# Developing Conceptual Models for Monitoring Programs

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## SUMMARY

Conceptual models are a key element of environmental monitoring programs. They integrate current understanding of system dynamics, identify important processes, facilitate communication of complex interactions, and illustrate connections between indicators and ecological states or processes. Well-constructed conceptual models provide a scientific framework for the monitoring program and justification for the choice of indicators.

This document describes two types of models commonly used to conceptually represent ecological systems, and it outlines the steps involved in developing useful conceptual models. Examples models are provided, as well as short reviews of adaptive management, hierarchy theory, and state and transition models.

This is a working draft and I welcome comments, suggestions, and materials.

## Contents

## 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 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
- 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).

*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.

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

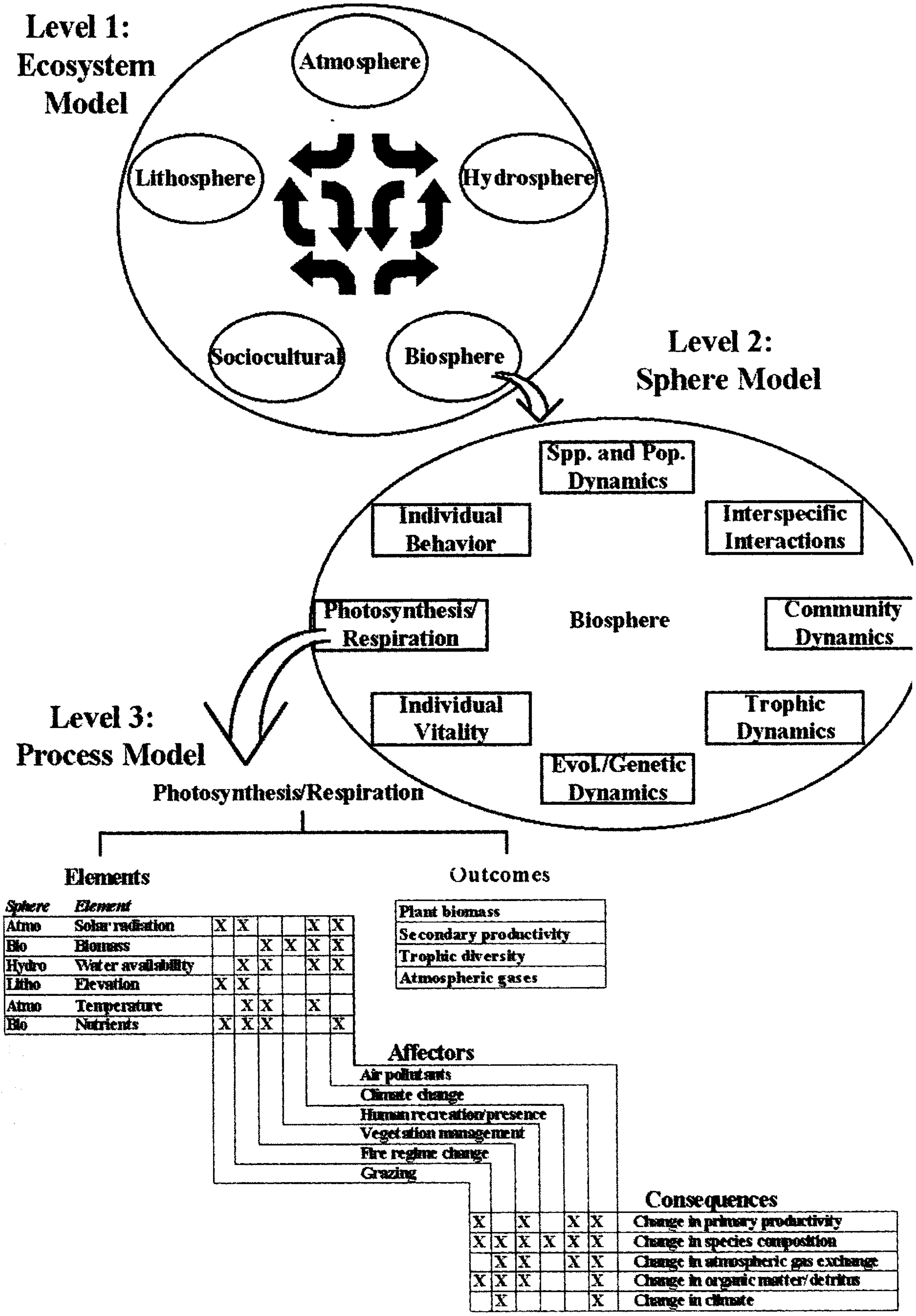
Most ecological systems are complex and management decisions are based on ecological, social, political, and economic considerations. To accommodate the full range of considerations, a set of models with different spatial domains and relevant subsystems will be necessary. Thus you can anticipate the 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.

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).



**Elements**

| *Sphere* | *Element* | Grazing | Fire regime change | Vegetation management | Human recreation/presence | Climate change | Air pollutants |
|---|---|---|---|---|---|---|---|
| Atmo | Solar radiation | X | X |  |  | X | X |
| Bio | Biomass |  |  | X | X | X | X |
| Hydro | Water availability |  | X | X |  | X | X |
| Litho | Elevation | X | X |  |  |  |  |
| Atmo | Temperature |  | X | X |  | X |  |
| Bio | Nutrients | X | X | X |  |  | X |

**Outcomes**

| |
|---|
| Plant biomass |
| Secondary productivity |
| Trophic diversity |
| Atmospheric gases |

**Affectors**

- Air pollutants
- Climate change
- Human recreation/presence
- Vegetation management
- Fire regime change
- Grazing

**Consequences**

| Grazing | Fire regime change | Vegetation management | Human recreation/presence | Climate change | Air pollutants | |
|---|---|---|---|---|---|---|
| X |  | X |  | X | X | Change in primary productivity |
| X | X | X | X | X | X | Change in species composition |
|  | X | X |  | X | X | Change in atmospheric gas exchange |
| X | X | X |  |  | X | Change in organic matter/detritus |
|  | X |  |  |  | X | Change in climate |

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

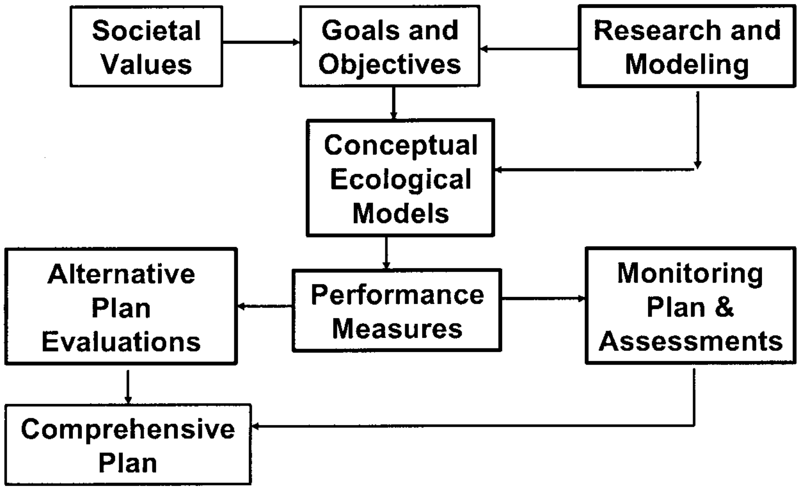


Figure 2. Flow chart of the "Applied Science Strategy" process adopted by the South Florida Ecosystem Restoration Working Group. The "Applied Science Strategy" effectively met the need to use a broadly accepted process to organize and convert large amounts of scientific and technical information into 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 (Appendix A, March 2003 RECOVER draft plan; http://www.evergladesplan.org/pm/recover/aat.cfm).

## 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 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.

S*tressor 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. The appendices to Everglades Restoration Plan (http://www.evergladesplan.org/pm/recover/recover_map.cfm) include a set of well constructed and documented stressor models; some of these are reproduced in Appendix IV.

### 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).

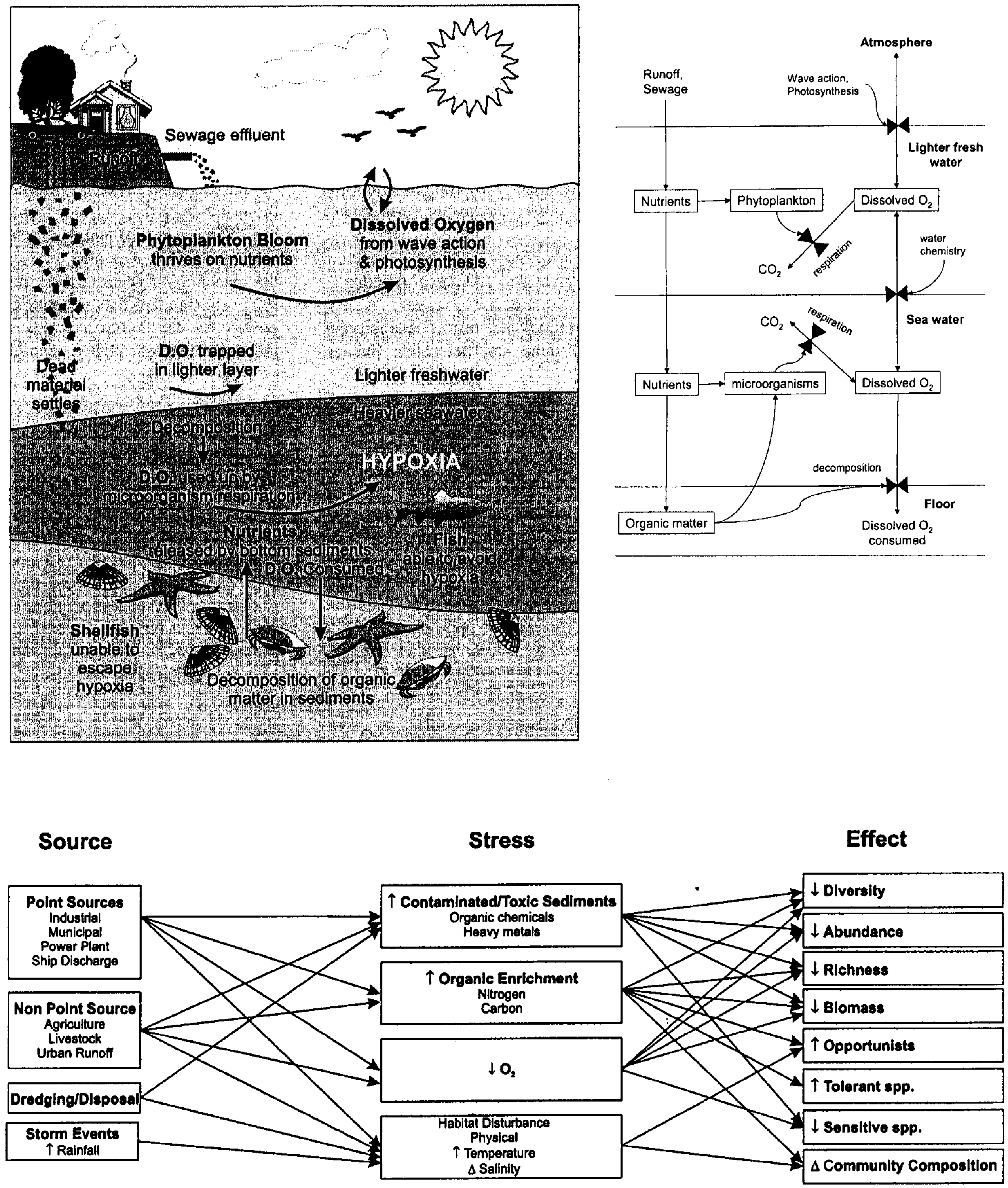


Figure 3. Three representations of the same system (modified from Kurtz et al. 2001). The top figures are control models, with feedbacks and elementary mechanistic connections between system components. The bottom model is a stressor model, which more clearly communicates the links between stressors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

### *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.
- 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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## APPENDIX I. RELATED TOPICS.

This appendix includes brief reviews of topics useful to a variety of networks. The reviews provide short descriptions of topics that will be familiar to ecosystem ecologists or modelers, but that may not be common knowledge to ecologists in general. Citations to seminal publications are provided. These sections can be included in reports "as is" or revised as desired.

Topics currently in this appendix:

- Adaptive management
- Hierarchy theory
- State and transition models

Topics for consideration:

- Natural variation, disturbance (extent, frequency, etc)
- Ecological stability, resilience, resistance

### Adaptive Management

Adaptive management refers to a structured process of "learning by doing" where management plans are explicitly designed to generate information that can be used to improve management in the future (Walters 1986, 1997). Deliberate manipulations of ecosystems are used to probe ecosystem responses in ways that yield new information about the system. New knowledge is incorporated into management decisions, and this leads to a cycle of continuous improvement in policies and practices.

The term "adaptive management" is now widely used by natural resource managers and there are now many interpretations of its meaning. A liberal interpretation of adaptive management is management by trial-and-error. In this case, there is no formal program for manipulating the system in a manner that generates new knowledge, nor a defensible program for monitoring the results of management actions. Nyberg and Taylor (1995) proposed the following working definition for adaptive management:

> Adaptive management is a systematic process for continually improving management policies and practices by learning from the outcomes of operational programs. Its most effective form – active adaptive management – employs management programs that are designed to experimentally compare selected policies or practices, by evaluating alternative hypotheses about the system being managed. The key characteristics of adaptive management include:
>
> - Acknowledgement of uncertainty about what policy or practice is "best" for the particular management issue;
> - Thoughtful selection of the policies or practices to be applied;
> - Careful implementation of a plan of action designed to reveal the critical knowledge;
> - Monitoring of key response indicators;
> - Analysis of the outcome in consideration of the original objectives; and
> - Incorporation of the results into future decisions.

This definition clearly enunciates the structured set of activities that comprise an adaptive management program, especially the deliberate, experimental manipulation of the system.

Adaptive management begins with problem assessment and construction of dynamic models that represent alternative hypotheses of system functioning and that make predictions of alternative management policies (Holling 1978; Walters 1997). In the formal sense, adaptive management involves much more than responding to anticipated effects of management actions, and it is more than a slight enhancement to monitoring programs. Adaptive management acknowledges complexity and uncertainty, and addresses uncertainty in processes, models, and measurements. When adaptive management is implemented correctly, it can replace learning by trial and error (an evolutionary process) with learning by careful tests (a process of directed selection) (Walters 1997).

Walters and Holling (1990) succinctly distinguish adaptive management modes:

"(1) evolutionary or "trial and error," in which early choices are essentially haphazard, while later choices are made from a subset that gives better results; (2) passive adaptive, where historical data available at each time step are used to construct a single best estimate or model for response, and the decision choice is based on assuming this model is correct; or (3) active adaptive, where data available at each time step are used to structure a range of alternative response models, and a policy choice is made that reflects some computed balance between expected short-term performance and long-term value of knowing which alternative model (if any) is correct."

The monitoring program can contribute substantially to the goal of adopting adaptive management principles in Park management. Walters (1997) noted that the modeling step is intended to serve 3 functions:

1. clarify the problem and enhance communication among scientists, managers, and other stakeholders
2. screen policy options to eliminate options that will most likely fail because of inadequate scope or type of impact
3. identify key knowledge gaps that make model predictions suspect.

In many situations, the monitoring program can directly contribute to the first and third functions identified by Walters (1997). Furthermore, by generating models that clearly state hypotheses on how systems function, the monitoring program has the opportunity to contribute to the second goal.

### Hierarchy theory

Ecological systems are inherently complex and we therefore need some way to reduce this complexity to a manageable level. Hierarchy theory provides a general framework for structuring complex systems, and it has been widely adopted by ecologists and others working with dynamical systems. Hierarchy theory is founded on the idea that complex systems frequently consist of a number of integrated subsystems that are in turn composed of their own subsystems (Simon 1962). This decomposition can be repeated again and again, until an elementary or primitive component is reached. Decisions on how far to decompose a system will be dependent on both the nature of the system and the questions being asked.

Hierarchical systems have both a vertical and horizontal structure. Vertical structures are separated by different process rates and, typically, spatial extent. Interactions between levels are asymmetrical, and theory suggests that one look up in scale for limiting factors or constraints, and look to a lower level for mechanistic explanations of pattern (Figure 1 in Appendix IV); O'Neill et al. 1986). Interactions are stronger at a particular horizontal level than between levels. Thus in a model (conceptual or otherwise), the focus of the model (e.g., plant community, lake, etc) is represented at the intermediate model scale, with drivers typically at a higher level and detailed mechanisms at a lower level.

As a general rule, it is best to initially limit a model to three levels of aggregation. For example, community, population, and individual-level functions can usually be included in the same model without undue difficulty, but conceptual and technical difficulties are much more likely if add individual physiology or landscape-level functions are added to the same model. While some people have successfully incorporated more than 3 levels of integration into a single model, it usually results in a greatly increased level of model complexity. O'Neill et al. (1986) and Allen and Hoekstra (1992) provide a thorough introduction of hierarchy theory with reference to ecosystems, and Wu (1999) and Wu and David (2002) expand the theory in the context of hierarchical patch systems.

**State and transition models - From NCPN Phase I report (Evenden et al. 2002):**

Ideas related to ecological thresholds are represented in a variety of existing conceptual models. The most common approach for modeling threshold phenomena in relation to management is through *state-and-transition models*. State-and-transition models are management-oriented tools for organizing information and posing hypotheses about ecological thresholds, irreversible transitions among states, and effects of management activities on transition probabilities (Westoby et al. 1989, Stringham et al. 2001, Jackson et al. 2002, Bestlemeyer et al. 2003). In the application of state-and-transition models used here (Figure 4), a *state* is defined as "a recognizable, resistant and resilient complex of two components, the soil base and the vegetation structure" (Stringham et al. 2001:4). These two ecosystem components interactively determine the functional status of the primary ecosystem processes of energy flow, nutrient cycling, and hydrology (water capture, retention, and supply). A *threshold* is defined as "a boundary in space and time between any and all states, or along irreversible transitions, such that one or more of the primary ecological processes has been irreversibly changed and must be actively restored before return to a previous state is possible" (Stringham et al. 2001:5). Thus states and thresholds are defined with respect to the functioning of primary ecosystem processes. *Transitions* are defined as "trajectories of change that are precipitated by natural events and/or management actions which degrade the integrity of one or more of the state's primary ecological processes" (Stringham et al. 2001:5). In terms of resistance and resilience, a threshold is crossed when the capacities for resistance and recovery of one or more primary processes are exceeded. After the threshold is crossed, the transition is irreversible under current climatic conditions without substantial inputs of energy by management (Stringham et al. 2001). In this type of application, a specific state-and-transition model is developed for a specific ecological site[1]. For monitoring applications, state-and-transition models should be accompanied by mechanistic models describing how stressors affect key ecosystem components and processes (e.g., biotic functional groups, disturbance regimes, and soil/water resources and dynamics) and influence transition probabilities.

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[1] An *ecological site* is defined as "a kind of land with specific physical characteristics which differs from other kinds of land in its ability to produce distinctive kinds and amounts of vegetation and in its response to management" (Society for Range Management, Task Group on Unity in Concepts and Terminology 1995:279). Ecological sites are land units defined and recognized on the basis of climate, landscape position, and inherent soil properties (texture and mineralogy by depth); typically they are described or named on the basis of the dominant vegetation. Ecological sites are basic land units for resource management and analysis by the Bureau of Land Management and the USDA Natural Resource Conservation Service. The concept is synonymous with "ecological types" of the USDA Forest Service (Society for Range Management, Task Group on Unity in Concepts and Terminology 1995).

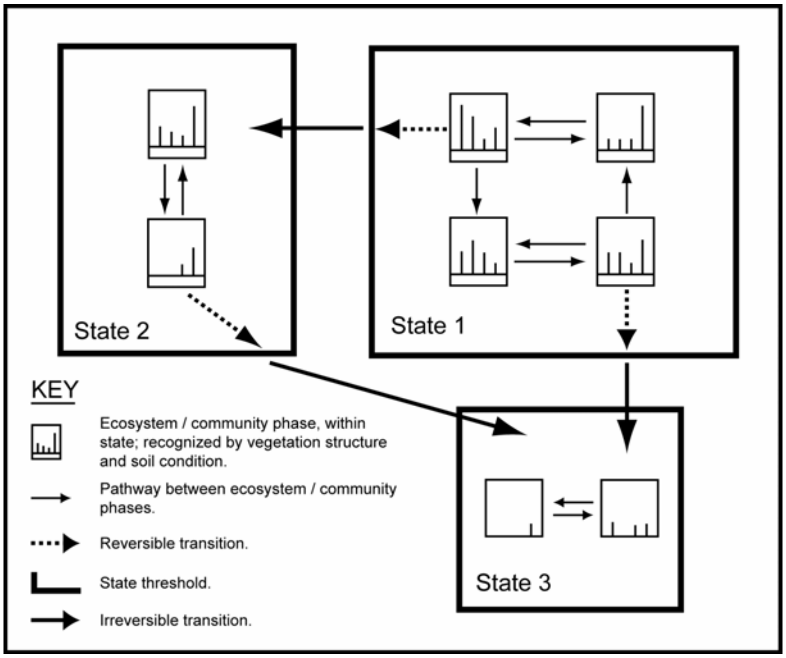

Figure 4. State-and-transition model–a management-oriented tool for organizing information and posing hypotheses about ecological thresholds and irreversible transitions among dynamic states. Dynamics within the dark-lined boxes (i.e., within a dynamic state) are within the natural range of variability and include normal successional changes (adapted from Stringham et al. 2001a).

Whisenant (1999) presented a process-based conceptual model that identified two types of thresholds in relation to restoration and management (Figure 5). As in the application of state-and-transition models described above, primary ecological processes in his model include water capture and retention, nutrient cycling, and energy capture and flow. Whisenant's approach is based in part on earlier work by Archer (1989) and Milton et al. (1994), and it is closely allied with concepts of rangeland health and landscape function (National Research Council 1994, Ludwig et al. 1997, Ludwig and Tongway 2000, Pellant et al. 2000, Rosentreter and Eldridge 2002). The fundamental hypothesis underlying these approaches is that health and sustainability of arid-land ecosystems are dependent on maintaining the capacity of these systems to capture and retain water and nutrients (Whitford 2002).

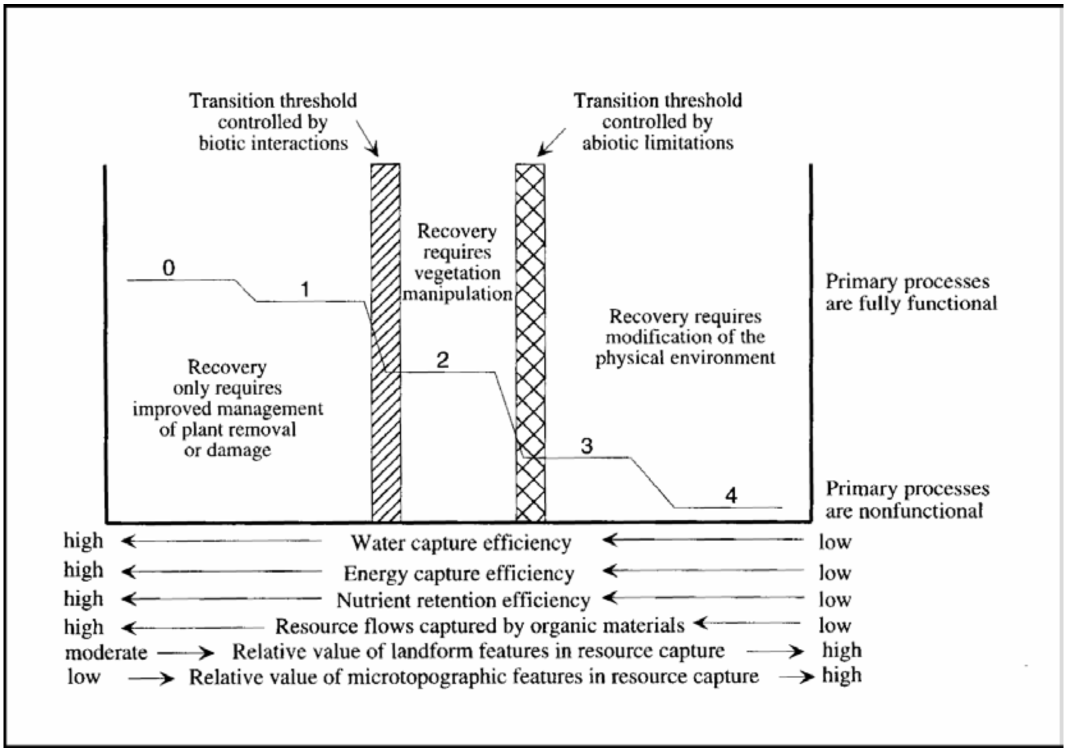

Figure 5. Conceptual model illustrating the application of threshold concepts to restoration and management (from Whisenant 1999). In this framework, "primary processes" include water capture and retention; nutrient capture, cycling and retention; and energy capture.

## More on State and Transition models

A fundamental goal of ecologists and natural resource managers is to acquire an understanding of ecological systems that permits them to predict the effects of management actions. Management of many systems has been based on the concept of succession and a climax state as proposed early in the 1900's (Clements 1916; Tansley 1935). The guiding principle of this concept is that ecological communities move along a relatively deterministic pathway towards a single climax state. The theory postulates that disturbances tend to move a system towards an earlier state, and upon removal of the disturbance the system will again return to a pathway leading to a climax state. This model of succession-regression-succession was almost universally used to guide natural resource management for decades, even though there was early recognition that some systems, once disturbed, did not return to an earlier state over any time frame we could observe (Muller 1940; Glendening 1952; Scheffer et al. 2001). A response to the lack of congruence between theory and observations in rangelands was development of conceptual models that represented rapid transitions between different vegetation states (Westoby 1989). These models, referred to as "state and transition models", represent multiple plant communities and the processes thought to lead to rapid (and sometimes effectively irreversible) transitions between communities. In many areas, especially arid and semi-arid rangelands, state and transition models were particularly appealing because quantitative models did not accurately represent observed rapid transitions from one stable vegetation type to another. Rapid transitions in rangelands (e.g., from grass to shrub-dominated vegetation) were attributed to management actions such as changes in fire frequency or grazing regime. In many cases, these transitions were unidirectional and removal of stress or disturbance did not lead to "recovery".

State and transition models were rapidly and widely adopted by land management agencies, mostly in arid and semi-arid regions (Laycock 1991; Ash et al. 1994; Stringham et al. 2001, 2003). These models have certainly contributed to communication of ecological processes and provided a conceptual basis for management decisions. However, state and transitions models are fundamentally phenomenological and the mechanistic underpinning of observed dynamics is only vaguely acknowledged in some models. In this case, it is difficult to link a quantitative endpoint for an indicator directly to such a model. Difficulties in linking indicators to state and transition model remain, even when the underlying mechanisms are reasonably well understood (e.g.,Trimble and Mendel 1995; Breshears and Barnes 1999; Bestelmeyer et al. 2003). In the context of the monitoring program, state and transition models can be accompanied by more mechanistic models that represent dynamics internal to a particular state and/or that represent transitions between particular states. A combination of these models offers the significant advantages of both approaches.

State and transition models have usually been presented as an alternative to “equilibrium” approaches such as the succession-climax model. However, Briske et al. (2003) noted that ecological patterns and processes are highly scale-dependent, and that theoretical investigations of equilibrium and non-equlilibrium models explicitly emphasize the importance of scale. At smaller scales, there may be dramatic changes in vegetation composition or structure, while at a landscape scale there can be little or no change (Ryerson and Parmenter 2001). Furthermore, Briske et al. (2003) stressed similarities of “equilibrium” and “non-equilibrium” systems and they noted that the distinction between these systems are more related to spatial and temporal scale than processes or functions. This interpretation is more consistent with the concept of a dynamic equilibrium, where systems are regulated by a combination of equilibrium and non-equilibrium dynamics (Ellis and Swift 1988; Jackson et al. 2002).

An approach that can combine the strengths of state and transition type models and simulation models is “frame-based modeling” (Starfield et al. 1993; Hahn et al. 1999). Simulation models that operate on spatial and temporal scales relevant to management are often unable to accurately simulate major changes in vegetation structure or composition, even thought they may accurately represent dynamics (e.g., hydrological functions, N flows, plant growth, etc) within the relevant vegetation types. For example, it is typically very difficult to mechanistically simulate the transition from a grass to shrub-dominated system, even though simulation models accurately simulate primary production in either grass or shrub dominated systems. Frame-based modeling provides a means that can potentially harness the predictive ability of a mechanistic model to, e.g. forecast grass production or cover, and employ a state and transition approach to represent major state changes that are difficult to simulate.

The USDA NRCS is developing a large set of state and transition models. The models are actively being developed, and those available for viewing can be found at:

`http://www.nm.nrcs.usda.gov/technical/fotg/Section2/ESD/sd2.html`
`http://www.nm.nrcs.usda.gov/technical/fotg/Section2/ESD/wp3.html`
`http://www.nm.nrcs.usda.gov/technical/fotg/Section2/ESD/sd3.html`

## APPENDIX II. DEFINITIONS

Adaptive Management: A systematic process for continually improving management policies and practices by learning from the outcomes of operational programs. Its most effective form-"active" adaptive management-employs management programs that are designed to experimentally compare selected policies or practices, by implementing management actions explicitly designed to generate information useful for evaluating alternative hypotheses about the system being managed.

Attributes: Any living or nonliving feature or process of the environment that can be measured or estimated and that provide insights into the state of the ecosystem. The term Indicator is reserved for a subset of attributes that is particularly information-rich in the sense that their values are somehow indicative of the quality, health, or integrity of the larger ecological system to which they belong (Noon 2003). See Indicator.

Bounds: The extent of a model, typically defined with regard to subsystems of interest and spatial extent. May include dimensions for time and space.

Control model: A model that includes major system components, drivers, and feedbacks. The intent is to be an accurate representation of the system at a particular level of aggregation (contrast with stressor model).

Deterministic model or function: Without random variation. For a given set of inputs, a deterministic model (function) will always yield the same results. Contrast with stochastic model.

Ecosystem driver or driving variable: Major external driving forces such as climate, fire cycles, biological invasions, hydrologic cycles, and natural disturbance events (e.g., earthquakes, droughts, floods) that have large scale influences on natural systems. In coupled models, a driver can be an output from another model. E.g., using a global climate model to generate weather that is an input to an ecosystem dynamics model.

Indicators: A subset of monitoring attributes that are particularly information-rich in the sense that their values are somehow indicative of the quality, health, or integrity of the larger ecological system to which they belong (Noon 2003). Indicators 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.

Mechanistic model: System description based on processes and interactions known or hypothesized to account for dynamics of the system. Contrast with statistical model.

Nonlinear function: In common modeling useage, a function describing a process or model which does not respond to a driver in a linear form (i.e., does not scale as a simple function).

Parameter: Generally a constant in a quantitative model (e.g., kcal/g of fat). In exceptional cases, parameters may change slowly for long model runs.

State variable: Quantity that describes the current conditions in a model. For ecosystem models, common state variables include the mass of an element (C, N, P, etc.), for population models the number of animals.

Statistical model: Equation or set of equations with parameters estimated solely from observations. The functional form of the equation(s) may not relate to any known or hypothesized functional relationship. Every statistical hypothesis test is based on a statistical model.

Stochastic model: A model that incorporates one or more parameters or variables that vary randomly. Randomness in a stochastic model is often introduced by drawing a random number from a known distribution to determine the magnitude and/or frequency of an event (e.g., the probability of birth, death, precipitation). A stochastic model (or function) can provide a different result for every run, even when the inputs are exactly the same. Contrast with deterministic model.

Stressor: 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

Stressor model: An abstraction of a particular system or part of a system focused on the links between stressors, ecosystem responses, effects, and in some cases indicators. A stressor model does not incorporate all relevant system components, feedbacks, or interactions.

System: The complete set of components and their interactions of interest. A system could be a forest, a desert, a manufacturing plant, or a town. In our case, the system of interest usually includes terrestrial, atmospheric, hydrological, and human-dominated components.

Variable: A quantity that changes during a model run. E.g., number of trees, temperature, animal mass, soil moisture, acres of cleared forest, dissolved oxygen content, etc.

## APPENDIX III. SUGGESTIONS FOR CREATING CLEAR DIAGRAMS; WORKSHOPS

Designing and creating clear model diagrams is both a craft and art. These suggestions are useful after you've decided on the scope and structure of the model, and you need to refine a hand-drawn diagram or build a new diagram.

There are a number of software packages that can be used to create flow charts. Specialized modeling languages (e.g., Stella, Vensim) provide graphical interfaces which can be used to quickly create flow charts with appropriate shapes. A free "lite" version of Vensim can be downloaded from the internet (www.vensim.com). It will take most people 1-2 hours to figure out how to efficiently use the diagramming capabilities of Vensim. Other common alternatives include MS PowerPoint, MS Visio or other drawing programs. PowerPoint and Visio provide a range of tools and shapes that can be used to create model diagrams and charts. If you use PowerPoint, it's often easiest to use connectors to draw lines between model components so lines and arrows remain connected to when you move objects around on the diagram.

Regardless of the program used to create the diagrams, your diagram will be easier to read and understand if you follow a few general rules.

- Minimize the amount of ink used to draw elements that with content. Don't draw boxes or other shapes around things that don't need them. Include objects on charts only when they convey significant content. Encourage the reader to focus on content-rich elements.
- Align model components is a consistent way (vertical, horizontal, in a circle, etc.). Try to arrange related model components so that arrows can be straight lines in a vertical or horizontal direction.
- Avoid crossing lines whenever possible.
- Don't put too much on a single diagram. In general, you will want to display 3 or fewer levels of integration on a single diagram. Aggregate complex subsystems in higher-level diagrams and use sub-model diagrams.
- For simple charts, use only black and white. Your diagram will likely be reproduced on a B&W copier at some point. Shaded backgrounds reproduce poorly.
- Use consistent shapes for model elements, or don't use any outline when the meaning is clear (e.g., minimize non-content ink).
- Use white board for workshops, preferably in concert with a laptop and projector.
- List key elements on flip charts; diagrams in software (for editing)

## APPENDIX IV. EXAMPLE CONCEPTUAL MODELS

This appendix is comprised of diagrams of conceptual models and related topics. Due to the large file size, it has been saved as a separate file (CModels_AppendixIV.pdf).