ELSEVIER

Ecological Indicators 6 (2006) 6–23

ECOLOGICAL INDICATORS

This article is also available online at:
www.elsevier.com/locate/ecolind

Network perspectives on ecological indicators and actuators: Enfolding, observability, and controllability

Bernard C. Patten

Institute of Ecology, University of Georgia, Athens, GA 30602, USA

Abstract

The subject of ecological indicators is both complex and technical. Indicators are low signal/noise read-outs from systems reflecting deeply embedded processes. Informal, single factor indicators reflect superficial properties. Complex systems require formal, multifactorial measures. Conceptual basis, importance and bandwidth of variables, reliability and statistical properties, data and skill requirements, data quality and archiving, robustness under technology change, and cost/benefit issues are factors in indicator design.

Network models enable formalism to be brought to the indicator problem. Networks are oriented in time-forward and reverse directions, giving rise to environs. Output environs span network flows derived from inputs, and input environs encompass flows leading to outputs. Both have mathematical descriptions. Variable embedding is a key difficulty in defining and interpreting indicators. Formally, all system energy and matter flows are enfolded within each empirical stock and flow. Embedding in output flows is the source of low signal/noise ratios of indicators. Network enfolding is a powerful expression of systemic holism and the source of what is termed the ‘‘indicator problem’’.

Observability and controllability are formal system properties related, respectively, to indication and its reciprocal, actuation. These are defined and illustrated for simple cases. Composite systems have mixed controllable (c), observable (o), uncontrollable (c′), or unobservable (o′) elements, in four possible combinations—(c, o), (c, o′), (c′, o), and (c′, o′). To exert control based on indicators, what available indicators indicate must be matched to what available actuators actuate. That is, (c, o) sectors must jointly be in output environs of manipulated inputs and input environs of indicator outputs—the relevant environs must intersect.

If S_a is a linear system to be controlled and S_b a linear controller, theory gives that if S_a and S_b are individually controllable (c) or observable (o), then any uncontrollable (c′) or unobservable (o′) elements of the control system $S_aS_bS_a\ldots$ will always be in S_b, never in S_a. This means the system to be controlled can be ignored as a source of c′ or o′, and improved control can be sought exclusively within the management system, S_b. Though this is limited to linear systems, it illustrates how formal theory can help structure the indicator problem and its relationship to management. A wildlife management (deer) example is discussed both without and with modeling incorporated into S_b.

Application of ecological indicators to monitor and manage complex systems is a difficult technical problem. Guidance from formal theory can help clarify its technical dimensions.

Keywords: Indicators; Actuators; Network perspectives

E-mail address: bmpatten@earthlink.net.

1470-160X/$ – see front matter
doi:10.1016/j.ecolind.2005.08.002

1. Nature of ecological indicators

Ecological indicators are scientific variables designed to give quick and easily acquired information reflecting the state of ecological systems in terms meaningful to the assessment of their health, vitality, sustainability, ability to provide resources or needed services or perform needed functions, and other characteristics. Indicators may give information about existing conditions, and also, over time, about changes and trends. Indicators are needed because it is not possible to measure everything about a system. Indicators may be qualitative or quantitative. A general definition taken from the Internet is: *ecological indicator*—"a characteristic of the environment that, when measured, quantifies magnitude of stress, habitat characteristics, degree of exposure to a stressor, or ecological response to exposure. The term is a collective term for response, exposure, habitat, and stressor indicators" (http://www.sciencedictionary.org/other-science-term-details/Ecological-Indicator).

1.1. The indicator problem—"embedding"

Organisms individually, and also their populations, communities, and ecosystems, must withstand stresses from a great variety of natural and human, physical, chemical, and biological, causes. When these stresses are intense enough to produce adverse states, ecological processes may become disrupted or unbalanced. Indicators are needed to relate the nature and extent of dysfunction, and appropriate avenues for mitigation (Rapport, 1992; Regier, 1992; Reid et al., 1992). Development of information about indicators typically requires sustained environmental monitoring (Griffith and Hunsaker, 1994). Monitoring over time can help determine the onset of problems ("early warning"), whether or when, and what kind, of action should be taken, and how successful previous actions have been. The problem with environmental monitoring, however, is that indicator variables are output signals from complex ecosystems arising from processes deeply embedded within the systems whose status they are intended to reveal. The signal-to-noise ratio is inherently low, the signal components being masked by complexity. To bring embedded variables to the surface as meaningful indicators with signal/noise ratios high enough to provide reliable and sufficient information is a difficult technical problem. The purpose of this paper is to consider some of the dimensions of this problem.

1.2. Discrete, informal indicators

Human use of biological indicators probably traces back to ancient times when correlations between biota and specific conditions were noted. From the time when plants and animals were first employed to signal harmful environmental conditions, indicators were anecdotal quantities. When a canary in a cage died in a mine, or fish died off in a lake, the signal was clear that something was wrong although the exact cause (anoxia, toxic substance, etc.) may initially not have been. Early choice of indicators was informal, based on experience, or other criteria related to the system and interests in question.

Informal indicators may be extremely simple and based on direct observations. The Kansas (USA) Department of Health and Environment (*Notes for Water Watchers*, December, 1993; Revised October, 1997) lists some typical examples: absence of lightning bugs and paucity of insects around street-lights or on automobile windshields may indicate toxic chemical contamination. If fruit does not ripen correctly it may signify pesticide contamination. Blue–green algae blooms in water bodies indicate pollution from exogenous sources. In the abiotic realm, jet aircraft vapor trails are larger, more "fluffy", and more persistent in dirtier air, and smog is a well-known "broad-band" indicator of air pollution.

Such informal indicators often do not give accurate specification of the exact causes of deleterious conditions. To that extent ("canary alarms" as a type notwithstanding) they are only weak as signals, more or less fortuitously chosen, emanating from deeper processes within. A next step toward development of more comprehensive diagnostic criteria was to engage a broader set of variables. Use of taxonomic or functional groups instead of individual species was adopted as a bioindicator approach (Harrison, 1976). Diatom assemblages (Dixit et al., 1992), algae in general (Shubert, 1984), invertebrates, and earthworms in reference to soil quality (Stork and Eggleton, 1992; Ebing et al., 1984; Paoletti et al., 1991), honeybees for monitoring pollutants (Bromenshenk,