity?

Ulanowicz (2000)[15] notes that ecological integrity explicitly subsumes the notion of "health." He argues that the function (vigour) of a system relates to its overall level of activity in processing material and energy and that its structure (organization) is how effectively its overall processes are linked with each other. Ulanowicz adds a third dimension, resilience to perturbation. Thus we have three potential perspectives for assessing the "total performance" or total health of ecosystems: function, structure and resilience.[16]

Indicators could be developed that measure the condition of all three dimensions of an ecosystem, with the ultimate goal of assessing the biological condition of the ecosystem as a living and whole system.

Karr (2000)[17] notes that ecological integrity can be defined and measured in terms of the condition of places at one end of a continuum of human influence (Figure 1). Figure 1 shows that ecological conditions decline away from biological integrity as human disturbance increases. Karr describes biological integrity as the condition of a place that has its evolutionary legacy—its parts (e.g., species) and processes (e.g., nutrient cycles)—intact. Degradation of the biological condition beyond a threshold (in the vicinity of T) is where an ecosystem becomes unhealthy because its functionality has become unsustainable. Karr's model considers the ideal or "pristine" biological condition as a biota that is a balanced, integrated, adaptive system with the full range of elements and processes that are expected in areas with minimal human influence. Karr cautions that it is inherently difficult to define with any clarity the tipping point.

Figure 1: Biological Integrity Continuum



Karr, J.R. 2000. "Health, Integrity, and Biological Assessment: The Importance of Measuring Whole Things," in D. Pimentel, L. Westra and R. Noss (eds.), *Ecological Integrity: Integrating Environment, Conservation and Health* Island Press, Washington, DC, pp. 209-226.

Karr's model provides a meaningful framework within which to conceptualize measurement of ecosystem integrity that tracks the trends in human disturbance pressures (e.g., resource extraction and ecosystem fragmentation from linear disturbance, pollution and emissions) combined with a biological "health" assessment that tracks shifts in the parts and processes of living ecosystems (e.g., sampling and monitoring to assess loss of salmonids as stream temperature increases or area-sensitive birds as forests are fragmented). While monitoring the pressures on living ecosystems from human disturbance may be relatively straightforward, identifying the point beyond which a system goes from healthy to unhealthy or from sustainable to unsustainable (that is, "T") is far more difficult. Moreover, it is difficult to measure the resilience and performance of complex systems.

Karr points out that it is not enough to measure the cumulative influence of human society (e.g., amount of resources extracted or effluent created) or to calculate the economic value of ecosystem services to human society.[18] Karr states that we must track carefully and broadly the condition of the biota of places influenced by human society. He makes a clear distinction between "biota" and "ecosystem," noting that an ecosystem may well continue to exist independently of the actions and effects of human society, but that such human impacts can have different effects on individual species of flora and fauna and these need to be tracked. Tracking the condition of these key biota is like keeping track of the principal in a bank account. With respect to tipping points (T), Karr suggests that different components of the biota have different tipping points and different combinations of human actions in a region will result in tipping points that may have different thresholds. Rather than precise "tipping thresholds," Karr sees a monotonic decline along a complex gradient of human actions. Karr's Index of Biological Integrity (IBI), which is discussed later in this paper, is an ecological health accounting system that integrates multiple measures of biological conditions of biota for any given region.

2.4 How Can Ecosystems Be Assessed as Living Systems?

How should we design a measurement and monitoring system of ecological health and integrity that a) takes a holistic approach, and b) reconciles with our more linear measurement systems, including a "capital" approach to measuring natural capital and environmental services? An important debate on the subject is emerging.[19]

Dr. James Kay, one of Canada's leading thinkers on ecosystem integrity measurement, notes that operationalizing the notion of integrity and reporting on it are complicated by the fact that ecosystem dynamics are complex, not deterministic, self-organizing and unpredictable; they exhibit phases of rapid and catastrophic change, and are continually evolving at temporal and spatial scales that will require both an analytic and a synthesis approach to understanding how interactions of the ecosystem's components (holons) and human influence translate into ecosystem integrity.[20] Kay[21] seems less certain that ecosystem integrity can really be measured. He argues that neither a reductionist nor a holistic approach is sufficient. We must take a whole-systems perspective to understand the complexity of relationships of subsystems and their components in a cycle of birth, growth, death and renewal. Kay refers to this cycle as the Holling[22] "figure eight" life-cycle succession of states or phases—nested cycles of both time and space scales based on understanding of catastrophe theory. Kay shows a figure-eight life cycle moving from exploitation to conservation to release to reorganization, then recycling back to a new phase of exploitation or moving to a completely new modified state.

Both Karr and Kay support the notion that operationalizing ecosystem integrity measurement first requires measuring the changes in the organizational structure of ecosystems, such as species diversity, as well as human impacts that affect ecological integrity. This means identifying a set of ecological characteristics to be monitored for change away from a benchmark or baseline (i.e., pristine) condition. Measures of integrity will be required for several different hierarchical levels and scales that are sensitive to the biological and socio-economic issues within bioregions. Some measures will help diagnose the overall condition of the ecosystem, while others will focus on specific known threats to integrity. We must also understand how ecosystem components (e.g., species) respond to natural and human impacts (as Karr argues as the building blocks of his IBI).

Kay notes that dealing with the catastrophic behaviour of ecosystems has important implications for measurement. Ecosystems can have several stable states and exhibiting sudden change is normal (e.g., fire, pest outbreaks). Knowing the current value of environmental variables is not enough to know the state of the ecosystem, because its history must also be known, and suppression of these sudden changes only sets the system up for bigger changes later.

Quantifying the changes in the organization of ecosystems will require regular biological assessment and monitoring, aerial imagery of land use changes and cover types, and monitoring of human impacts. This necessitates an understanding of: a) the makeup of a healthy ecosystem on a spectrum of integrity (from pristine to "nothing alive," as per Karr's Figure 1); b) the key determinants (i.e., key indicator species or key condition parameters) of ecosystem functionality; and c) the wider environment in which these components function and relate. Finally, we need to resolve issues of evaluation. As Kay notes, "What values of the measures will integrity be deemed to have been lost? Who will make this decision and who will act?"[23] Kay offers a useful framework for evaluating ecological integrity in a stepwise ecosystem approach (see Appendix A).

Boyle and Kay (1996) have devised an "adaptive ecosystem approach" conceptual framework for developing indicators of ecosystem integrity (see Figure 3, Appendix A). Their framework identifies factors that should be considered in developing an effective ecosystem integrity monitoring system.

Rubec and Marshall (cited in Kay's paper)[24] identify three priorities for Canada in evaluating ecosystem integrity; these will be useful for the NRTEE's SDI to consider:

- A first order of business must be integrating and synthesizing human activity and ecoregional information across Canada.
- Development of national measures of ecosystem health and integrity will also require the creation of a national network of stable, secured and intercomparable benchmark reference sites with at least one such site in all ecoregions.
- We must ensure that existing interdisciplinary monitoring sites and networks are maintained to provide the long-term perspective essential to monitoring; these include the Experimental Lakes Area, and the Dorset, Turkey Lakes, Lac Laflamme and Kejimkujk watersheds developed in the national acid rain program.

In conclusion, although a methodological framework for evaluating ecosystem integrity has emerged, the practical application of these evaluation systems is still being developed. At the very least, reporting on trends in human pressures for various bioregions would be a first step towards ecosystem health and integrity measurement.

3. Practical Approaches to Measuring Ecosystem Integrity

This section of the report examines some of the emerging practical approaches and tools for evaluating ecosystem integrity. Composite indices like Karr's Index of Biological Integrity (IBI), the Living Planet Index (World Wide Fund for Nature),[25] the World Resources Institute's ecosystem condition scorecard,[26] the Ecological Footprint analysis, and forest ecosystem fragmentation indices (e.g., Pembina Institute's GPI Forest Integrity and Fragmentation Index) hold some promise.

3.1 Potential Ecological Integrity Indicators and Reporting Systems

Boyle (1998)[27] offers a useful framework for stratifying and organizing what could be a large list of ecological integrity indicators into three category levels. Level I indicators are indicators of ecological integrity for immediate use. Other characteristics of Level I indicators include: a) being outcome-oriented, scientifically valid, statistically and analytically sound, and practical; and b) data are comparable over time, understandable to potential users, unambiguous and easy to use. Level II indicators are those with demonstrated potential use, but where data are not yet being collected or there is a lack of historical data or insufficient geographic coverage. Level III indicators are those where there is evidence that the measure could be worthwhile, but further scientific research and/or case studies are needed to confirm their utility.

In addition to this list produced by Boyle, the inventory of indicators of ecosystems prepared by Delaney and Associates[28] for the Land and Soils Cluster Group of the NRTEE's SDI also provides the beginning of a potential suite of indicators for measuring pressures on ecosystems as well as some measures of ecosystem functionality and integrity. This list is categorized according to *direct* measurement indicators, indicators of *demand* placed on ecosystems, and indicators of the *outcome* of services derived.

Direct

- Indicators of Grassland health in military training areas
- Habitat fragmentation, based on areas of land that are less than 20 hectares, 20 to 40 hectares, and over 40 hectares compared with number of fragments
- Estimated percentage of provincial riparian forest land area logged within the past 20 years
- Hectares of major terrestrial ecosystems

Demand

- National Pollutant Release Inventory (NPRI) information of annual substance releases
- Municipal solid waste to landfills
- Household waste and recycling
- Area of exceedance of wet sulphate deposition above critical loads
- Spills of toxic substances in Arctic ecosystems
- Contaminant levels in double-crested cormorant eggs (e.g., DDE and PCBs)
- State of Alberta's wetlands (GPI indicator #43)

Outcome

- Health of tall grass prairie using key beetle and spider indicator species

- Percentage of known animals that are "threatened"
- Status of species at risk based on Committee on the Status of Endangered Wildlife in Canada (COSEWIC) assessments
- Populations of wild birds as an indicator of habitat and agri-environment
- Number of threatened species
- Percentage of prairie ponds with margins or basins affected by agricultural practices
- City of Calgary Christmas bird count
- Percentage of historical range where wildlife populations are improving or decreasing
- Plant diversity in semi-improved grasslands and in "streamsides"
- Potential indicators/databases for trends in changes in land use (this indicator applies to all three categories)

What is apparent from Boyle's list and from that of Delaney and Associates is that there is no easy way to organize the indicators—they do not fit into a structured accounting system and there is no right or wrong suite of indicators. An accounting system, potentially as part of the natural resource and environmental accounting system of Statistics Canada, could be developed to a) draw data from sub-accounts that would include direct, demand and outcome indicators, or b) derive outcome indicators according to types of ecosystems.

Steven Woodley (1997)[29] has developed a framework for assessing and reporting on the ecological integrity of Canada's **national parks**, according to the broad parameters of biodiversity, ecosystem functions (resiliency, evolutionary potential) and stressors.

Ted Weins has used Statistics Canada's Survey of Agriculture data for the prairies to propose a **prairie habitat indicator** for agricultural ecosystems.[30] Weins's agrobiodiversity indicator aims to monitor biodiversity change in agricultural ecosystems by measuring changes in habitat availability and in species diversity and abundance. The indicator would track progress towards environmentally sustainable agriculture.[31]

Wrona, Cash and Gummer describe the development of **aquatic ecosystem indicators** as part of the Northern River Basins Study (NRBS).[32] One of the primary objectives of the NRBS was to define a potential suite of ecological indicators that could be used to assess the present and future health of the aquatic ecosystems in these basins.

David Schindler's work[33] in monitoring and assessing **aquatic systems** at the Experimental Lakes Area has yielded nearly 30 years of records for weather, streamflow, stream and lake chemistry, and physical, chemical and biological variables.[34] This important longitudinal study is providing the kind of information required on reference ecosystems, to use in interpreting the results of whole-lake, living system experiments.

Dr. Stan Boutin[35] at the University of Alberta is beginning to develop a framework and reporting mechanism for **boreal forest ecosystem integrity** indicators that may provide the basis of terrestrial ecosystems integrity assessments.

Satellite mapping and spatial analysis (e.g., GIS analysis) being conducted by agencies such as Natural Resources Canada and Environment Canada are important tools for profiling ecosystem integrity and mapping ecosystem functional integrity using various parameters. Environment Canada's Ecological Monitoring early warning system (EMAN) is intended to monitor ecological activities in Canada.[36] "A national early warning system must be based on the ability to detect meaningful ecosystem changes, to establish a "tripwire" capability that need not include consideration of causes."[37] It will be possible to develop ecological profiles based on a variety of search fields (e.g., species, time, location, agency, chemical parameter) with the capacity to view the results as lists of data sources or as a geospatial map.[38]

Satellite imagery can also be used to construct ecosystem integrity measures such as leaf area index profiles[*] or net primary productivity profiles. Such data would enable the development of colour-coded ecosystem productivity profiles at resolutions of 30 metres or less. Much of this information resides in scientific research circles but is not being used for public reporting.[39] Combining satellite imagery with the land use and human impact data that could be housed with natural resource and environmental accounts maintained by Statistics Canada would provide a robust ecosystem integrity monitoring and reporting system for Canada.

3.2 Composite Indices

One of the most innovative approaches to reporting on ecosystem integrity is the development of composite indices. The strength of composite indices is their capacity to communicate a complex issue like ecological integrity in a single metric. Their weakness is the assumptions that must be made about the weighting of importance of individual components of the composite index and the value judgments needed to choose individual indicators to make up the composite index.

3.2.1 Index of Biological Integrity (IBI)

One of the more sophisticated yet elegant composite indices is Dr. James Karr's (2001)[40] **Index of Biological Integrity,** or IBI. The IBI is a multimetric of biological indicators that, taken together as an index, can be used to assess trends in the overall health of ecosystems affected by human disturbances relative to a benchmark condition (i.e., pristine or wild). This means selecting biological monitoring tools, ecosystem condition benchmarks, and key parameters that are sensitive to human disturbance, then tracking the site condition over time as human disturbance occurs. Karr identifies the steps required for an assessment system that would ultimately lead to biological indices like the IBI that integrate indicators of biological condition and cover many levels of biological organization—from the health of individuals to taxa richness and trophic organization.

The IBI is constructed from a range of biological indicators that rely on observations of the real world and of the conditions of an ecosystem, based on sound scientific and ecological theory. The ideal state is defined as a condition where there are no, or minimal, human disturbance impacts. The degree of "whole" health is thus measured in terms of relative condition of similar ecosystems from the complete integrity benchmark. Methods used to assess the conditions or attributes of the ecosystem are scientifically rigorous. In terms of the criteria for choosing relevant parameters for assessing ecosystem health, Karr adopts a methodology whereby

[*] Leaf area index profiles are based on detailed carbon mapping showing levels of carbon sequestration by vegetation.

indicators are chosen because they reflect specific, predictable responses of organisms to changes in landscape conditions and human disturbance impacts—that is, they are sensitive to a range of physical, chemical and biological factors that alter biological systems and are relatively easy to measure and interpret (Karr 2001).

Karr[41] identifies three critical components needed to develop IBIs:

- We need to know the economic throughput or flows (production, extraction, pollution) corrected by environmental effects;
- We need to know the smaller-scale issues of the resources and flows; and
- We need to know the trends in the effluent produced from the extraction of natural resources.

The IBI is empirically robust but does not need to resolve all the theoretical debates about ecological functions, as it is focused on key determinants of ecological health. The IBIs are useful for policy makers since they provide a macro index of ecological integrity at relevant scales (e.g., watersheds, forest ecosystems) and taxonomic groupings reflecting human activity impacts.

Karr's[42] IBI methodology has been used to assess the condition of aquatic systems (rivers and streams), and efforts are underway to apply the IBI methodology to terrestrial ecosystems such as forests (Loucks 2000);[43] it is being applied in Alberta by Dr. Stan Boutin,[44] and is now being used in the U.S.[45] The IBI methodology may be better suited for assessing aquatic systems because biological monitoring and indicators of system integrity are better developed and because aquatic systems move towards equilibrium faster than terrestrial ecosystem when under stress or disturbance.

In his work on terrestrial ecosystem integrity, Loucks[46] distinguishes between the impacts of naturally occurring perturbations (e.g., wind, drought, disease, fire) and human impacts (such as timber harvesting and linear disturbance). Loucks constructed a **mean functional integrity (**MFI), similar to the IBI. In assessing forest ecosystem health, the key question is to determine the magnitude of the naturally occurring departure from full functionality, or full integrity. As long as a system is capable of restoring full function it can be said to be resilient or healthy, even if there are measurable departures from full integrity due to natural or human disturbances.

The construction of IBIs or MFIs for aquatic and terrestrial ecosystems for Canada's sustainable development and environmental indicators reporting system is a viable approach but requires a commitment to constructing a national database and accounting system for completing the measures and key indicators.[47]

3.2.2 Living Planet Index

The World Wide Fund for Nature (WWF) has developed the Living Planet Index (LPI), which measures the natural wealth of the Earth's forests, freshwater ecosystems, oceans and coasts at the global scale with the capacity of reporting at ecosystem and national scales. The LPI is constructed by averaging three indices of the changes over time in populations of animal species in forest (Global Forest Ecosystem Index), freshwater (Freshwater Species Index) and marine ecosystems (Marine Species Population Index). The LPI represents a type of "state" indicator with its focus on population counts of animal species. Each ecosystem index measures the change over time in a population that is typical of the sample of species in the index.

The Living Planet Index provides a useful measure of the condition of ecosystems according to the populations of key wildlife species. The LPI is easy to communicate and is meaningful since it reports on the trends over time from a benchmark year that can be compared with other natural capital, economic, human and social capital indicators. The LPI is a species population accounting system that could be used with the Canadian Species at Risk monitoring system completed by COSEWIC for monitoring species populations.[48]

3.2.3 The Ecological Footprint

The Ecological Footprint (EF) developed by Mathis Wackernagel and Bill Rees[49] is a conservative estimate of the human pressure on global ecosystems. It is linked to the consumption of energy and material goods by households relative to an estimate of the biological productive capacity of land and sea ecosystems for the generation of essential ecosystem services on which humanity depends. Ecological Footprint Analysis (EFA) converts the consumption of food, energy and other materials (using personal consumption expenditure data as a proxy for physical material consumption) to the equivalent area of biologically productive land that would be required to produce the food, energy and other materials to meet human needs. The EF of any individual is the sum of six separate components:

1. The area of cropland required to produce the crops that the individual consumes;
2. The area of grazing land required to produce the necessary animal products;
3. The area of forest required to produce the wood and paper;
4. The area of sea required to produce the marine fish and seafood;
5. The area of land required to accommodate housing and infrastructure; and
6. The area of forest that would be required to absorb the CO_2 emissions resulting from that individual's energy consumption.[50]

The sum of the land requirements for the six individual land categories represents the community's ecological footprint—the total area "appropriated" from nature for the provision, maintenance and disposal of every consumption good.[51] The EF is expressed in land "area units" (in hectares), where each area unit corresponds to one hectare of biologically productive space with world-average productivity.

What makes ecological footprint accounting so attractive is that it is one of the few tools that attempt to integrate resource accounting under one umbrella. Ecological footprint analysis seeks to measure both the sum total of human activity pressures (consumption of natural capital and the stress of waste emitted to the biosphere) and the biological productive capacity within which human economies operate. It provides one of the most elegant tools for measuring sustainability by addressing both human consumption of natural capital and the integrity of ecosystems to provide resources and environmental services. The assessment of biological capacity is based on the original work by Vitousek et. al. (1986),[52] which assesses appropriation of net primary productivity of the biosphere. Ecological footprint analysis is consistent with basic thermodynamic principles as it avoids double counting. The footprint thus approximates the cumulative impact of human activities and warns about "overshoot"[†] of biological carrying capacity. The ecological footprint has its supporters and critics, but despite its limitations it does describe a minimum condition for ecological sustainability—that is, that a nation's or region's ecological footprint must be smaller than the available ecological capacity.

Like other indicators, the EF and EFA have strengths and weaknesses. The March 2000 issue of *Ecological Economics*: *The Transdisciplinary Journal of the International Society for Ecological Economics* contains a good discussion and debate about ecological footprint methodology. One of the strengths of EFA is that it builds on the critical importance of natural capital to economic well-being and suggests a comparative and comprehensive natural capital accounting framework.[53]

Some critics of ecological footprinting[54] note that it may be misleading in that it does not capture the full range of ecologically significant impacts, such as the impact of toxic waste emissions. Van den Bergh and Verbruggen (1998) present five key objections to ecological footprint analysis.[55] Other criticisms of eco-footprinting are that it oversimplifies nature and society, that it has little predictive value, and that it is not sensitive to technological change.[56] Rapport (2000)[57] notes that the eco-footprinting calculus is inadequate to portray the relationship between the impact of people on natural whole and living systems. What is needed, Rapport argues, is an assessment of how human activities have led to the degradation of many ecosystems and transformed once healthy systems into pathological states, compromising economic activity, human health and community well-being. Rapport notes that indicators of ecosystem pathology and "ecosystem distress syndrome" would include losses in biodiversity, declines in long-lived native species and loss of resilience.

Other researchers are attempting to improve on the original EF model in many important ways; they include Deutsch et al. (2000),[58] who are building EF estimates from the bottom up by first using available ecological data and an understanding of local and regional ecosystem performance.[59] Deutsch et al. regard the EF as an "excellent tool for communication of human dependence on life-supporting ecosystems," because it shows people how much they depend on ecosystems to generate resources and services of which they may have been unaware without such an account. They argue that EF is a way to engage citizens, making real how their lifestyles affect the resilience, adaptive capacity and renewal capability of complex ecosystems.

We believe EF accounting and analysis can and should play a key role in sustainability accounting and reporting; we need to build on its current strengths and address its weaknesses with more research and development. It is possible to conduct ecological footprint accounting using Statistics Canada's national income accounting system (to measure EF based on personal consumption expenditures) combined with the environment and natural resource accounting system.

[†] Ecologists define "overshoot" as a state when natural capital stocks are being harvested at rates faster than they can regenerate, thereby depleting the capital stock. Wackernagel and Silverstein (2000) note that some fear that human overshoot could follow the dynamics of fisheries where unsustainable harvest rates can trigger rapid, sudden and systemic collapse of ecosystems leaving the resource stock irreversibly damaged.

3.2.4 World Resources Institute's Ecosystem Condition Scorecard

The World Resources Institute (WRI) has emphasized, as part of the joint reporting in partnership with the United Nations Development Programme, the United Nations Environment Programme and the World Bank, the need to account for the condition of the world's ecosystems and has developed an ecosystem condition scorecard. The first results were released in *World Resources 2000-2001—People and Ecosystems: The Fraying Web of Life* as part of its Millennium Ecosystem Assessment initiative.[‡]

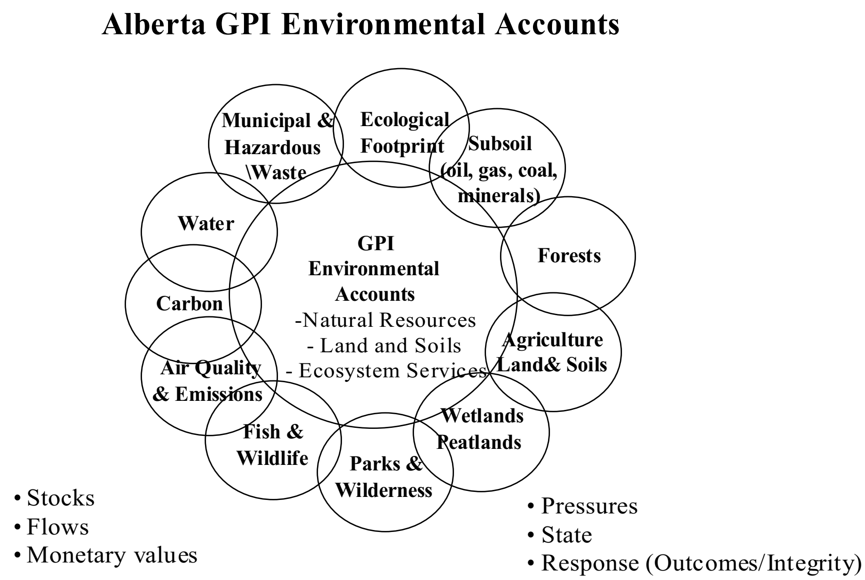
The WRI analysis is based on the "Pilot Analysis of Global Ecosystems" (PAGE), which examined the condition of coastal, forest, grassland, freshwater and agricultural ecosystems in terms of their ability to produce the goods and services on which the world currently relies. These services include the production of food, provision of pure and adequate water, storage of atmospheric carbon, maintenance of biodiversity, and provision of recreation and tourism opportunities. These conditions are reported in a "scorecard" in which a range of conditions (from "excellent, good, fair, poor, bad or not assessed") per ecosystem type is cross-tabulated by ecosystem service functions. These condition ratings are colour-coded, while trends in the capacity of these ecosystems are reported using trend arrows (increasing, mixed [either increasing or decreasing], decreasing or unknown). Scoring is based on expert judgments (its principal weakness) about each ecosystem good or service over time, using a variety of data. The WRI ecological scorecard is a good example of a pressure-state accounting system that combines information on trends in human consumption of natural capital with indicators of ecosystem integrity using spatial and land area information. The reporting system is intuitively attractive for communicating both current conditions and trends in ecosystem conditions according to various ecosystem functions. The WRI ecosystem condition scorecard offers a meaningful accounting and reporting tool for consideration for Canada.

4. The Alberta GPI Environmental Accounts for Measuring Ecological Integrity

The Alberta GPI sustainable well-being accounts (see www.pembina.org) show what is possible in the development of a natural capital and environmental services accounting system that could be used to account for the integrity of ecosystems. The Alberta GPI natural resource and environmental accounts were structured as independent sub-accounts and as an integrated set of accounts (see Table 2 in Appendix B for a listing of GPI environmental accounts and indicators).

[‡] See http://www.wri.org/wr2000/index.html

Figure 2: Integration of Alberta GPI Environmental Accounts to Measure Ecosystem Integrity



The GPI environmental accounts were based in part on the natural resource and environment accounting model developed by Statistics Canada, with some expectations and additions to the suite of sub-accounts. The Alberta accounting structure is consistent with the "capital" approach to measuring natural capital advocated by Statistics Canada for the SDI project. The Alberta GPI sustainability accounts track 40 years of trends in the stocks, flows, pressures, conditions of Alberta's renewable and non-renewable natural capital and ecosystems (i.e., forests, wetlands, peatlands). The accounts also include ecological footprint analysis. While not yet fully integrated, the GPI accounting structure lends itself to the development of a dynamic, "living" systems accounting structure suitable for monitoring ecosystem integrity and for constructing and reporting elegant metrics such as Karr's IBI.

5. Conclusions and Recommendations

Assessing the biological capacity, integrity or health of ecosystems is challenging and complicated. There is no simple or easy methodological approach but rather a number of methods we can use for meaningful measurement and reporting. Understanding ecosystems as living, dynamic and sometimes chaotic systems and accounting for these characteristics presents a unique problem, particularly within traditional linear accounting systems. Taking a living-systems accounting approach will require a creative system of reporting that is sensitive to the life-cycle phase of any ecosystem being observed and measured. Such an accounting will require a system for measuring both structural and functional aspects of ecosystem integrity. This means that different measurement and diagnostic tools will need to be organized and managed within a holistic information system that combines an account of human pressures with spatial mapping.

Measures like Karr's IBI could provide a robust profile of both aquatic and terrestrial ecosystems based on a integrated biological monitoring and assessment accounting system. However, such systems will take years to develop and must be maintained through regular biological monitoring. Although progress has been made in developing aquatic IBIs, similar measures for terrestrial ecosystems are in their infancy. Other composite indicators like the ecological footprint are intuitively attractive and could be constructed with existing Statistics Canada data at a national and provincial scale and, in some cases, at the community or municipal scale. However, more work is needed to determine ecological carrying capacity.

There is no right or wrong approach to measuring ecosystem integrity given the complexity of dynamic living systems. Yet, practical steps can be taken and indicators developed to expand our knowledge of integrity. First, we can account for trends in human activity pressures and demands on ecosystems, including natural resource stocks and flows, and we can identify proxies for ecosystem conditions (e.g., air and water quality) at the national, provincial and eco-region scale. This could be done using existing natural resource and environment accounting systems being developed by Statistics Canada. Second, a commitment to ongoing ("real time") spatial imagery and analysis from satellite photography in GIS systems is required to generate colour-coded portraits of ecosystem health. Third, we need elegant composite indices like the IBI, ecological footprint or ecosystem health scorecards that take a complex array of information and distill it into a clear and meaningful indicator that all Canadians can comprehend and that is as significant a measure of ecosystem health as GDP is a measure of economic health.

Appendix A: James Kay's Ecosystem Evaluation System

Table 1: Kay's Ecosystem Approach to Evaluating Ecological Integrity

A. Define the ecosystem
- a. Hierarchy (the vertical perspective, what is a part of what?)
  - i. Define the nested holons (nested living systems); this defines the contextual relationships.
- b. Scale and extent (the horizontal perspective, where do things begin and end?)
  - i. What are the boundaries of observation?
  - ii. What are the processes that define the whole?
  - iii. What are the boundaries of the ecosystem, the holon of focus?
- c. Structure
  - i. The vertical and horizontal connections between holons.

B. Describe the ecosystem as a self-organizing entity
- a. Non-linear models: The synergistic relationships, the cycles, the feedback loops, virtual worlds.
- b. The attractors (organizational state) and their domains.
- c. What are the attractors?
  - i. In what direction will the ecosystem tend to develop? What are the propensities? (Self organization theory of dissipative structures helps answer this.)
- d. What is the behaviour of the ecosystem about the attractors?
  - i. Homeostatic, stable, figure eight, unstable but persists, chaotic?
- e. Are there bifurcation points?
- f. What are the potential flips between attractors?
  - i. What triggers the flips?
  - ii. How can we monitor for them?
- g. What is the interplay of energy, exergy, information and environmental conditions (in space and time), which shapes the ecosystem?
  - i. Think carefully about the figure eight, their scale and extent, the nested holons and their interactions and connections, the information available to the ecosystem, and the environmental conditions it must live with. (Ecological history and non-equilibrium thermodynamics help answer this.)

C. How do we evaluate integrity for this ecosystem?
- a. What states of ecosystem organization are acceptable to us?
- b. What are the ecological processes (at each level of nested levels) we value and/or need?
- c. How do we identify these?
- d. How do we measure the status of these processes? (This takes us back to step A above.)
- e. Which attractors represent unacceptable ecosystem conditions?

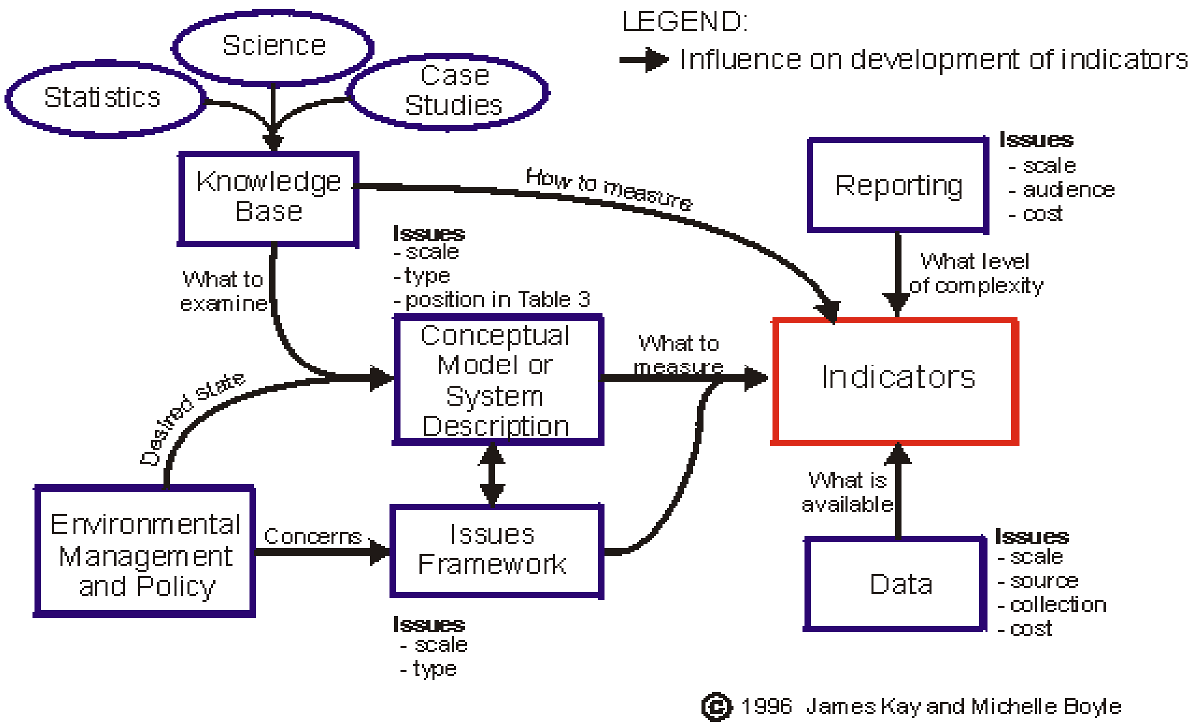
D. Is this integrity threatened?
- a. What external forces could affect the organizational status of the system?
- b. Use the nested ABCE methodology[60] to identify the external influences on the organization of the ecosystem (stress-response ecology).
- c. What are the thresholds of flips to the unacceptable attractors? (states of ecosystem organization)
- d. How do we monitor to make sure these thresholds are not crossed?

E. How do we maintain integrity in this system?
- a. How do we mitigate known threats?
- b. How do we promote positive influences (for example, fire in a prairie)
- c. How do we monitor the ecosystem so as to detect changes due to previously identified external influences?

F. How to deal with emergent complexity?
When all is said and done, our ability to predict is severely limited. Unexpected events and trends will occur. Surprise will happen, complexity will emerge. We must therefore rely on anticipatory and adaptive management. These are the challenges of a "system imbedded in another system, imbedded in another system" and the challenge of sustaining a dynamic, changing, evolving, self-organizing, self-entailing, adaptive system.

Source: Kay, James J. 1994. *Some notes on: The Ecosystem Approach, Ecosystems as Complex Systems and State of the Environment Reporting.* Accessed October 31, 2001 at www.fes.uwaterloo.ca/u/jjkay/pubs/nac/index.html

Figure 3: Indicator Development Within the Adaptive Ecosystem Approach[61]



Appendix B: Alberta GPI Natural Resource and Environmental Accounts

Table 2: Alberta GPI Natural Resource and Environmental Accounts

Alberta GPI Natural Resource and Environmental Accounts	**Sustainability Indicators**
Forests	• Timber sustainability index (ratio of annual growth to annual total of depletions) • Age-class distribution of forests (% of forest remaining that are "old growth") • Carbon sequestration rate of forest ecosystems
Agriculture	Agriculture Sustainability Index, a composite of the following parameters: a. Crop yields b. Soil erosion c. Salinity d. Pesticide/Herbicide use e. Irrigation f. Farm debt Also included are measures of organic agricultural land use and organic soil carbon (see carbon accounts)
Non-renewable resources (oil, natural gas, gas byproducts and coal)	• Conventional crude oil reserve life • Natural gas reserve life • Synthetic/bitumen crude oil (from oilsands) reserve life • Coal reserve life (sub-bituminous, bituminous)
Energy use intensity	• Energy use (GJ) • GHG emissions
Carbon budget	• Ratio of carbon dioxide emissions (all sources) to annual sequestration by forests, peatlands and agricultural soils.
Ecosystem integrity	• Forest fragmentation index (% of forest ecosystems that have a given degree of linear disturbance and industrial development) • Percentage of land and water that has been designated as parks, wilderness, "special places" or other designation
Biodiversity (fish and wildlife)	• Population levels of fish and wildlife species • Endangered species list
Wetlands	• Area of wetlands remaining of original (pre-settlement) area
Peatland	• Area of peatland • Peatland volume harvested • Carbon content of peatland
Water quality	Water quality composite index including: a) pulp effluent b) percent of municipal population with tertiary sewage treatment c) *Giardia* and *Cryptosporidium* cases d) long-term monitoring of dissolved oxygen,

Alberta GPI Natural Resource and Environmental Accounts	**Sustainability Indicators**
	nitrogen, phosphorus and fecal coliforms along six major Alberta rivers.
Air quality and emissions	• Percentage of increased risk of death for Edmonton and Calgary attributed to city-specific factors • Change in air pollution concentrations of carbon monoxide, nitrogen dioxide, sulphur dioxide and ozone
Toxic (hazardous waste)	• Volume of toxic releases and storage • Volume of toxic (hazardous) waste eliminated
Landfill waste	• Volume of waste to landfills • Percentage of landfill waste recycled
Ecological footprint	Ecological footprint per capita (the amount of land, water and other resources required to meet the current consumption demands of Albertans, also broken down by income group and major cities)

Endnotes

[1] *Background Paper on Indicators for Land and Soils CG3*, prepared for the National Round Table on the Environment and the Economy by Delaney and Associates, September 28, 2001.
[2] *A Proposed Framework for the Development of Environment and Sustainable Development Indicators Based on Capital,* prepared for the National Round Table on the Environment and the Economy by Robert Smith and Claude Simard, Environment Accounts and Statistics Division, Statistics Canada, and Andrew Sharpe, Centre for the Study of Living Standards, January 2001.
[3] *Technical Guidelines for Indicator Selection*, prepared for the National Round Table on the Environment and the Economy by Alice Born, Claude Simard and Robert Smith, Statistics Canada, October 2001.
[4] *Ecological Integrity: Integrating Environment, Conservation, and Health*, D. Pimentel, L. Westra and R. Noss (eds.), Island Press, Washington, DC, 2000.
[5] Boyle, M. 1998. *An Adaptive Ecosystem Approach to Monitoring: Developing policy performance indicators for Ontario Ministry of Natural Resources.* Thesis document in fulfillment towards a Master in Environmental Studies, University of Waterloo. Available at http://ersserver.uwaterloo.ca/jjkay/gard/mboyle/th_pdf.html
[6] Kay, J.J. 1994. *The Ecosystem Approach, Ecosystems as Complex Systems and State of the Environment Reporting.* Available at www.fes.uwaterloo.ca/u/jjkay/pubs/nac/index.html
[7] *Background Paper on Indicators for Land and Soils CG3*, prepared for the National Round Table on the Environment and the Economy by Delaney and Associates, September 28, 2001.
[8] *A Proposed Framework for the Development of Environment and Sustainable Development Indicators Based on Capital,* prepared for the National Round Table on the Environment and the Economy by Robert Smith and Claude Simard, Statistics Canada, Environment Accounts and Statistics Division, Statistics Canada, and Andrew Sharpe, Centre for the Study of Living Standards, January 2001.
[9] *A Proposed Framework for the Development of Environment and Sustainable Development Indicators Based on Capital,* prepared for the National Round Table on the Environment and the Economy by Robert Smith and Claude Simard, Statistics Canada, Environment Accounts and Statistics Division, Statistics Canada, and Andrew Sharpe, Centre for the Study of Living Standards, January 2001.
[10] *A Proposed Framework for the Development of Environment and Sustainable Development Indicators Based on Capital,* prepared for the National Round Table on the Environment and the Economy by Robert Smith and Claude Simard, Statistics Canada, Environment Accounts and Statistics Division, Statistics Canada, and Andrew Sharpe, Centre for the Study of Living Standards, January 2001.
[11] Personal conversation with Dr. James Karr, University of Washington, Seattle, Washington, September 21, 2001.
[12] *Webster's New World Dictionary*, Second College Edition, Prentice Hall Press, 1986, 645 pp.
[13] Karr, J.R. 2000. "Health, Integrity, and Biological Assessment: The Importance of Measuring Whole Things," in D. Pimentel, L. Westra and R. Noss (eds.), *Ecological Integrity: Integrating Environment, Conservation and Health*. Island Press, Washington, DC, pp. 209-226.
[14] Constanza, R. 1992. "Toward an operational definition of ecosystem health," in R. Constanza, B.G. Norton and B.D. Haskell (eds.), *Ecosystem Health: New Goals for Environmental Management*, Island Press, Washington, DC, pp. 239-256.
[15] Ulanowicz, R.E. 2000. "Toward the Measurement of Ecological Integrity," in D. Pimentel, L. Westra and R. Noss (eds.), *Ecological Integrity: Integrating Environment, Conservation and Health*, Island Press, Washington, DC, pp. 99–113.
[16] Ulanowicz, R.E. 2000. "Toward the Measurement of Ecological Integrity," in D. Pimentel, L. Westra and R. Noss (eds.), *Ecological Integrity: Integrating Environment, Conservation and Health*, Island Press, Washington, DC, pp. 99-113.
[17] Karr, J. 2000. "Health, Integrity, and Biological Assessment: The Importance of Measuring Whole Things," in D. Pimentel, L. Westra and R. Noss (eds.), *Ecological Integrity: Integrating Environment, Conservation and Health,* Island Press, Washington, DC, pp. 209-226.
[18] Personal e-mail of November 3, 2001, from James Karr to Mark Anielski.
[19] An important transdisciplinary dialogue is emerging among ecologists, ecological economists and epidemiologists about the issue of ecological integrity (see *Ecological Integrity: Integrating Environment, Conservation, and Health,* D. Pimentel, L. Westra and R. Noss [eds.], 2000, Island Press, Washington, DC). Ecologists like James Kay, James Karr, Ellen Chu, Robert Ulanowicz, Oulie Loucks, Peter Miller, Mark Sagoff, Bill Rees and others (who are contributing authors to the aforementioned book *Ecological Integrity*) have contributed a timely wealth of knowledge to the debate about how to measure ecological integrity.
[20] Kay, J.J. 1994. *Some notes on: The Ecosystem Approach, Ecosystems as Complex Systems and State of the Environment Reporting*. Accessed October 31, 2001 at www.fes.uwaterloo.ca/u/jjkay/pubs/nac/index.html

[21] Kay, J.J. 1994. *Some notes on: The Ecosystem Approach, Ecosystems as Complex Systems and State of the Environment Reporting*. Accessed October 31, 2001 at www.fes.uwaterloo.ca/u/jjkay/pubs/nac/index.html
[22] Holling, C.S. 1986. "The Resilience of Terrestrial Ecosystems: Local Surprise and Global Change," in *Sustainable Development in the Biosphere*, W.M. Clark and R.E. Munn (eds.), Cambridge University Press, Cambridge, pp. 292–320.
[23] Kay, J.J. 1994. *Some notes on: The Ecosystem Approach, Ecosystems as Complex Systems and State of the Environment Reporting*. Accessed October 31, 2001 at www.fes.uwaterloo.ca/u/jjkay/pubs/nac/index.html
[24] Kay does not provide a reference for Rubec and Marshall.
[25] World Wide Fund for Nature. 2000. *Living Planet Report 2000*, Gland, Switzerland.
[26] See www.wri.org/wri/wr2000/scorecard.html accessed September 14, 2000.
[27] Boyle, M. 1998. *An Adaptive Ecosystem Approach to Monitoring: Developing policy performance indicators for Ontario Ministry of Natural Resources*. Thesis document in fulfillment towards a Master in Environmental Studies, University of Waterloo. Available at http://ersserver.uwaterloo.ca/jjkay/gard/mboyle/th_pdf.html
[28] *Background Paper on Indicators for Land and Soils CG3*, prepared for the National Round Table on the Environment and the Economy by Delaney and Associates, September 28, 2001.
[29] Woodley, S. 1997. *Developing Indicators of Ecological Integrity for Canadian National Parks*. Paper presented at the Third National Science Meeting: The Ecological Monitoring and Assessment Network, Saskatoon, Sask., January 21–25.
[30] Weins, T. 1997. *Constructing a Meaningful Prairie Habitat Indicator*. Paper presented at the Third National Science Meeting: The Ecological Monitoring and Assessment Network, Saskatoon, Sask., January 21–25.
[31] An agroecosystem habitat monitoring system would tell us how much habitat there is in agricultural areas, where it is, and how it is being used or changed. From Weins' analysis he notes that the total area of agricultural land in Canada has remained relatively stable since the 1970s, while the amount of quality wildlife habitat has decreased.
[32] Wrona, F.J., Cash, K.J., and Gummer, Wm. 1997. *Development of an Integrated Framework for Ecosystem Indicator Selection Management: The Northern River Basins Study as a Case Example*. Paper presented at the Third National Science Meeting: The Ecological Monitoring and Assessment Network, Saskatoon, Sask., January 21–25.
[33] Schindler, D. 1997. *What and Why and Where Should We Monitor? Twenty-Nine Years of Ecological Monitoring and Assessment at the Experimental Lakes Area*. Paper presented at the Third National Science Meeting: The Ecological Monitoring and Assessment Network, Saskatoon, Sask., January 21–25.
[34] Indicators include lake temperature, nitrogen, phosphorus, silica and DOC (dissolved organic carbon) used to monitor the integrity or health of these benchmark aquatic systems.
[35] Personal conversation with Dr. Stan Boutin, professor of forest ecology, University of Alberta, November 1, 2001.
[36] http://eqb-dqe.cciw.ca/eman/emi/intro.html
[37] http://eqb-dqe.cciw.ca/eman/research/trends/intro.html
[38] For example, EMAN includes a "frogwatch" and "wormwatch" monitoring system. The actual EMAN database will be dispersed and as up to date as participants make it.
[39] Personal discussions with Josef Cihlar, Natural Resources Canada, October 23, 2001. The satellite mapping (Landsat) and remote sensing (e.g., CGDI [Canadian Geospatial Data Infrastructure] and GeoGratis [free satellite and other geospatial data])[39] being developed Natural Resources Canada should also yield data to construct profiles of ecosystem integrity by tracking changes in land cover. Land cover is often a key determinant of biodiversity.
[40] Karr, J.R. 2001. "What from ecology is relevant to design and planning?" in B. Johnson and K. Hill (eds.), *Ecology and Design: Frameworks for Learning*, Island Press, Washington, DC, pp. 133–172.
[41] Personal conversation with Dr. James Karr, University of Washington, Seattle, Washington, September 21, 2001.
[42] Karr, J. 1981. "Assessment of biotic integrity using fish communities," *Fisheries* 6(6): 21–27.
[43] Loucks, O. 2000. "Pattern of Forest Integrity in the Eastern United States and Canada: Measuring Loss and Recovery," in D. Pimentel, L. Westra and R. Noss (eds.), *Ecological Integrity: Integrating Environment, Conservation and Health*, Island Press, Washington, DC, pp. 177–190.
[44] Personal conversation with Dr. Stan Boutin, professor of forest ecology, University of Alberta, November 1, 2001. Scientists in Alberta have begun developing a biodiversity monitoring system that examines different forms of diversity of Alberta forest ecosystems first in terms of structure and eventually in terms of functions (productivity). The Alberta initiative involves remote sensing to examine habitat configuration changes due to land use and human disturbance patterns. Scientists are examining and critiquing several potential indicators of boreal forest integrity, short-listing indicators and working towards a key set of indicators that reflect determinants of boreal forest integrity. This process involves a "dose-response" approach of examining trends in human disturbance "loading" in boreal forest ecosystems, such as seismic lines, roads and habitat conversion, and their measurable impact on key

indicators of boreal forest ecosystem integrity. This work is in the early stages but is expected to provide important key indicators (roughly 30) for long-term biological monitoring combined with spatial analysis from aerial and satellite imagery of linear disturbance. The Alberta initiative is examining the breadth of diversity of taxa and thus is taking a whole-systems approach to measurement. While the Alberta biological integrity measurement initiative is initially focused on indicators of ecosystem structural integrity, there is an expectation that functional integrity could eventually be measured in terms of indicators of productivity, similar to those being developed by Loucks in the U.S. It would appear that Alberta is leading the country in this important area of research.

[45] Personal conversation with Dr. James Karr, University of Washington, Seattle, Washington, September 21, 2001.

[46] Loucks measured these functions in three U.S. forest ecosystem case studies, assessing how each measure responded to natural stressors like fire or clearcutting and human disturbance.

[47] More scientific research is undoubtedly needed to create the kinds of benchmarks that the IBI of Karr and the MFI of Loucks demand. Operationalizing these intuitively attractive multi-variable metrics will also require a sustained commitment to spatial/satellite imagery and analysis of ecosystem disturbance trends as well as the on-ground biological assessment and monitoring, consistently applied across similar ecosystems in North America.

[48] Committee on the Status of Endangered Wildlife in Canada (COSEWIC), April 1999 and May 2000. *Canadian Species at Risk.*

[49] Wackernagel, M., and Rees, W.E. 1996. *Our Ecological Footprint: Reducing Human Impact on the Earth*, New Society Publishers, Gabriola Island, BC, ISBN-1-55092-521-3.

[50] World Wide Fund for Nature. 2000. *Living Planet Report 2000*, www.panda.org/livingplanet/lpr00/ecofoot.cfm accessed October 24, 2000.

[51] Rees, W.E., and Wackernagel., M. 1994. “Ecological Footprints and Appropriated Carrying Capacity: Measuring the Natural Capital Requirements of the Human Economy,” in A-M Jannson, M. Hammer, C. Folke and R. Costanza (eds.), *Investing in Natural Capital: The Ecological Economics Approach to Sustainability*, Island Press, Washington, DC, pp. 362-390.

[52] Vitousek, P.M., Ehrlich, P.R., Ehrlich, A.H., and Mateson, P.A. 1986. “Human appropriation of the products of photosynthesis,” *BioScience* 34 (6): 368-373.

[53] Rees, W.E. 2000. “Eco-footprint analysis: merits and brickbats,” Commentary Forum: The Ecological Footprint, *Ecological Economics* 32: 391–394.

[54] Rees, W.E. 2000. “Eco-footprint analysis: merits and brickbats,” Commentary Forum: The Ecological Footprint, *Ecological Economics* 32: 391–394.

[55] Van den Bergh and Verbruggen (1998) have several objections to the ecological footprint. First, they argue that the EFA requires a conversion of consumption to land area equivalents that is “necessarily incomplete, rough, based on sometimes arbitrary data, while no account is taken of regional and local features of land types and land use.” Second, the EF does not distinguish between sustainable and unsustainable use of land. They argue that indicators such as the EF should reflect the quality and quantity of renewable resources and be related to some measure of safe margins or threshold values of sustainability. Third, they are uncomfortable with the measurement and aggregation procedure used to address environmental impacts associated with energy use. They object to the simple treatment of energy land footprint analysis. Fourth, they object to the “arbitrariness of the spatial scale at which the EF is calculated.” Finally, they feel the EF may not be the ideal planning tool to translate sustainability concerns into public action as Wackernagel and Rees (1996) have suggested given the concerns with arbitrary weighting and aggregation procedures. Many of these criticisms may be valid; however, they also point to improvement in the EF process and not to a full-scale abandonment of the tool in assessing sustainability and human impacts on ecological integrity.

[56] Rees, W.E. 2000. “Eco-footprint analysis: merits and brickbats,” Commentary Forum: The Ecological Footprint, *Ecological Economics* 32: 391–394.

[57] Rapport, D.J. 2000. “Ecological footprints and ecosystem health: complementary approaches to a sustainable future,” Commentary Forum: The Ecological Footprint, *Ecological Economics* 32: 367–370.

[58] Deutsch, L., Jansson, A., Troell, M., Rönnbäck, P., Folke, C., and Kautsky, N. 2000. “The ‘ecological footprint’: communicating human dependence on nature’s work,” Commentary Forum: The Ecological Footprint, *Ecological Economics* 32: 351–355.

[59] Deutsch et al. note that EF methodology provides only a snapshot of the demand for nature’s services by people. Deutsch et al. take an intuitively attractive approach to accounting for the biophysical services appropriated annually from ecosystems by an average person for their social and economic well-being. The services they track are for timber and terrestrial food production, which includes the storage of carbon, phosphorus and nitrogen, as well as the freshwater requirements needed to generate these services.

[60] See Kay, J.J. 1994. *Some notes on: The Ecosystem Approach, Ecosystems as Complex Systems and State of the Environment Reporting* Accessed October 31, 2001 at www.fes.uwaterloo.ca/u/jjkay/pubs/nac/index.html

[61] Boyle, M., and Kay, J. 1996. *Supplementary Appendices to State of the Landscape Reporting: A background literature review and database on monitoring and indicators*, prepared for the Ontario Ministry of Natural Resources. See also Boyle, M. 1998. "An Adaptive Ecosystem Approach to Monitoring: Developing Policy Performance Indicators for Ontario Ministry of Natural Resources," Masters' Thesis, Department of Environment and Resource Studies, University of Waterloo. http://www.fes.uwaterloo.ca/u/jjkay/about/ecosys.html