Developing Conceptual Models for Monitoring Programs

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NPS Inventory and Monitoring Program

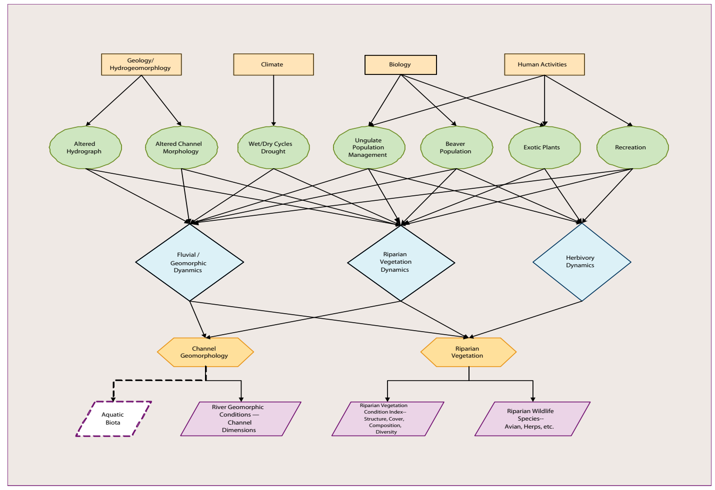
Introduction And Objectives

Environmental monitoring focuses on measuring resources over time, with the intent of providing data that reflect changes in the status or trends of the system or system components. Because environmental systems are inherently complex and managers are increasingly concerned with changes that occur over larger scales of space and time, conceptual models and diagrams are almost universally used to synthesize and communicate understanding of system dynamics, to identify key system components, and to communicate interactions between system components.

Given the complexity of natural systems and the huge variety of factors that influence natural processes, there is an obvious need for conceptual models that help organize information and make sense of system components and interactions. Failures in the development of major ecosystem monitoring programs have repeatedly been attributed to the absence of sound conceptual models that articulate key system components and their interactions (NRC 1995; Busch and Trexler 2003). The need for monitoring programs to develop useful conceptual models is clear, but the recognition of this need has not led to documentation of a simple process for constructing the necessary models. The goal of this document is to provide guidance that will facilitate creation of sound conceptual models to meet the needs of the NPS ecosystem monitoring programs.

Conceptual models are important throughout all phases of development of a monitoring program. Early in the process, simple conceptual models provide a framework that relates information in discussions and literature reviews to a broader context – it's a rack to hang things on. In some cases, the process of developing the models is more important than the actual model. Learning that accompanies the design, construction, and revision of the models contributes to a shared understanding of system dynamics and appreciation of the diversity of information needed

OVERVIEW



to identify an appropriate suite of ecosystem indicators. Wright et al. (2002) noted that the collaborative learning experience that accompanied development of the USFS LUCID program was an unanticipated and predominant activity that emerged as a tangible product of the process. The tangible contributions of conceptual models will vary with the maturity of the program, but a consistently important role of conceptual models is to improve understanding and communication. I believe that construction of conceptual models should be one of the first tasks in developing a monitoring program, and this should be undertaken even before an inventory of existing resources. The reason for this is simple: system models provide a context for organizing information and understanding. For complex systems, this context is essential. Most of us are unable to keep track of what's known and to understand why it's important without an integrating framework, and this framework is necessary to evaluate the importance of data from studies outside our area of expertise.

Conceptual models can thus:

- *Formalize current understanding of system processes and dynamics*
- *Identify linkages of processes across disciplinary boundaries*
- *Identify the bounds and scope of the system of interest*

and they contribute to communication

- *Among scientists and program staff*
- *Between scientists and managers*

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- *With the general public*

These roles are important throughout the life of a monitoring program. Once the program is underway, proper interpretation of indicators is greatly facilitated by sound and defensible linkages between the indicator and the ecological function or critical resource it is intended to represent (Kurtz et al. 2001). These key linkages should be explicit in conceptual models and their articulation is essential to justifying the measurements and its interpretation.

Conceptual models need to support goals of the NPS I & M program. The five NPS service-wide goals for the vital sign monitoring program are:

- *Determine status and trends in selected indicators of the condition of park ecosystems to allow managers to make better-informed decisions and to work more effectively with other agencies and individuals for the benefit of park resources.*

- *Provide early warning of abnormal conditions of selected resources to help develop effective mitigation measures and reduce costs of management.*

- *Provide data to better understand the dynamic nature and condition of park ecosystems and to provide reference points for comparisons with other, altered environments.*

- *Provide data to meet certain legal and Congressional mandates related to natural resource protection and visitor enjoyment.*

- *Provide a means of measuring progress towards performance goals.*

These goals will only be achieved by a monitoring program that is very well designed and that considers the full range of natural and human-caused variation. These goals relate to both the current status of the system, as well as future directions. Thus the models need to address system dynamics over time, as well as the appropriate spatial scales.

Conceptual Models for Monitoring Programs

Conceptual models can take the form of any combination of narratives, tables, matrices of factors, or box-and-arrow diagrams. Jorgensen (1988) discusses 10 kinds of models and evaluates their advantages and disadvantages. Most monitoring programs will use a combination of these forms, and it may occasionally be useful to combine several forms in the same figure (Figure 1).

> ***Conceptual models express ideas about components and processes deemed important in a system, document assumptions about how components and processes are related, and identify gaps in our knowledge – they are working hypotheses about system form and function (Manley et al. 2000, from others).***

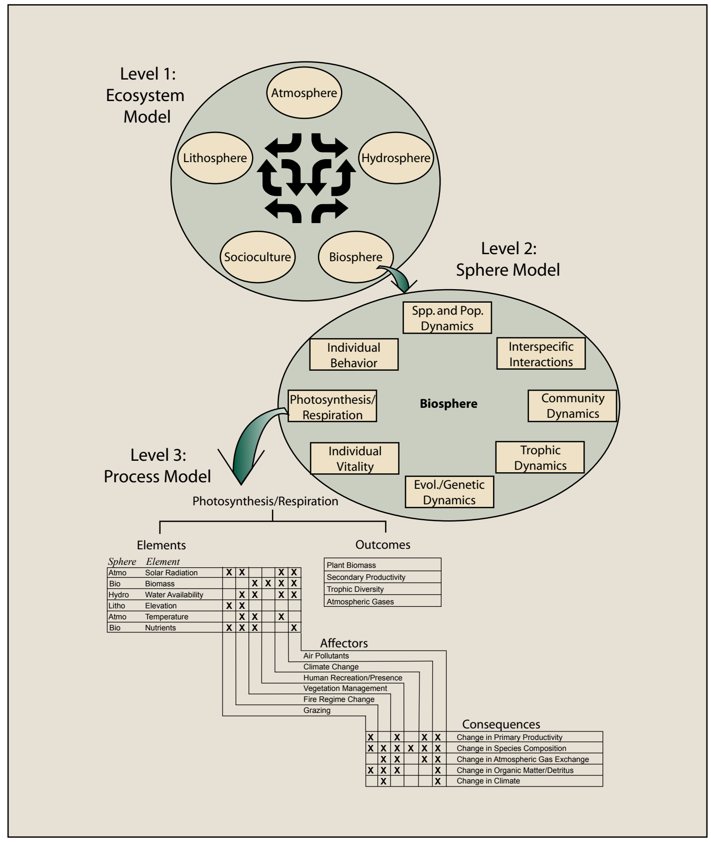

Figure 1. General ecosystem control model (after Manley et al. 2000).

Table and matrices provide a convenient means to summarize large quantities of information, including interactions between components. However, many people find it difficult to comprehend how a system works from tabulated data, especially where the spatial context is significant.

Diagrams are usually necessary to clearly communicate linkages between systems or system components. Most monitoring programs eventually end up with a set of conceptual models that consist of diagrams and accompanying narratives. The narrative describes the diagram, justifies the functional relationships in the figure(s), and cites sources of information and data on which the models are based.

The process of constructing system diagrams almost always identifies inadequately understood or controversial model components. There isn't a single "correct" conceptual model, and it can be insightful to explore alternative ways to represent the system. These different representations of the system can help articulate important, and often exclusive, hypotheses about drivers, stressors, or interactions that are central to understanding how the system operates. These alternative hypotheses can form the basis of an effective adaptive management program, and it will likely be worthwhile to make the extra effort to clearly document and "archive" alternatives that arise during the process of model construction. Workshops to construct conceptual models are brainstorming sessions, and they provide an important opportunity to explore alternative ways to compress a complex system into a small set of variables and functions.

Most ecological systems are complex and management decisions are based on ecological, social, political, and economic considerations. To accommodate the full range of considerations, a set of models with different spatial domains and relevant subsystems will be necessary. Thus you can anticipate the need to construct different models that vary in scope, detail, spatial extent, relevant time frame, and focus. For realistic systems, it probably will not be particularly insightful or rewarding to attempt to construct a single model with all important components and interactions. An all-encompassing model will be too complex for most people to understand. In most (all?) cases, you should limit the detail in a model to that which will fit comfortably on a single page.

All models are wrong, but some are useful (Box 1979)

This document focuses on approaches and techniques are most likely to be useful in the context of an ecological monitoring program. In this context a useful conceptual model will:

- *articulate important processes and variables*
- *contribute to understanding interactions between ecosystem processes and dynamics*
- *identify key links between drivers, stressors, and system responses*
- *facilitate selection and justification of monitoring variables*
- *facilitate evaluation of data from the monitoring program*
- *clearly communicate dynamic processes to technical and non-technical audiences*

These are ambitious goals for the conceptual models. It will clearly require deep thought and hard work to achieve the goals, and compromise among those involved. Development of conceptual models should be viewed as a work in progress, with updates to be made as information and understanding improves through time.

While the monitoring program does not intend to develop quantitative ecosystem models or dictate management policy, constructing a set of realistic, focused conceptual models is an important starting point for designing effective monitoring programs and for evaluating effective management policies. Monitoring programs founded on a solid conceptual model are more likely to identify key processes and indicators, and thereby contribute significantly to Parks management. The central role of models (both conceptual and quantitative) is well illustrated in the "Applied Science Strategy" adopted by the South Florida Ecosystem Restoration Working Group (Figure 2).

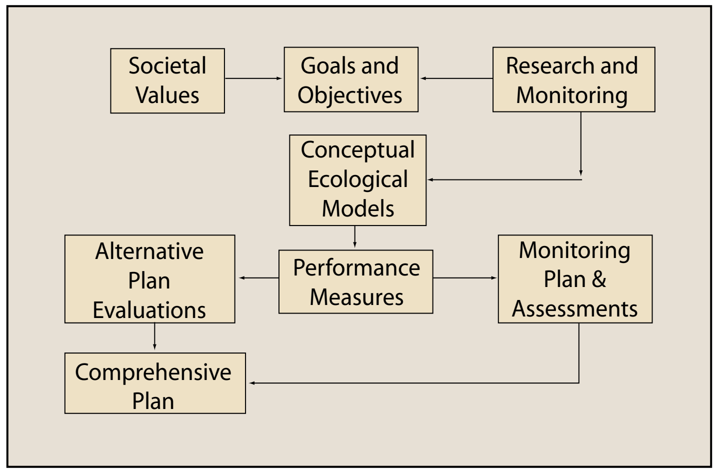

Figure 2. Flow chart of the "Applied Science Strategy" process adopted by the South Florida Ecosystem Restoration Working Group. The "Applied Science Strategy" effectively met the need to use a broadly accepted process to organize and convert large amounts of scientific and technical information into planning and evaluation tools that directly supported restoration programs. Conceptual models, which consisted of diagrams and narratives, were central to the success of the approach . Note iterative development of models, informed by research and other sources of information.

Developing Conceptual Models

In many cases, it will be difficult to create even a single conceptual model, and the more complex the system is, the more difficult it will be to reach consensus on the elements to be included, the key interactions between elements, and the response of the system to drivers and stressors. It may require a number of meetings, repeated trips to the library, and multiple iterations to obtain general agreement on model structure and content. Keep the end in mind – you want to develop a suite of models that address the time and

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spatial scales of interest, at an appropriate level of detail.

The final conceptual models will likely consist of a set of diagrams, tables, and one or more detailed narratives (Figure 1). Diagrams are usually necessary to communicate links between ecosystem components and to illustrate interactions between components, especially when spatial context is important. Tables are frequently the most efficient means for summarizing information on a large number of variables (stressors, drivers, and responses). A detailed narrative is necessary to document the model – it cites references for key relationships, justifies the model structure, and is a critical link to information on which the model is based.

Control and stressor models - two types of conceptual models

Depending on the intended use of the conceptual model, two fundamentally different model structures have been used by I & M Networks and other agencies. A control model is a conceptualism of the actual controls, feedback, and interactions responsible for system dynamics. A control model therefore needs to represent, in a mechanistic way, the key processes, interactions, and feedbacks (Figure 3, top). Quantitative ecosystem simulation models are control models, and they vary in complexity from relatively simple to highly complex. Most groups begin by constructing a set of control models since this is the way we typically think about how systems operate. For a particular system (e.g., Park or other land) control models are typically hierarchical, with a "top level", highly aggregated model and more detailed models of subsystems. In quantitative simulation models, the subsystems are usually functional units (e.g., soils, plant, fire, etc.) that overlap in space, whereas conceptual models often first decompose a larger system into more-or-less spatially distinct vegetation or habitat types. Jackson et al. (2000) describe the process of creating simple simulation models.

Stressor modes are designed to articulate the relationships between stressors, ecosystem components, effects, and (sometimes) indicators. Stressor models normally do not represent feedbacks and they include only a very selective subset of system components pertinent to a monitoring or other program. The intent of a stressor model is to illustrate sources of stress and the ecological responses of the system attributes of interest. These models are founded on known or hypothesized ecological relationships, frequently derived from control models, but they do not attempt a mechanistic representation of the system (Figure 3, bottom). The Everglades restoration program has produced a comprehensive set of stressor models, and they have excellent documentation on how the models contribute to their overall management strategy. The Greater Yellowstone and Northeast Coastal and Barrier Networks have also developed sets of stressor models to guide their monitoring programs.

It may be necessary to develop both kinds of model, at least for some subsystems or habitats. Control models present a more complete and accurate picture of system components and their interactions. Stressor models are likely to more clearly communicate the direct linkages between stressors, ecological responses, and indicators.

STEPS IN CONSTRUCTING CONCEPTUAL MODELS

A systematic program that leads to a set of conceptual models will include the following tasks. These tasks are described in more detail below.

1. *Clearly state the goals of the conceptual models.*
2. *Identify bounds of the system of interest.*
3. *Identify key model components, subsystems, and interactions.*
4. *Develop control models of key systems and subsystems.*
5. *Identify natural and anthropogenic stressors*
6. *Describe relationships of stressors, ecological factors, and responses.*
7. *Articulate key questions or alternative approaches.*
8. *Identify inclusive list of indicators. (Prioritize indicators)*
9. *Review, revise, refine models.*

These steps appear in a sequential list, but it will be necessary to at least partially address the goals of some tasks simultaneously. For example, the construction of control models (steps 3 & 4) must include substantial discussion and consideration of stressors and relationships between stressors and ecological functions (steps 5 & 6).

1. Clearly state the goals of the conceptual models.

Some general goals are outlined above, but the relative importance of these goals will vary as the program matures and with the audience that you most need to engage. Primary goals for the conceptual model common to networks will likely include:

- *Synthesize understanding of ecosystem dynamics.*

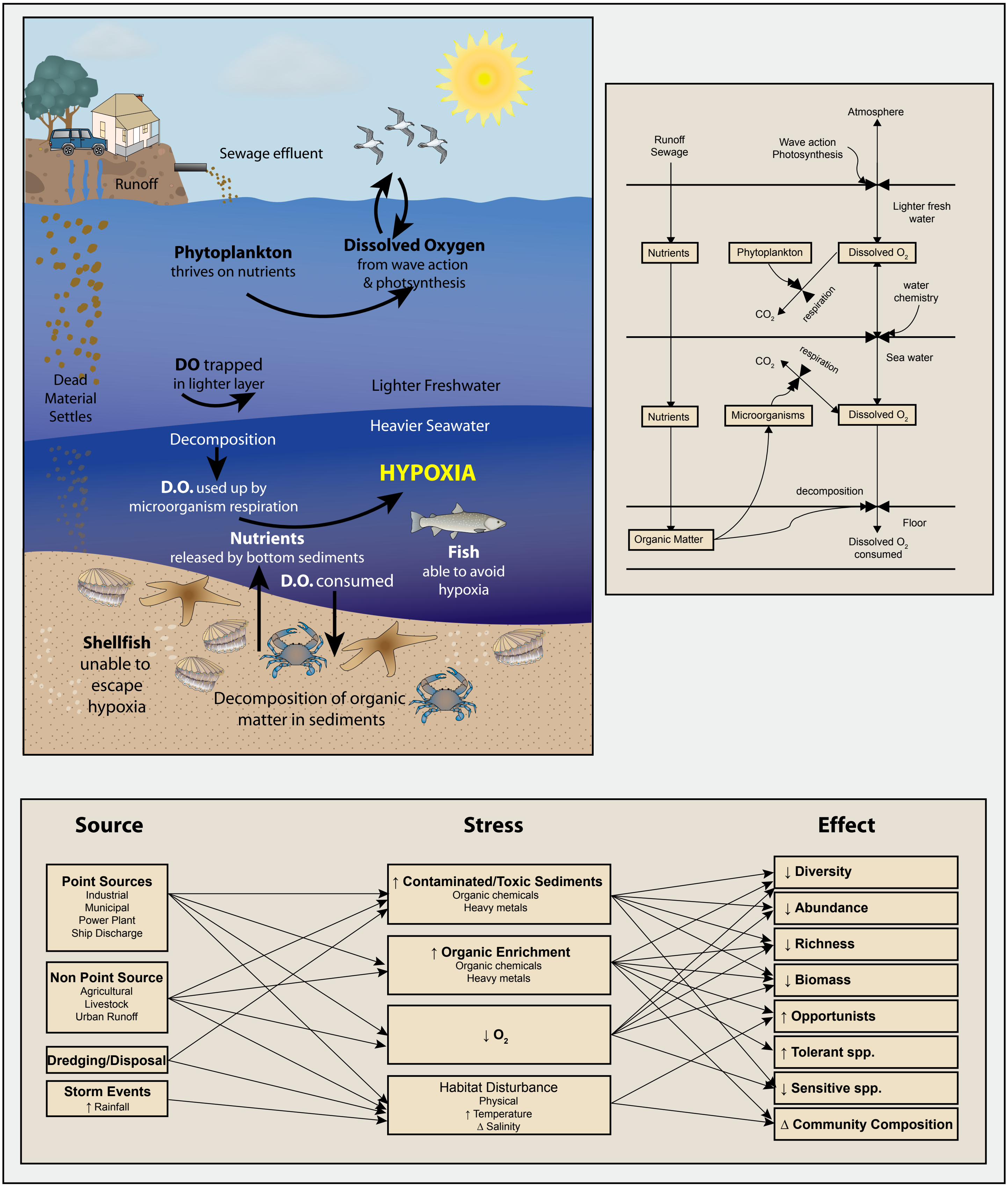

Figure 3. Three representations of the same system (modified from Kurtz et al. 2001). The top figures are control models, with feedbacks and elementary mechanistic connections between system components. The bottom model is a stressor model, which more clearly communicates the links between stressors and effects.

- *Provide a firm conceptual foundation for selecting vital signs indicators.*

- *Identify and illustrate relationships between vital signs indicators and key system processes and variables.*

- *Provide a clear means of illustrating major subsystems and system components and their interactions.*

- *Facilitate communications on system dynamics and the vital signs monitoring program among network staff, managers, technical and non-technical audiences.*

Other goals may include:

- *Identify areas where knowledge is inadequate and further research is needed.*

- *Describe and illustrate alternative hypotheses about key processes or system dynamics.*

- *Provide management staff with models of sensitive habitat types to support management decisions*

- *Develop models to support management of species of concern (an exotic taxon, T&E species, park icon, keystone species, etc)*

Note that different model structures and different levels of detail will likely be required to meet different goals. When first embarking on development of conceptual models or for a particular meeting/workshop, it may be useful to explicitly address a smaller subset of goals – e.g., develop a highly aggregated control model of the Colorado River system in Grand Canyon National Park. At workshops, consider the utility of posting the immediate and long-term goals in an effort to retain focus. It can be challenging to maintain a group's focus during a model construction workshop.

2. Identify bounds of the system and important subsystems

When working with a multi-disciplinary group it will be important to establish a common vision of the relevant spatial and temporal bounds, as well as the most important system components. What are the major subsystems and processes that must be represented? Do the properties to be addressed contain obvious vegetation/topographic types or gradients? Can you identify dominant ecological processes that require separate submodels? Do these processes cross vegetation/habitat types, or are they contained largely within a vegetation/habitat type? Commonalities are most likely to occur at higher levels, and thus most groups will find it easier to start by considering the big picture and then working down to more detailed processes and viewpoints.

One way to initiate the model development process is to first develop a highly aggregated control model of a particular property. This model can serve as the basis for discussions on the scope of the system, recognizing that you will simultaneously need to consider major processes and the scales over which they operate. Model bounds are defined along spatial, temporal, and disciplinary axes. What is the physical space that must be represented to include all major factors, and what are the time scales that must be considered? Some systems may not be clearly bounded (e.g. marine coastal zones, sources of atmospheric deposition), and an explicit definition of the spatial bounds isn't realistically possible. Some factors need to be considered as external inputs outside the scope of the model, even if they are monitored (e.g., air quality in some areas).

All areas will be influenced by very large-scale factors (global change), but these large-scale drivers and stressors may be model inputs outside the bounds of the conceptual models. For workshops, it will usually be useful to have a map of the area(s) that all can refer to, and one product may be a map of the approximate bounds of the main systems of interest.

The key output of this step is an initial assessment of the system bounds. The agreed bounds may be revised later, but they are important to constrain the domain of models in the next step.

3. Develop control models of key systems and subsystems.

This is a big step. It will require participants to consider a wide range of ecosystem processes, spatial and temporal scales, and disciplines. To develop useful control models, you will simultaneously need to identify major system drivers. Thus there is considerable overlap between this and the next task ("identify stressors") and while they are described separately, you will surely be working on them simultaneously.

Once there is agreement on the bounds of the system of interest, you can effectively address the construction of control models of the system and important subsystems. These models may appear in a final report, or they may turn out to be an intermediate step towards development of stressor models. An important function of the control models is to provide explicit, mechanistic links between ecosystem components and processes. It is very difficult to justify the selection of an indicator or to evaluate the quality of data and logic underlying a monitoring program without an explicit understanding of the mechanisms that link indicators to the trait of interest.

A common difficult in beginning this process is to identify an overarching theoretical framework that helps decompose a complex system into a set of less complex parts. In this context, hierarchy theory can help. Hierarchy theory provides a strong theoretical basis for constructing a set of models that hold together in a coherent way (O'Neill et al. 1986; Allen and Hoekstra 1992). In brief, hierarchy theory (as applied to ecosystems) postulates that most complex systems have both a vertical and horizontal structure, and the complex system can be decomposed into a set of less complex elements. The vertical levels are characterized by different rates and (usually) different spatial scales. At each level of interest (an organizational level, which could be an individual, a population, community, or entire ecosystem), higher levels provide a context and they constrain or control lower levels, while mechanisms and components that explain a pattern are contained within lower levels. The concept of a hierarchical structure to ecosystems – the ability to construct a complex system model from a set of less complex submodels – has been widely adopted by ecologists and it provides a framework for constructing control models.

A typical system decomposition is to separate a larger area into habitats. Figure 2 in Appendix IV is an example of a hierarchical decomposition of habitats in a representative park area. Decomposition by habitat/vegetation type is a common axis for subdivision, but an ecosystem could also be divided along other axes, such as important elements or nutrients (e.g., C, N, P, O), topographic position (upslope, runon/runoff, by aspect, etc.), or trophic structure (primary producer, herbivore, carnivore, etc.). Appendix I includes a short review of hierarchy theory and its application to ecosystem science.

There are a range of strategies that can be used to initiate development of the control models. Some find it easiest to begin by constructing a general, highly aggregated model that encompasses the entire system. At large scales, some fundamental principles of ecosystem science can help by providing an overarching structure for an initial model. For example, if the focus is often on vegetation, the dominant structure of vegetation at large scales is largely determined by water balance (Stephensen 1990). At the scale of an ecosystem or habitats, Chapin et al. (1996) embellished Jenny's (1941) conceptual model of ecosystem function to include state factors and interactive controls central to the functioning of sustainable ecosystems (Figures 5 & 6 in Appendix IV). Thus the factors in the Jenny-Chapin model can be considered drivers that will need to be included in most terrestrial systems. This over-arching framework can provide a starting point for discussions of most terrestrial systems, although it's still too general to guide decision-making.

The next step will be to develop models for the key subsystems. Most networks are likely to develop a set of submodels that focus on key habitats or vegetation types, while in some cases additional models will be developed for other attributes. Examples for the focus of submodels include grasslands, forests, wetlands, nitrogen, fire, runoff, a population model (for a focal plant or animal), or a community dynamics submodel (e.g., aspen stand, carnivores, herbivores, etc.). These submodels should contain sufficient detail to represent processes that relate directly to attributes that might be included in the monitoring program. Margulis and Safansky (1998) elegantly summarized the goal of these models: "A good Conceptual Model does not attempt to explain all possible relationships or contain all possible factors that influence the target condition but instead tries to simplify reality by containing only the information most relevant to the model builder. One of the difficulties in building models is to include enough information to explain what influences the target condition without containing so much information that the most critical factors or relationships are hidden. Too much information can conceal important aspects of the model, while too little information in the model leads to oversimplification which in turn leads to a higher likelihood that the portrayal is not accurate."

While constructing submodels, you may identify differences in opinion on driving variables, the functional relationships between model components, feedbacks, or the predicted response to a driver. You will certainly identify gaps where information is lacking, and where there's a serious need for better understanding of system dynamics. These factors emphasize the need to treat the control models as hypotheses of how you think the system operates. The Everglades Plan (Section 3) provides an outstanding example where control models are used as a scientifically defensible basis for the selection of indicators and for identifying crucial management and research needs. This approach has been adopted by the Greater Yellowstone Network (TODO: add examples).

Each control model will need to be supported by a narrative description of the model. The narrative should include an overview of the (sub)model, review published and unpublished literature, document key sources of conceptual structure and data, and identify model attributes that are poorly understood or controversial.

4. Identify natural and anthropogenic stressors

The I & M Program has adopted the definition of a stressor as: physical, chemical, or biological perturbations to a system that are either (a) foreign to that system or (b) natural to the system but applied at an excessive [or deficient] level (Barrett et al. 1976:192). Stressors cause significant changes in the ecological components, patterns and processes in natural systems. Examples include water withdrawal, pesticide use, timber harvesting, traffic emissions, stream acidification, trampling, poaching, land-use change, and air pollution.

Each group will need to adopt a framework for addressing this task. Stressors act at different time and spatial scales, some cross all vegetation/habitat types, and other are specific to a species or group of species. An organizational framework is necessary to ensure that all necessary scales and disciplinary areas are addressed.

Many potential stressors will have been identified as driving variables during construction of the control models, and a comprehensive set of control models will help identify key ecosystem processes and the factors that most influence them. The control models can help structure discussions in workshops focused on expanding and prioritizing the list of potential stressors and indicators.

Networks have generally used a workshop approach to generate an extensive list of potential stressors and responses. These stressors reflect the diversity of important subsystems in the Park's properties and the range of concerns of stakeholders. The usual product of this task is a set of lists and/or matrices that tabulate stressors (e.g., Figure 1; TODO: add examples to appendix), with a narrative that summarizes the findings.

5. Model relationships of stressors, ecological factors, and responses

The goal of this step is integrate the understanding of system dynamics and stressors in a set of stressor models that clearly communicate linkages between drivers, stressors, ecological responses, and ecosystem attributes. The intent of stressor models is to clearly communicate linkages directly relevant to the monitoring program without adding confusion by including any extraneous information. Example stressor models of aquatic, estuarine, and terrestrial systems are included in Appendix IV. My impression is that the most useful stressor models are relatively simple, and they focus on a single major subsystem, group of stressor (e.g., water pollution), or taxon/taxa. Again, a hierarchically structured set of models may provide for a high-level framework that encompasses a set of small, simple, and specific models. Models that include too many systems (e.g., animals, water, plants) usually have only vague connections between indicators to ecological processes. In my opinion, a relatively large number of detailed models is more useful than a smaller number of more complex and less detailed models.

Stressor models need to specifically address an area or attribute that may be measured. Since the scale of attributes and stressors include a huge range of scales, it will likely be necessary to develop models at different scales and with different levels of resolution. It is crucial that there be sufficient detail in the model to clearly link a potential indicator to relevant processes.

Stressor models are likely to be key elements in presentations to managers, policy makers, and with the public. For presentations, especially to non-technical audiences, it may be useful to create several diagrams with increasing detail. Stressor models should be easy to understand and explain. If they don't easily fit on a single page, they almost certainly need to be divided into or otherwise simplified.

6. Articulate key questions or alternative approaches.

Questions and alternative hypotheses on system function are likely to arise during the construction of both control and stressor models. Ideally, these will have been recorded and documented as they were identified. Clear documentation of these alternatives will help ensure that institutional knowledge is not lost with personnel changes, and it will facilitate periodic review and revision of the models. A short summary of peer-review comments may provide a context, and alter network personnel to questions or concerns that may arise during presentations. Models are an incomplete representation or reality, and the need for detail or focus will change through time.

Alternative hypotheses and models are also the basis of an effective adaptive management program. They can stimulate discussion on alternative management options, and provide justification for future research. If these alternative hypotheses have important consequences for directing management actions, they may identify key variables that should be part of the monitoring program.

7. Identify and prioritize indicators.

This step isn't really part of the process of developing conceptual models, but it's listed here since it's a key step in developing the monitoring plan, and it will likely result in revision of the conceptual models. After a prioritized list of indicators is selected, you will need to revisit the conceptual models and ensure they adequately address all indicators.

8. Review, revise, refine models.

All models represent an incomplete abstraction of reality, and most models will need to be revised to accommodate new observations, information, or to meet changing goals. Planned, periodic review is most certain means to ensure the conceptual models continue to reflect current knowledge. During the review, consider concerns and alternative representations that arose during initial model construction, and have the models reviewed by management and scientific staff.

Execution and Network Experiences

Networks and prototypes have employed a wide variety of processes to develop conceptual models and the resulting models reflect this diversity. From discussions with network coordinators, these general observations emerged:

- *It is was very useful to have an overall conceptual model to focus groups on linkages between submodels and that encourages model builders to conform to a common process or model structure.*

- *Hierarchical sets of models work well. At intermediate levels, submodels most commonly focus on vegetation types.*

- *It can be difficult to include animal species or animal communities of special interest in ecosystem models and they often require separate models.*

- *Models that address different scales are insightful, even when they focus on the same process or variables, but at different scales.*

- *It is very time-consuming to build useful conceptual models. Engage collaborators with appropriate disciplinary expertise as early as possible and allow time for repeated revision.*

- *There is a large return on investment in documenting the ecological theory that underpins a modeling approach. The underlying theory supports use of a common approach and shared vision of system processes and linkages. The NCPN report (currently being revised) is an excellent example.*

- *At the lowest levels, models must include sufficient detail to link indicators to ecological processes and, where possible, to management actions. Insufficiently detailed models have limited utility. It is a substantial challenge to construct a model with just the "right" amount of detail, and to decide when to split a model into separate submodels to avoid an overly-complicated model.*

- *Provide definitions of key terms and phrases. Syntax is important.*

Greater Yellowstone Network - is using the I&M program as an opportunity to review and integrate a variety of NR programs. Up to July 2003, they have developed a comprehensive set of control and stressor models, and a few hybrids. The models operate on a variety of scales (e.g., the include a "dry timberland" model as well as a "Lake Bob" model).

Northern Colorado Plateau Network - report has an excellent discussion of underlying ecosystem theory. They have adopted state and transition models as a structural framework for representing dynamics of many systems. In conversation, they noted that insufficient detail in early models limited their usefulness.

Mediterranean Coast Network – Developed an initial set of Everglades-type stressor models, but had difficulties adequately incorporating animal communities. The Network is currently developing energy flow models to better represent trophic relationships.

Cape Cod – Implementation of stressor models and tables. Excellent early work on conceptual foundation of these models (Roman and Barrett 1997).

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