REALLY USEFUL CONCEPTUAL MODELS: METAPHORS, CENSORSHIP AND NEGOTIATED KNOWLEDGE

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What is a conceptual model?

- There is no sense in which science can be said to be equivalent with reality. It must be perpetually a picture or model of reality. Quantification is the scientific process of building a metaphoric or conceptual basis for understanding the complexities of reality.

- Conceptual models are then simply socially negotiated pictures of the universe that inform the ongoing life of society (Christie 1990).

- **Concept** defined by Webster as
  
  “A general understanding derived from specific information”

- **Model** defined by Webster as
  
  “a small object usually built to scale that represents another often larger object” or “a tentative description of a system that accounts for all its known properties.”

- Thus, a **conceptual model** can be operationally defined as
  
  “a generalized reduced-form description of the structure and function of a larger system that is excogitated from scale-dependent information (Plumb 2003)”

  “a visual or narrative summary that describes the important components of an ecosystem and the interactions among them (NPS 2003)”

How does one devise a useful conceptual model?

- Regardless of the format (table, schematic, narrative), developing a conceptual model involves selecting a particular abstraction of reality and fitting our reliable knowledge into that construct or picture.

- One must first identify the intended outcomes of using the conceptual model and then employ basic guiding principles of **relevance**, **reliability**, and **censorship** to devise a model or series of models that efficiently achieves the objective.
Relevance: Conceptual abstraction must be relevant to audience and scale.

Audience: Decide if the purpose of the conceptual model is to inform or influence, or both.

Scale: It is crucial to be able to identify the spatial and temporal scales that are of interest and relevant to outcomes.

Reliability: Conceptual abstraction must be underpinned with reliable knowledge.

Censorship: Conceptual abstraction must avoid over-simplification or oversophistication.

- Employ a deliberate step-wise conceptual model formulation process (adapted from Grant et al. 1997).

| 1. State the model objectives. |
| 2. Bound the system of interest. |
| 3. Categorize discrete model components within the system of interest. |
| 4. Articulate the relationships among the components of interest. |
| 5. Represent the conceptual model. |
| 6. Describe the expected pattern of model behavior. |

What does the NPS Vital Signs Monitoring Program need from conceptual models?

Primary outcomes include both knowledge and action:

1. Comprehend the relevant structure and function of multiple levels of ecological organization of important park ecosystems (Knowledge).

2. Translate understanding of ecological organization through deliberate and transparent decision support systems to identify the vital signs (ecological indicators) of environmental health in parks (Action).

3. Comprehend the range of natural (e.g. evolutionary) variability and ecological thresholds of dynamic “vital” ecological parameters (Knowledge).

4. Translate understanding of thresholds of natural variability into deliberate and transparent long-term monitoring protocols capable of adequately detecting important departures from natural range of variability (Action).

5. Comprehend the range of anthropogenic-induced ecosystem variability that overlays the range of natural (e.g. evolutionary) variability and ecological thresholds of dynamic “vital” ecological parameters (Knowledge).
6. Translate understanding of anthropogenic-induced ecosystem variability into deliberate and transparent adaptive management alternatives for park managers to attempt mitigation (Action).

**What types of conceptual models are there?**

*Narrative conceptual models* are generally articulated in alpha & numeric form as informal or formal hypotheses, in a few sentences, formulae, or combinations of both. Extended narrative (e.g. single or multiple paragraphs) invariably encompass multiple tiered or linked conceptual models.

Example of informal narrative conceptual model:

“Wolves in Yellowstone National Park, along with other carnivores, will regulate elk at lower density than during the previous wolf-free period, resulting in a “trophic cascade” of top-down effects on herbivores and vegetation (Boyce 1999).”

Example of formal narrative conceptual model:

Wolf numerical response

H1: Wolf population density in Yellowstone National Park will be limited by preferred prey biomass. Alternatively, wolf density might be limited by total prey biomass, territoriality or disease. $W = fn(N, W, D)$ where $W$ is the number of wolves, $N$ is the number of elk, $D$ is disease prevalence, and $fn$ is the functional response of wolf population density (Boyce 1999).

*Tabular conceptual models* generally present an array of ecosystem components in some form of a row-column structure, and can vary in complexity depending on the absolute number of cells presented (see Figure 2 and 3). In Figure 2, Heathcote (1998) utilizes a standard row-column format with cell-embedded symbols to convey the proposed relative importance of a series of anthropogenic effects on an array of ecosystem elements, components, and levels of organization. This tabular conceptual model captures a large amount

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**Figure 1.** Example of a formal equational narrative conceptual model.

$$m(C) = \frac{\sum_{i=1}^{k} m_1(A_i) \cdot m_2(B_k)}{1 - \sum_{i=1}^{k} m_1(A_i) \cdot m_2(B_k)} \times \begin{cases} 1 & \text{when } A_j \cap B_k = C \\ 0 & \text{when } A_j \cap B_k = \emptyset \end{cases}$$

where $m_1$, $m_2$ and $m(C)$ are, respectively, basic probability assignments for focal elements $A_j$, $B_k$ and combined evidential support for the subset $C$ over the same frame of discernment. In this case, the theory of evidence (Shafer, 1976) also provides us the following relationships:

\begin{align*}
\text{Belief}\{S\} &= m(S) \\
\text{Belief}\{S'\} &= m(S') \\
\text{Ignorance} &= m(S, S') = 1 - m(S) - m(S')
\end{align*}

**Figure 2.** Example of tabular conceptual model (Heathcote 1998).
of hypothetical information about the relationships between human activities and inherent ecosystem structure and function, but does not allow the user to understand assumptions of linearity or anything about scale-dependent feedback responses that could modify either human activities or ecosystem integrity.

In Figure 3, the tabular conceptual model of Williams et al. (1997) does not utilize a strictly defined row-column structure or any symbolism as described above. Rather, this model purports to represent generic ecosystem functioning (including both terrestrial and aquatic) by five primary classes of ecosystem “factors” that reflect some, but not necessarily complete, information about ecosystem structure, interactions, and temporal variability. Although this model varies in construct from Heathcote (1998), it likewise does not allow the user to understand assumptions of linearity or anything about scale-dependent feedback responses that could modify either human activities or ecosystem integrity.

Schematic conceptual models come in a seemingly unending, and sometimes alarming, variety; but for our purposes can be generally classified as 1) picture models, 2) box-arrow models [state-transition, hierarchical, input-output, and 3) matrix models.

Picture models are very illustrative and can be devised in most any configuration to represent any reduced-form abstraction across a variety of temporal and spatial scales. Five examples are presented below (Figure 3-7).

Figure 4. Example of a universal-scale picture conceptual model that describes all conceivable evolutionary states and pathways that can be reached from the present (Schellnhuber 1999).
Figure 5. Example of three axis ordination picture conceptual model that purports, without any reference to scale, to represent broad sweeping generalization about the temporal dynamics of ecosystem resilience and transition as a function of system connectedness and integrity (Gunderson and Pritchard 2002). This model allows the user to comprehend sweeping and broad theoretical concepts without bogging the user down with scale-dependent details.

Figure 6. A simple polygon-structured picture conceptual model that purports to represent functional habitat types within a generic Pacific coast watershed. The nested polygons confer an understanding that when planning for considering watershed restoration, management prescriptions will likely vary according to the ecological importance and value attached to the variety of habitats types. While this picture reaffirms the importance of recognizing variation in ecological importance, it does not provide any substantive understanding of scale-dependent variability of ecosystem structure and function (Adams 2002).

Figure 7. A X-Y axis picture conceptual model that purports to represent the dynamic tradeoffs between the scope of mechanistic understanding and significance of ecological phenomenon. The X axis is conceptualized along a L->R continuum of increasing ecological complexity and time; with the Y axis unlabeled but from B->T representing increasing level of knowledge.
Figur 8. Another X-Y axis picture conceptual model that purports to represent a two dimensional continuum time and space variability of key ecological components and processes. This type of conceptual model allows the user to quickly comprehend the difficult concept of time x space, but the user cannot understand how much of the model is based on strong mechanistic understanding or hypothetical projections (Gunderson et al. 1995).

Box-arrow conceptual models can also be presented in a variety of forms that can convey a variety of information of variable complexity. Three box-arrow conceptual models presented below (Figure 9-11) capture many of the preferable traits of such models.

Figure 9. A state-transition box-arrow conceptual model that is a classic reduced-form representation of the planetary ecology of Earth. This “wiring diagram of Earth is static and inconsistent and represents a tremendous level of censorship that cannot hope to allow the use to understand the effects of starfish population dynamics on the rise of atmospheric CO2 (Schellnhuber 2003).

Figure 10. A box-arrow reduced-form conceptual model that displays hypothetical details of some of the internal and external factors and their linkages and interactions that underpin the BICA system (Patten 2002). Although this model does not allow the user to understand scale-dependent spatial or temporal dynamics, it does reinforce the importance of activities in the surrounding and upstream watersheds.
**Input/Output - Matrix models** are only variations from box-arrow models, as there are box-arrow models with indications of in- and outputs. A model for energy flow in an oyster reef community (Kcal m⁻²d⁻¹) and storage (kcal m⁻²) (Figure 12) can be considered to be an input/output matrix model (Grant 1997) where the matrix has a direct causal flow or interaction from compartment J (column) to compartment I (row) while expressing the probabilities that a substance in J will be transferred to I in one unit of time.

**Input/output models** often use a symbolic language where rectangles represent state variables, parameters or constants are small circles, sinks and sources are clouds, flows are arrows, and rate equations connect state variables to the flows. Figure 13 describes the transfer of energy from herbivores to carnivores as a function of the # of both [sensu wolf numerical response described above by Boyce (1999)].
How can conceptual models meet the needs of the NPS Vital Signs Monitoring Program?

Desirable Characteristics of a Vital Sign / Indicator. The development of conceptual models of park ecosystems involves the identification, inclusion, and scale-dependent linking of system variables such as drivers, stressors, effects, attributes, metrics (NPS 2003); state variables, constants, auxiliary variables, material transfers, sources and sinks (Grant et al. 1997), and other variables, often in a hierarchal form. It has been suggested that the inclusion of variables into conceptual models can take two forms (Jorgensen 1988, Grant et al. 1997). The first involves inclusion of a limited suite of model variables as simple as possible and subsequent iterative addition of critical components that were initially overlooked. The other approach is to include virtually all model components that could possible have any importance and then delete the superfluous ones (Grant et al. 1997). Given the inherent levels of uncertainty in ecosystem modeling, it is often better to use a slightly more complex model than a too simple approach. The criteria used for inclusion or exclusion of conceptual ecosystem model variables, thus provides the pool of variables that is drawn upon for the selection of ecological indicators that possess the desirable characteristics described below. Indeed, the desirable characteristics of conceptual model variables must then underpin those of ecological indicators. Grant et al. (1997) suggests that conceptual model variables and components have the following desirable characteristics: 1) state variables should represent vertices of accumulation of resources within an ecosystem (e.g. energy contained in plants, herbivores, predators); 2) driving variables should affect but not be affected by the rest of the system (e.g. transfer of energy from the sun to plants defines season within a year); 3) constants should not vary under assumptions of the conceptual model (e.g. coefficients that are part of a rate equation); 4) auxiliary variables arise out of calculation and should represent explicit model concepts; 5) source and sink variables represent origin and termination points of material transfers (e.g. energy) into and out of a system; 6) material transfers should describe quantitatively the flow of material (e.g. energy) between two state variables, between a source and a state variable, or between a state variable and a sink.

Fancy (2003) recently described a suite of top-to-bottom hierarchal conceptual model components including: drivers/disturbances that exert major forcing of large-scale influences on natural systems; stressor/consequences that cause significant changes in ecological components, patterns and relationships in natural systems; ecological effects that are responses to drivers and stressors; attributes/indicators that are any information rich living or non-living feature of an ecosystem that may be independent or integrative and can be measured or estimated and that provide insights into the state of the ecosystem; measurements that are specific measures of an attribute or indicator. Fancy (2003) states that indicators is often used synonymously with vital sign and are a selected subset of the physical, chemical, and biological elements and processes of natural systems that are selected to represent the overall health or condition of the system, known or hypothesized effects of stressors, or elements that have important human values. Vital signs/Indicators may occur at any level of organization including landscape, community, population, or genetic levels, and may be compositional (referring to the variety of elements in a system), structural (referring to the organization or pattern of the system), or functional (referring to ecological processes)(Fancy 2003).

Thus, a “vital sign” is a variable that is selected from the larger pool of “candidate” indicators, and meets or exceeds a parsimonious suite of desirable characteristics that underpin decisive functionality, feasibility, informational power, and cost-effectiveness. The suite of criteria that optimally characterize a desirable vital sign is a topic that has been discussed widely in the
In 1998, a NPS vital signs monitoring workshop identified 12 desirable characteristics of a vital sign or ecological indicator for long-term ecological monitoring. A vital sign: 1) has dynamics that parallel those of the ecosystem or component of interest, 2) is sensitive enough to provide an early warning of change, 3) has low natural variability, 4) provides continuous assessment over a wide range of stress, has dynamics that are easily attributed to either natural cycles or anthropogenic stressors, 5) is sensitive enough to provide an early warning of change, 6) is distributed over a wide geographical area and/or are very numerous, 7) are harvested, endemic, alien, species of special interest, or have protected status, 8) can be accurately and precisely estimated, 9) have costs of measurement that are not prohibitive, 10) have monitoring results that can be interpreted and explained, 11) are low impact to measure, and 12) have measurable results that are repeatable with different personnel (NPS 2003). Additionally, it has been acknowledged that a NPS vital sign should fit into one of three categories: a) those vital signs or indicators that are required to be included in a monitoring program for legal reasons (e.g. T&E species or items included in a park’s enabling legislation); b) those that are required for Performance Management reporting purposes or because funding was provided for a specific purpose (e.g. impaired waters monitoring); or c) those selected from a list of recommended vital signs or identified as a priority (NPS 2003).

Angermeier (1997) states that for assessment of biological integrity, the ideal biological indicator is: 1) easy to measure and interpret; 2) sensitive to human impact prior to severe ecological damage; 3) sensitive to a wide range of impact types and levels; 4) able to distinguish between natural variation and impact-induced variation; 5) applicable over multiple regions; 6) helpful in identifying the cause of an ecological problem; and 7) meaningful to the public. Because no single indicator can capture and reflect upon the inherent complexity of wild land ecosystems, efforts such as the NPS Vital Sign Monitoring Program recommend utilization of suites of indicators as described by (Karr et al. 1986, Karr 1987; Fausch et al. 1990). Thus, a suite of indicators of biological integrity should a) have broad sensitivity to human impacts; b) represent multiple levels of ecological organization such as individual, population, community or landscape; and c) reflect key elements and processes (Angermeier 1997).

The characteristics that define indicator suitability must also reflect the context and purpose of the monitoring effort. Kershner (1997) described three types of natural resource monitoring for watershed management. **Implementation monitoring** should ask whether park management (as defined by park objectives) is being implemented properly and is would be designed to continually evaluate whether stated park management objectives are designed appropriately. This type of monitoring would likely apply strongly to adaptive management programs, wherein park management decisions are based on incomplete knowledge but where midcourse corrections can be implemented to adjust management outcomes. **Effectiveness monitoring** is often referred to as trend monitoring and attempts to estimate change (variability) over time that is then translated into quantifiable understanding of whether resource condition objectives are being met. This type of monitoring often requires some understanding of the physical, biological, and sometimes social factors that underpin ecosystem structure and function. **Validation monitoring** reflects a research motivation and is designed to generate explicit quantification of basic assumptions behind effectiveness monitoring. Thus validation monitoring is a research tool to examine the fundamental understanding of ecosystem structure and function (Kershner 1997). Incorporation of both validation and effectiveness monitoring is a vital component of any park-based adaptive management program. The use of ecological indicators in natural resource monitoring were similarly identified by Dale and Beyeler (2001) to 1) assess the
condition of the environment (e.g. implementation monitoring); 2) diagnose the cause of environmental variability (e.g. validation monitoring); and 3) provide an early warning signal of changes in the environment (e.g. effectiveness monitoring).

Green (1979) described 10 principles of environmental field studies that can also be seen as guidelines for desirable characteristics of ecological indicators. Indicators should 1) be concise, coherent, and comprehensible; 2) be able to be measured through replicate sampling; 3) be representative (e.g. able to be measured with an equal number of randomly allocated replicate samples); 4) be able to demonstrate effect through comparison with a control; 5) be based on preliminary sampling that describe inherent variability; 6) describe what is being sampled with equal and adequate efficiency across the range of sampling conditions; 7) be applicable to a variety of scales of ecological organization; 8) be able to include appropriate size, density and distribution of samples; 9) be transparent so that data can be tested to see if error variation is homogenous, normally distributed, and independent of the mean; and 10) be sustainable and measurable over the long-term.

Dale and Beyeler (2001) state that a suite of ecological indicators should represent key information about ecosystem structure, function and composition. As Karr (1987) stated, Dale and Beyeler (2001) also propose that a suite of ecological indicators must capture the complexities of ecosystems but also remain simple enough to be routinely monitored. They recommend that the desirable indicators should: 1) be easily measured; 2) be sensitive to stresses on the system; 3) respond to ecosystem stressors in a predictable manner; 4) be anticipatory; 5) predict changes that can be averted by management action; 6) be integrative; 7) have a known response to disturbances, anthropogenic stressors, and changes over time; 8) have low response variability; 9) be able to provide information relevant to another scale; 10) transparently reflect management long-term goals and objectives; and 11) arisen from a deliberate and defined protocol for identification of indicators. Easily measured indicator metrics should be easy to understand, simple to apply, and provide information that is relevant, quantitatively sound, easily documented and cost-effective. E.g. the proverbial coal mine canary (Stork et al. 1997, Lorenz et al. 1999).

The desirable characteristics of an ecological indicator described by Dale and Beyeler (2001) above can be translated into more focused indicator titles as follows. Stress sensitive indicators should display high sensitivity to particular, and perhaps subtle, stressors, thereby serving as an early warning signal of reduced system integrity (Karr 1991). Stress predictable indicators should be unambiguous and predictable even if responding to gradual rates of stress. Anticipatory indicators should reflect a threshold response dynamic wherein an observed response occurs prior to an important reduction in system integrity (e.g. the canary should die before the miner). Predictive management indicators should be scale-dependent and reflect the real temporal and spatial scales of management capabilities. Predictive management indicators cannot anticipate ecological catastrophes such as volcanoes or hurricanes. Integrative indicators should behave predictably across appropriate scales and can be aggregated to provide assessment of multi-scale systems (Brooks et al. 1998). Mechanistic indicators have a known functional response to ecosystem disturbances and stressors. These indicators have been adequately studied and the mechanisms of ecosystem response are well known. Minimal variability indicators should have a small range of variability of response to known stressors that can be distinguished from inherent background ecosystem range of natural variability.
Revenga et al. (1998) have attempted to provide a quantitative basis for integrated conservation management so as to gauge the nature and patterns of threats to watershed globally. They analyzed data from 145 watersheds around the world and presented 15 indicators grouped into three main themes: Watershed value – fish species richness and endemism, endemic bird areas, aridity, population density, and water scarcity; Watershed condition – landscape modification, irrigated cropland, existing major dams, remaining original forest, extent of forest loss, and soil erosion from water; and Future Vulnerability – urban population growth, tropical deforestation, planned major dams, and level of protection. Although Revenga et al. (1998) did not explicitly describe the criteria or process they employed to identify and select these indicators, they clearly placed a higher value on indicators that are 1) measurable and based on some knowledge of the historic range of variability (e.g. forest cover, fish sp. richness, population growth); and 2) management relevance (e.g. proposed new dams, level of protection/management). It is unclear whether Revenga et al. (1998) examined monitoring feasibility, efficiency or sampling adequacy.

During the late 1990s, the Ecological Monitoring and Assessment Network (EMAN) of Canada spent considerable effort in developing a suite of core variables that can be utilized to monitor the condition of natural resources across Canada and provide early warning of ecosystem change (Environment Canada 2000). These “core variables” can be viewed synonymously with vital signs and so the criteria utilized by Environment Canadian should have applicability to NPS efforts. There are eight primary EMAN criteria for a vital sign: 1) addresses one or more environmental themes and issues; 2) monitoring data may be related to an ecosystem moving out of its normal range of resilience that may lead to degradation; 3) is sensitive; 4) integrates ecosystem stresses over space and time; 5) is sufficiently valid and accepted; 6) can be used over a wide range of climatic, soil, topographic and vegetation conditions; 7) is cost-effective; and 8) can be implemented by anyone with appropriate training and/or using a detailed protocol.

An assessment of biological indicators of aquatic ecosystem stresses led Adams (2002) to conclude that the term “ecological indicator” is too general and should be reduced to yield more appropriate specificity. Adams (2002) proposes that there is meaningful distinction between “biocriteria”, “biomarkers”, and “bioindicators.” A biocriteria is defined within the context of regulatory processes at the population or community level and could include indices of the numbers and kinds of organisms present in an aquatic system of interest such as an index of biotic integrity (IBI), stream condition index (SCI), invertebrate community index (ICI) or the biological monitoring working party score (BMWP). Biomarkers are considered as functional measures of exposure to environmental stressors that are usually expressed at suborganismal level of organization such as molecular, biochemical and even physiological endpoints (Adams 2002). Bioindicators are defined as either structural entities such as sentinel species (Van Gestel and Van Brummelen 1996), or they can be functionally biological endpoints at higher levels of organization (Adams 1990, Engle and Vaughn 1996). Adams (2002) suggests that the desirable characteristics of a biomarker or bioindicator are 1) sensitivity and specificity to stressors; 2) relationship to cause; 3) response variability; 4) temporal scales of response; and 5) ecological or biological significance, but that degree of relevance of these criteria varies between biomarker and bioindicator (Table xx1). Generally, increasing levels of biological organization result in decreasing mechanistic understanding but increasing levels of ecological relevance (Figure 1). Thus, Adams (2002) recommends that ultimately, long-term monitoring of ecosystems should include a selected suite of measures (e.g. vital signs) along the continuum of levels of ecological organization where meso-scale responses centered near the organismal level provides the central focus through which mechanistic understanding and ecological relevance can be coupled.
Recently, the U.S. Environmental Protection Agency’s Office of Research and Development published a suite of evaluation guidelines for ecological indicators (Jackson et al. 2000) that include 15 recommended guidelines (see Table xx2) for the identification and selection of relevant ecological indicators that are organized around four crucial questions: 1) Is the potential indicator relevant to management concerns and to the ecological resource or function at risk?; 2) Is the potential indicator sampling methodology feasible, appropriate, and efficient for use in a long-term ecological monitoring program?; 3) Are the errors of measurement and range of natural variability over the relevant temporal and spatial scales sufficiently understood and documented?; 4) Will the indicator convey information on ecological condition that is relevant to resource decision-making?. Kurtz et al. (2001) summarized that these EPS guidelines are intended to provide a flexible yet consistent framework for indicator review, comparison, selection, and to provide direction for research on indicator development. The EPA states that the guidelines should not be viewed as criteria that can determine indicator applicability or effectiveness. Rather, these 15 guidelines can provide a framework for asking relevant questions about indicator relevance, feasibility, variability, and utility. (Kurtz et al. 2001).

Applicability of Conceptual Models in the Near-term. In the very near-term, NPS networks need to be able to comprehend the relevant structure and function of multiple levels of ecological organization of important park ecosystems and translate this understanding of ecological organization into identification of vital signs (ecological indicators) through deliberate and transparent decision support systems to identify the state of environmental health in parks. To achieve these outcomes, conceptual models need to be viewed as problem solving vehicles underpinned by narrative literature review that provides the reliable knowledge basis for conceptual modelling. Further, a variety of conceptual models (narrative, tabular and schematic) will need to be developed and linked to deliberate and transparent decision support systems (DSS) that will allow the qualitative and quantitative information that can be derived from conceptual models to be processed (continuous or categorical filtering and rank-ordering) to generate suites of vital signs or ecological indicators. To date, no single vital sign selection DSS has been recommended by the NPS to meet all the needs of the various networks.

To assist users to understand the variability in usefulness of conceptual models, I employed a simple row-column tabular conceptual configuration in Table 1 below to present my understanding (according to a relativistic scale of low, medium and high) of how well seven types of conceptual models present meaningful information that can be used to address six NPS programmatic needs and 35 desirable characteristics of vital signs or ecological indicators. The information in Table 1 suggests that narrative and tabular conceptual models have the widest and schematic models have the narrowest applicability to address programmatic outcomes or desirable characteristics of vital sign criteria. Simple picture conceptual models have the power to convey broad and sweeping concepts but often fail to relate sufficient knowledge detail that can be directed at vital sign selection processes. Multiple-axis picture models seem to be reasonable good at presenting both general concepts as well as more detailed quantitative understanding of scale-dependent ecosystem temporal and spatial dynamics. In general, the array of box-arrow models seem to have only limited applicability to selection of vital signs. However, box-arrow hierarchical models seem to have strong intuitive appeal and applicability to the objective of comprehending the relevant structure and function of multiple levels of ecological organization of important park ecosystems. The utility of box-arrow hierarchical models for this objective is scale-dependent. If the modeler selects too fine or coarse a scale,
then the information presented may be irrelevant. By default then, a meso-scale will become the most utilitarian scale of such models. Tabular and narrative models, underpinned by narrative literature review, also seem to be able to convey the most important information and knowledge basis for evaluating potential vital signs against a suite of desirable criteria, regardless of whether the criteria relate to conceptual relevance, feasibility of implementation, response variability, or interpretation and utility.

Applicability of Conceptual Models in the long-term. In the long-term, we need to be able to 1) comprehend the range of natural (e.g. evolutionary) variability and ecological thresholds of dynamic “vital” ecological parameters and translate this understanding into deliberate and transparent long-term monitoring protocols capable of adequately detecting important departures from natural range of variability; and 2) comprehend the range of anthropogenic-induced ecosystem variability that overlays the range of natural (e.g. evolutionary) variability and ecological thresholds of dynamic “vital” ecological parameters and translate this understanding into deliberate and transparent adaptive management alternatives for park managers to attempt mitigation. These objectives will be driven primarily by quantitative information derived from field surveys and monitoring. However, since quantification is the process by which science tries to build a conceptual basis for understanding the complexities of reality, our quantification will always be imperfect. Hence, there will must be a long-term role and function for a full complement of conceptual models to project and comprehend the complexities of ecological thresholds and anthropogenic-induced ecosystem variability.

Literature Cited


Table 1. GRYN Coarse and Fine Filter Ecological Indicator Criteria

<table>
<thead>
<tr>
<th><strong>COARSE FILTER</strong></th>
<th><strong>CONCEPTUAL RELEVANCE</strong></th>
<th><strong>FINE FILTER</strong></th>
<th><strong>CONCEPTUAL RELEVANCE</strong></th>
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<tbody>
<tr>
<td>1. Indicator structural or functional dynamics reflects relevance to ecosystem or component of interest</td>
<td>1. Indicator is harvested, endemic, alien, species of special interest, or have protected status</td>
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<td>2. Indicator transparently reflects management long-term goals and objectives</td>
<td>2. Indicator is meaningful to the public</td>
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<td>3. Indicator applies to a variety of scales of ecological organization</td>
<td>3. Indicator is integrative</td>
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<td>4. Indicator provides relevant information that is applicable to multiple scales of ecological organization</td>
<td>4. Indicator is responsive to a relevant assessment question</td>
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<td>5. Indicator is applicable to both terrestrial and aquatic systems</td>
<td>6. Indicator is applicable to both terrestrial and aquatic systems</td>
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<tr>
<td><strong>FEASIBILITY OF IMPLEMENTATION</strong></td>
<td><strong>CONCEPTUAL RELEVANCE</strong></td>
<td><strong>FEASIBILITY OF IMPLEMENTATION</strong></td>
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<td>4. Indicator measurement is not cost prohibitive</td>
<td>7. Indicator monitoring methodology already exists in scientific literature</td>
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<td>5. Indicator measurement impacts must meet NPS standards</td>
<td>8. Indicator is distributed over a wide geographical area and/or is very numerous</td>
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<td>6. Indicator measurement can be sustained over the long-term</td>
<td>9. Indicator can be accurately and precisely estimated (low error) across a range of sampling conditions</td>
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<td>10. Indicator is easy to measure and has measurable results that are repeatable with different personnel</td>
<td>11. Indicator can be measured through replicate sampling with an equal number of randomly allocated replicate samples that are independent</td>
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<td>12. Indicator can be measured by appropriate size, density and distribution of samples</td>
<td>13. Indicator monitoring design and measurements are appropriate for the spatial scale of analysis</td>
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<td>14. Indicator data management and quality assurance will be compatible with existing relevant info mgt system standards</td>
<td>15. Indicator has a rapid indicator lag time indicative of changes in ecosystem integrity</td>
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<td><strong>RESPONSE VARIABILITY</strong></td>
<td><strong>CONCEPTUAL RELEVANCE</strong></td>
<td><strong>RESPONSE VARIABILITY</strong></td>
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<td>7. Indicator is anticipatory and is sensitive enough to provide an early warning of change</td>
<td>16. Indicator has low natural variability</td>
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<td>8. Indicator responds to ecosystem stressors in a predictable manner and has high signal-to-noise ratio</td>
<td>17. Indicator has low response variability</td>
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<td>18. Indicator is sensitive to small changes in the environment</td>
<td>19. Indicator response thresholds for system degradation are known</td>
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<td>20. Indicator is sensitive to a wide range of impact types and levels</td>
<td>21. Indicator is sensitive to stresses beyond historic range of variability</td>
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<td>22. Indicator provides continuous assessment over a wide range of impact types and levels</td>
<td>23. Indicator provides continuous assessment over a wide range of impact types and levels</td>
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<td>24.</td>
<td>Indicator has a known response to disturbances, anthropogenic stressors, and changes over time</td>
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<td>Indicator must exhibit significantly different responses among sites along a known condition gradient</td>
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<td>26.</td>
<td>For integrative indicators, response variability of multiple measurements should be adequate</td>
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<td>27.</td>
<td>Indicator data can be tested to see if error variation is homogenous, normally distributed, and independent of the mean</td>
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<td>28.</td>
<td>Indicator temporal response variability within and across years can be understood</td>
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<td>29.</td>
<td>Indicator spatial response variability is understood and can be partitioned</td>
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<tr>
<td>30.</td>
<td>Indicator historic databases are well established and baseline conditions are already known</td>
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<td>9.</td>
<td>Indicator is anticipatory of ecosystem degradation that can be mitigated by management action</td>
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<td>10.</td>
<td>Indicator responses and results are concise, coherent, and comprehensible</td>
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<td>11.</td>
<td>Indicator measurements and results can be clearly understood by scientists, publics, and policy makers</td>
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<tr>
<td>31.</td>
<td>Indicator is helpful in identifying the causal mechanism of an ecological response</td>
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<td>33.</td>
<td>Indicator responds to ecosystem stressors in a predictable manner with known statistical power and low chance of type 2 errors</td>
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<tr>
<td>34.</td>
<td>Indicator response dynamics can be distinguished between natural variation and anthropogenic impact-induced variation</td>
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<tr>
<td>35.</td>
<td>Indicator provides information relevant to another temporal or spatial scale</td>
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</table>
Table 2. Relativistic scoring of how useful eight types of conceptual models may be in presenting meaningful information that can be used to address six programmatic needs and 35 desirable characteristics of vital signs or ecological indicators.

<table>
<thead>
<tr>
<th>NPS Vital Signs Monitoring Program Outcomes (6)</th>
<th>Informal or Formal Narrative</th>
<th>Tubular</th>
<th>Picture x-y-z axis</th>
<th>Picture Simple</th>
<th>Box-arrow State-transition</th>
<th>Box-arrow Hierarchical</th>
<th>Box-arrow In-out / Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>33% H 67% M 0% L</td>
<td>83% H 17% M 0% L</td>
<td>33 % H 33% M 0% L</td>
<td>0% H 33% M 100% L</td>
<td>33 % H 33% M 33% L</td>
<td>17% H 33% M 66% L</td>
<td>83% M 17% M</td>
</tr>
<tr>
<td>1. Comprehend the relevant structure and function of multiple levels of ecological organization of important park ecosystems (Knowledge).</td>
<td>M M M L L L</td>
<td>H H M L L L</td>
<td>H H H L L M</td>
<td>M M M L L M</td>
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<tr>
<td>2. Translate understanding of ecological organization through deliberate and transparent decision support systems to identify the vital signs (ecological indicators) of environmental health in parks (Action).</td>
<td>H H H L L M</td>
<td>H H M L M L</td>
<td>H H M L M L</td>
<td>H H M L M L</td>
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<tr>
<td>3. Comprehend the range of natural (e.g. evolutionary) variability and ecological thresholds of dynamic “vital” ecological parameters (Knowledge).</td>
<td>M H H H L H M</td>
<td>H H H H L M L</td>
<td>M H H H L M L</td>
<td>M H H H L M L</td>
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<tr>
<td>4. Translate understanding of thresholds of natural variability into deliberate and transparent long-term monitoring protocols capable of adequately detecting important departures from natural range of variability (Action).</td>
<td>H H H H L M L</td>
<td>H H H H L L M</td>
<td>H H H H L L M</td>
<td>H H H H L L M</td>
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<tr>
<td>5. Comprehend the range of anthropogenic-induced ecosystem variability that overlays the range of natural (e.g. evolutionary) variability and ecological thresholds of dynamic “vital” ecological parameters (Knowledge).</td>
<td>M H H H H L H</td>
<td>M H H H H L M</td>
<td>M H H H H L M</td>
<td>M H H H H L M</td>
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<tr>
<td>6. Translate understanding of anthropogenic-induced ecosystem variability into deliberate and transparent adaptive management alternatives for park managers to attempt mitigation (Action).</td>
<td>M H H H H L H</td>
<td>M H H H H L M</td>
<td>M H H H H L M</td>
<td>M H H H H L M</td>
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</table>

<table>
<thead>
<tr>
<th>GRYN Fine Filter Vital Sign or Ecological Indicator Criteria</th>
<th>Informal or Formal Narrative</th>
<th>Tubular</th>
<th>Picture x-y-z axis</th>
<th>Picture Simple</th>
<th>Box-arrow State-transition</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>91% H 9% M 0% L</td>
<td>94% H 6% M 0% L</td>
<td>20% H 43% M 37% L</td>
<td>11% H 29% M 60% L</td>
<td>0% H 23% M 77% L</td>
<td>6% H 6% M 88% L</td>
<td>3% H 54% M 43% L</td>
</tr>
</tbody>
</table>

**Conceptual Relevance**

1. Indicator is harvested, endemic, alien, species of special interest, or have protected status | H H H L L L | M L |
2. Indicator is meaningful to the public | H H M L L M | L L |
3. Indicator is integrative | M M H M H L | L H |
4. Indicator provides relevant information that is applicable to multiple scales of ecological organization | M M M M M L | H M |
5. Indicator is responsive to a relevant assessment question | H H H H H L | M L |
6. Indicator is applicable to both terrestrial and aquatic systems | H H H H H L | L M |

**Feasibility of Implementation**

7. Indicator monitoring methodology already exists in scientific literature | H H H L L L | L L |
8. Indicator is distributed over a wide geographical area and/or is very numerous | M H M M M H | H L |
9. Indicator can be accurately and precisely estimated (low error) across a range of sampling conditions | H H M M M L | L L |
10. Indicator is easy to measure with results that are repeatable with different personnel | H H H L L L | L L |
11. Indicator can be measured through replicate sampling with an equal number of randomly allocated replicate samples that are independent

12. Indicator can be measured by appropriate size, density and distribution of samples

13. Indicator monitoring design and measurements are appropriate for the spatial scale of analysis

14. Indicator data management and quality assurance will be compatible with existing relevant info mgmt system standards

**Response Variability**

15. Indicator has a rapid indicator lag time indicative of changes in ecosystem integrity

16. Indicator has low natural variability

17. Indicator has low response variability

18. Indicator is sensitive to small changes in the environment

19. Indicator response thresholds for system degradation are known

20. Indicator is sensitive to a wide range of impact types and levels

21. Indicator is sensitive to stresses beyond historic range of variability

22. Indicator provides continuous assessment over a wide range of impact types and levels

23. Indicator is based on preliminary sampling that describes inherent variability

24. Indicator has a known response to disturbances, anthropogenic stressors, and changes over time

25. Indicator must exhibit significantly different responses among sites along a known condition gradient

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