Evaluating Management Success: Using Ecological Models to Ask the Right Monitoring Questions

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Key issues addressed in this chapter

- *Effective monitoring programs depend on solid scientific thinking, much of it occurring in advance of actual monitoring.*
- *Construction of ecological models and the creation of monitoring plans should not occur separately from discussions of management planning.*
- *Development of a monitoring program is a four-step process: (1) understanding pattern and process, (2) divining essential properties, (3) arranging essential properties into an ecological model, and (4) determining the best indicators for specific aspects of the model.*
- *Ecological models are a conceptualization of critical entities and process. They directly suggest what needs to be monitored. It then remains to craft the best indicators for these things.*
- *Good indicators have three general scientific functions: assessment of ecosystem status, prediction of future problems, and diagnosis. No single indicator will fill all three roles. Therefore, it is best to use multiple indicators that are complementary.*
- *Developing clear quantitative thresholds of significant change is critical.*

Keywords: Monitoring ecological systems, role of models in monitoring, types of models, constructing ecological models, indicators, evaluating management success, dune ecosystem in California, riparian stewardship in Colorado

1 INTRODUCTION

1.1 Timely and Helpful Monitoring

Organizations monitor ecological systems for a variety of reasons, typically involving the need to track trends in resources, evaluate management actions, and provide timely warning of undesirable conditions. They monitor to generate timely and helpful answers to questions about the management and stewardship of their biological resources (see Box 1). Let us examine what "timely" and, especially, "helpful" might mean in a land management context.

Land managers are typically charged with the mid- to long-term stewardship of land and natural resources. This stewardship involves sustaining certain landscape and ecosystem *values* — species populations, landscape mosaics, commodity production, and so on — that generally have been prescribed in advance. Stewardship requires both management actions (to maintain or correct ecosystem trajectories) and periodic assessment and monitoring in a continuous cycle. Thus, timely monitoring (and evaluation) occurs with a periodicity that allows the productive correction of management actions. Helpful monitoring provides information that is explicit and focused on particular issues and problems, answering specific questions about the status of resources and the effectiveness of management.

There are two broadly overlapping areas of concern in the design of monitoring programs: issues of concept (the scientific and intellectual basis of the work), and issues of design and implementation. The latter is discussed in Tolle et al. (this volume). The current chapter discusses a broad constellation of issues that motivate the conceptual design and ultimate success of any monitoring study: the representation of current ecological understanding into a conceptual ecological model of the ecosystem and the derivation from this model of effective measurement instruments (see Box 2). We believe that effective answers to questions about ecosystem management must flow from an explicitly stated understanding of the ecosystem. A conceptual ecological model serves this purpose, not as a statement of "truth," but as a representation of our best current understanding (Starfield 1997). Such a written-down model can show us the way by laying bare our assumptions, by suggesting critical foci of measurement, and simply by existing as a table around which managers and others can debate the nature and effectiveness of stewardship work at a site.

BOX 1
DEFINITION OF MONITORING

Monitoring is the systematic observation of parameters related to a specific problem, designed to provide information on the characteristics of the problems and their changes with time (Spellerberg 1991).

Ecological monitoring is the acquisition of information to assess the status and trend of the structure and functioning of biological populations and communities, and their habitat, and larger-scale ecosystems (i.e., landscapes) over time, for the purpose of assessing and directing management activities (The Nature Conservancy 1997).

Some key features of monitoring are that (1) the measurements and evaluation are usually completed more than once over time, (2) monitoring is done for a specific purpose (e.g., to determine the status and trend of a process or entity, or to evaluate the progress toward a management objective) and (3) the results will generate an action of some kind, even if the action is to maintain current management.

BOX 2
KEY ISSUES ADDRESSED IN THIS PAPER

- Development of a monitoring program is a three-step process: (1) understanding ecosystem pattern and process and developing an ecological model, (2) incorporating management and conservation goals into the model explicitly, and (3) determining the best indicators for specific aspects of the model.
- Ecological models and monitoring plans are not created separately from discussions of overall management planning.
- An ecological model directly suggests the entities to monitor. It then remains to determine the best indicators for these entities. When indicators follow from components of the ecological model, we can clearly interpret data in terms of ecosystem process and management actions.
- Good indicators have three general scientific functions: assessment of ecosystem status, prediction of future problems (i.e., "early warning"), and diagnosis. No single indicator will fill all three roles. Therefore, it is best to use multiple indicators that are complementary and together best serve the evaluation of management.
- Indicators at lower levels of biological organization will tend to be most diagnostic, although they have certain limitations.
- Developing clear, quantitative thresholds or magnitudes of significant change is critical; otherwise changes observed in indicator values are incomprehensible and management cannot be evaluated.
- Setting explicit thresholds and magnitudes of significant change greatly facilitates the sampling and statistical design of monitoring programs.

1.2 Sound Management

Sound ecosystem management is guided by a set of well-articulated management and conservation goals. It is these goals that inform and drive the construction of a monitoring program (see Tolle et al., this volume). Yet two essential attributes of ecosystems complicate the design of ecosystem monitoring studies. First, ecosystems are extremely complex, often covering multiple spatial and temporal scales and involving many processes, patterns, and species. There are countless things that *could* be measured, but there are never enough resources or expertise to study everything. The research and monitoring focus must be narrowed to those components that are thought to be most critical, most likely to be affected by threats, or are the targets of management actions (Rapport 1992, Schindler 1995). There is no doubt that some misconceptions and errors arise from narrowing the focus, but monitoring programs can be refined as new information is collected — this is the essence of adaptive management (Holling 1978, Bormann et al., this volume).

To further complicate matters, we have an incomplete or even poor understanding of most ecosystems. Much of the work in ecosystems is either focused on a single entity and treated as disconnected from the entire system (e.g., commodity production), or at best, reflects our "best guesses" about critical functions. It is especially important that scientific work, both review of existing research and new research, *precede* the creation of monitoring plans as much as possible. Good plans are born of good scientific information.

The second attribute of ecosystems that complicates the design of monitoring studies is ecosystems tend to respond slowly (decades or longer) to manipulative forces (e.g., stress, management). A central purpose of monitoring is to track results of management actions and to provide a timely warning of ecosystem changes, but whole-ecosystem measures may not signal problems until degradation is well advanced (Rapport 1992, Schindler 1995). We require measures that are sensitive enough to be adequate indicators of change, while still maintaining a link to the whole ecosystem (Ryder and Edwards 1985, Schindler 1987, 1990). A conceptual understanding or model of ecosystem processes is important when we are measuring only a few things in a large ecosystem: the model articulates our understanding of how the measures relate to the whole system.

Monitoring programs can — and should — take dramatically different forms because their ultimate purpose is to provide information for decision-making (Box 1). The proximate drivers of the details of the monitoring plan are the stated management goals and objectives (see Tolle and Powell, this volume). These goals suggest in literal ways the quantities and processes to monitor. Ideally, they also state quantitative expectations for ecosystem performance (Fig. 1 and

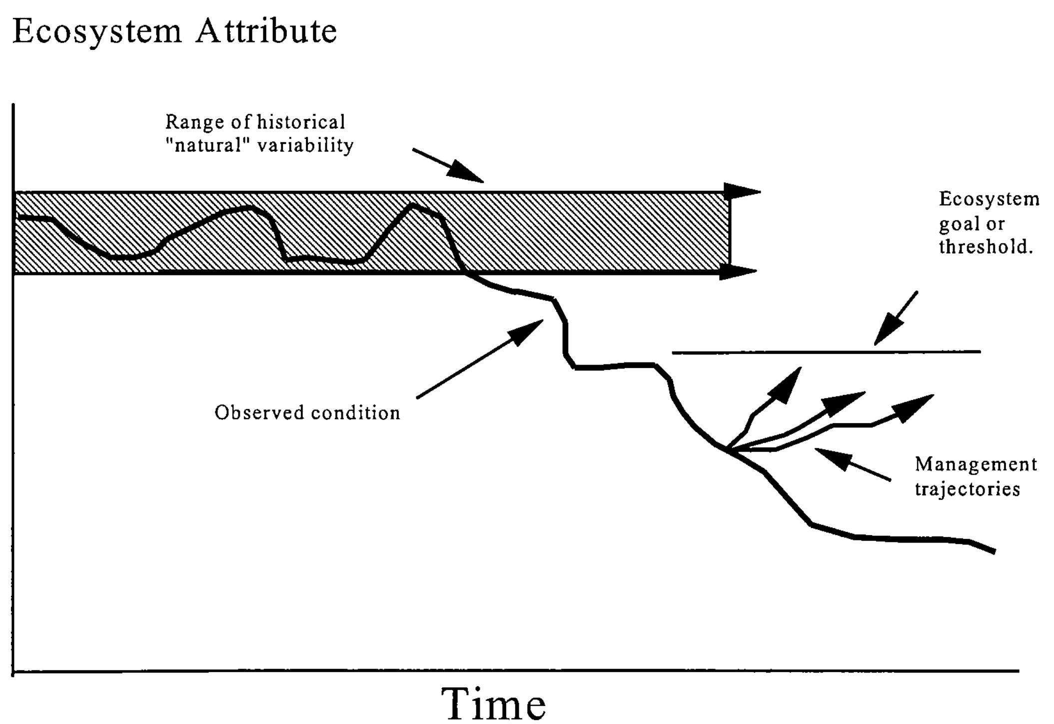

Fig. 1. Chronological time in an ecosystem, showing changes in overall aspect and the responses to management actions (modified from Cairns et al. 1993).

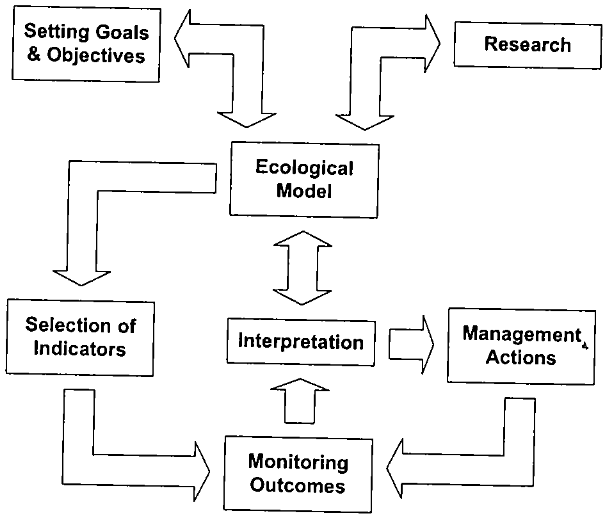

Fig. 2. Adaptive management integrates management actions and monitoring data through the prism of an ecological model.

Section 5). We argue, however, that the ultimate driver of the monitoring plan is our best understanding of the ecological facts of the ecosystem, embodied in an ecological model (Fig. 2). It is the ecological model, with its boxes and arrows depicting critical system components and processes, that tells us what to monitor. In fact, it also helps to tell us what to manage. We emphasize that construction of an ecological model, and by extension, planning and execution of a monitoring plan, does not occur in a vacuum. Management and monitoring planning occur together as part of an overall process of ecosystem study and adaptive management (see also Bormann et al., this volume).

This chapter outlines a progression of scientific thought that leads to the production of a monitoring plan that "asks the right questions." Central to this progression is the development of an ecological model that reflects and guides our thinking and drives our choice of monitoring and research questions. In particular, this chapter:

- Discusses the creation of a *conceptual ecological model* that arranges key ecosystem properties and processes into a causal path diagram. Central to this is the critical role of initial inquiry, a process that culls from the infinite number of questions that could be asked, and results in the identification of key patterns and processes—the essential properties of the ecosystem and its management. These essential properties are arranged in the model.
- Outlines how an ecological model, in its identification of key processes and links in the ecosystem, drives the selection of *monitoring indicators* that facilitate the evaluation of management success. Indeed, the ecological model informs the monitoring goals and plan, and the entire adaptive management process. We emphasize throughout this paper that ecological modeling is not a goal in itself. It is a tool for organizing knowledge in the service of management.

We conclude with two case studies that illustrate how the successful use of ecological models helps organize and communicate ideas and informs management and monitoring decisions.

2 THE ROLE OF MODELS IN MONITORING

2.1 Three Roles of Ecological Models in Monitoring

Ecological models express a progression of scientific thought that starts with determining key ecological components, and ends with a summary of the causal ordering and relationships among them. We can view ecological models as maps or flowcharts that literally help navigate direction and interpret results, guiding monitoring programs in three general ways (Box 3).

First, models summarize the most important ecosystem descriptors, spatial and temporal scales of major biological

BOX 3
THREE ROLES OF ECOLOGICAL MODELING IN MONITORING PROGRAMS

- A model summarizes the most important ecosystem descriptors, spatial, and temporal scales of biological processes and current and potential threats to the system. That is, the model explicitly summarizes the *current* biological understanding of the system. The model (a) does not represent "the truth"; (b) is not "final" or unmodifiable; (c) is not expected to be "complete" or include the entire ecosystem. It is a flexible framework that should evolve as understanding of the ecosystem increases.
- A model plays an important role in determining indicators for monitoring. Because the model is a statement of important biological processes, it therefore identifies aspects of the ecosystem that should be measured. If your model is a good reflection of current understanding, but your measurement indicators cannot be seen in the model, then your measurements do not have much to do with the ecosystem.
- A model is an invaluable tool to help interpret monitoring results and explore alternative courses of management. An explicitly stated model is a summary of current understanding of and assumptions about the ecosystem. As such, it can motivate and organize discussion and serve as a "memory" of the ideas that inspired the management and monitoring plan.

processes, and current and potential threats to the system. They provide feedback to, and help formulate, goals and objectives, indicators, management strategies, results, and research needs (Fig. 2). These issues will be discussed in more detail throughout this paper; the point here is that models are a "best-now-possible" description of how the ecosystem is put together. Such an explicit description can identify both the strengths and weaknesses of our understanding of the ecosystem, and thus it can guide planning research and monitoring. This is not to say that the model is "true" or "correct" necessarily, but it should represent your best understanding (Starfield 1997). Nor is the model expected to be "complete" and all-encompassing; rather, it should illuminate components of the ecosystem that relate to management and its impacts. An ancillary benefit of such a description concerns communication. It facilitates open discussion and debate about the nature of the system and important management issues.

Second, ecological models play an important role in determining indicators for monitoring. The model is a statement of important biological processes. It therefore identifies aspects of the ecosystem that should be measured. If your model is a good reflection of current understanding but your measurement indicators cannot be seen in the model, then your measurements do not have much to do with the ecosystem.

Third, ecological models provide a useful tool to help interpret monitoring results and explore alternative courses of management. We can view results from monitoring within the context of key ecological components and processes as identified by the model and modeling process. Questions generated from monitoring results can be answered more easily with the help of an ecological model. Are values within the natural range of variability expected for the system or component? Do results point to the deterioration of key processes? If so, are other system components affected or influenced? Should these be investigated or monitored? Do management strategies need adjustment to address these issues? Is more research needed? Are goals and objectives realistic?

We use monitoring results as part of an adaptive and iterative management process to revise our understanding of the ecosystem. We should use this new information to update and improve the ecological model, our summary statement of the system. Monitoring information may support or conflict with current understanding, inspiring an evolution of understanding. Results sometimes uncover missing links in system dynamics or reinforce well-understood relationships. We can prioritize future research according to such gaps.

Models offer powerful templates for assessing possible alternative management strategies. In particular, models are useful for understanding the impacts of various management actions (e.g., Johnson et al. 1987, Costanza et al. 1990, Liu et al. 1995), natural ecological variability (e.g., Baker 1994), and human-influenced change (e.g., Pearlstine et al. 1985, van Wilgen and Richardson 1985, Keane et al. 1990, Sirois et al. 1994, Ellison and Bedford 1995, Poiani and Bedford 1995).

2.2 Everybody Does It

Every monitoring biologist plans, executes, and interprets monitoring based on some underlying understanding of the biological system. Although this understanding is not necessarily written down, they have a *model* of the way the system works and the things that are important. They use this model to plan and execute monitoring. A central point of this paper is that this model should be explicit and written down for anyone to see and discuss. An explicit model makes the inherent world view clear, and consequently available for discussion, evaluation, and refinement.

We emphasize conceptual modeling and models as a *tool* for depicting and organizing understanding and as a *template* for interpreting data. There is another thread of models that are explicitly mathematical in nature (i.e., deterministic or simulation models). While these can be helpful in certain monitoring and many research contexts (Starfield 1997), we do not emphasize them here. Rather, we encourage the use of conceptual ecological models that depict ecological relationships. Such models are not ends in themselves, but rather helpful organizers of thought, information, and ideas.

Starfield (1997 and references therein) provides an excellent review of modeling in wildlife management. Of particular interest is his "seven misconceptions about modeling" (reproduced in Box 4). We highly recommend his paper, in which he discussed at length these misconceptions, which are often cited by monitoring biologists as impediments to modeling. Starfield's point, also promoted in the current paper, is that modeling in a management and monitoring context is primarily an exercise of intellectual organization.

3 UNVEILING THE SYSTEM

We and others stress the spatial and temporal complexities associated with natural systems (e.g., Turner et al. 1995, Jensen et al. 1996, Lewis et al. 1996, Willson 1996). It is these complexities that make ecological systems so valuable, and at the same time so difficult to manage and monitor. Identification of ecosystem components, relationships, and essential properties, however, can help us sort through complex patterns and

BOX 4
SEVEN COMMON MISCONCEPTIONS ABOUT MODELING (IN ITALICS), AND WHY THEY ARE INCORRECT (from Starfield 1997)

1. *A model cannot be built with incomplete understanding of the behavior of a system or population.* In fact, management decisions are typically made without a full understanding of the system. This is additional incentive to build a model rather than an excuse for not building one.
2. *It is not useful to build a model if there are gaps in the data the model is likely to need (so the priority is to collect data).* In fact, management decisions are often made with missing or incomplete data. Again, this is incentive to build a model, since a model can help us judge which data are needed and the potential effects of missing data.
3. *A model cannot be used in any way until it has been validated or proven to be accurate.* In fact, models in management should be viewed as thought experiments that help us evaluate the consequences of our assumptions. We should use them to ensure that our assumptions are reasonable and consistent and the data we collect is relevant. In this context, "validation" in the usual sense is irrelevant.
4. *A model must be as realistic as possible, accounting for all the detailed intricacies of a biological system.* In fact, we design models in management in order to evaluate specific alternatives. Such purposeful models should be restricted to their essential components.
5. *Modeling is a process akin to mathematics; as such it cannot be used or understood by most managers and field biologists.* Although some mathematical models are complicated, an important reason for building models is to facilitate communication. Essential simplicity and clarity are important criteria for any model.
6. *The primary purpose of building models is to make predictions.* In fact, management oriented models are pragmatic, and should be focued on the evaluation of alternatives.
7. *Modeling is time-consuming and expensive; it follows that models must be designed to answer all the questions that have been thought of, or questions that may arise in the future. The more multipurpose the model, the better the investment value.* In fact, models should be focused problem solving tools that target specific issues of concern. they are most effective when we use them to distill our thought.

processes and guide our monitoring efforts for the most effective results. Fortunately, ecological models can help formulate and articulate relationships among complex ecosystem components.

There is a process of intuitive and inductive thought that leads to the development of an ecological model and monitoring program. The first stages of this process involve acquiring at least a preliminary understanding of key components and processes and the spatial and temporal scales at which they operate. For many or most ecosystems, knowledge will be incomplete and patchy. However, sources of information include previous research, particularly historical patterns and other management experience, comparison of similar ecosystems, and biological experience and intuition (Box 5).

BOX 5
SOURCES OF INFORMATION FOR EARLY DEVELOPMENT OF AN ECOLOGICAL MODEL

- Previously collected data, photos, and published research.
- The experience of other experts.
- Your own biological intuition.
- Pilot research.

Ultimately, the success of a monitoring program rests on the quality and scientific defensibility of the indicators used in measurement (Cairns et al. 1993; and see below). Defensibility rests in both quality of the methods used to measure the indicators and the relevance of the indicators to the management problems at hand. Asking the right questions at the outset, and subsequently translating the answers into an ecological model, is the foundation of this defensibility.

3.1 Types of Models

An ecological model is a conceptual or mathematical representation of a natural phenomenon or system. Ecological models are abstractions or simplifications of

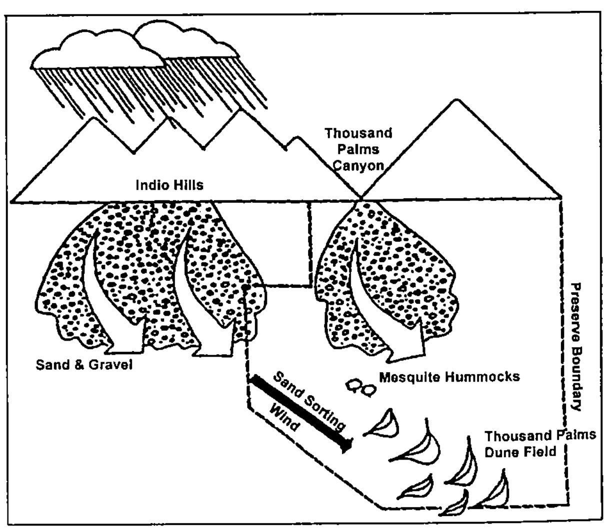

Fig. 3. Ecological model of sand transport for the Thousand Palms preserve, Palm Springs, California (from Barrows 1996).

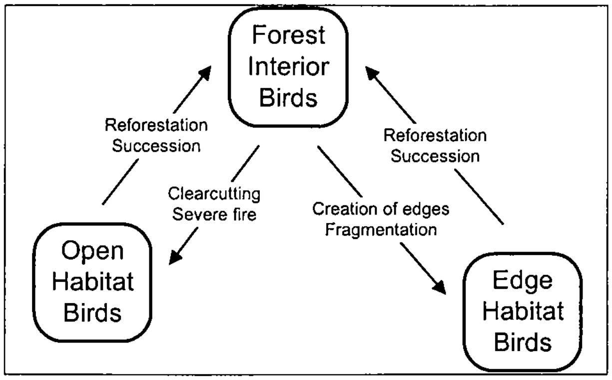

Fig. 4. Forest interior bird state-transition model.

the real world. Typically, they define relationships among system variables or *states* and system processes or *transitions*. These relationships help predict change in a system over time, depending upon trajectories of, or perturbations to, key processes.

Ecological models come in a variety of forms and levels of complexity and can be profitably applied to numerous problems in ecological analysis. Models can consist of narrative descriptions, schematic diagrams (Fig. 3), or box-and-arrow flowcharts (state-transition models, Fig. 4). They also may be analytical (simple or complex numerical equations) or programmed within a computer environment (dynamic simulation model). This latter group of models varies greatly. Examples of simulation models include population viability models (e.g., Lindenmayer et al. 1993, Ruggiero et al. 1994, Marcot and Murphy 1996), small-scale forest gap models (Shugart 1984), spatially explicit population-, community- or landscape-level programs (e.g., Costanza et al. 1990, Poiani and Johnson 1993, Baker 1994, Ellison and Bedford 1995, Liu et al. 1995), and regional-scale, complex whole-ecosystem models that often consist of smaller-scale models embedded within them (e.g., Burke et al. 1990, Lauenroth et al. 1993). Conceptual relationships form the basis of all simulation models (i.e., states and transitions that are mathematically programmed). We can usually construct conceptual models relatively quickly. Dynamic simulation models, in contrast, can require extensive resources to develop.

We can develop conceptual ecological models for a wide variety of ecosystem components or whole systms, depending upon the needs and uses of the model. Conceptual models illustrate species, population, or groups of species dynamics, including life cycles of key organisms (Fig. 5), population response and viability (Fig. 6), or compositional changes (Fig. 3). We can construct models for natural vegetation community types or mosaics of community types that form broad habitats (Fig. 7). Models can be constructed for ecosystems in their entirety (Fig. 8), or focused primarily on ecological processes such as nutrient cycling (Fig. 9).

The type of model constructed for any given situation depends on the scientific questions being asked, goals and objectives of the program, and characteristics

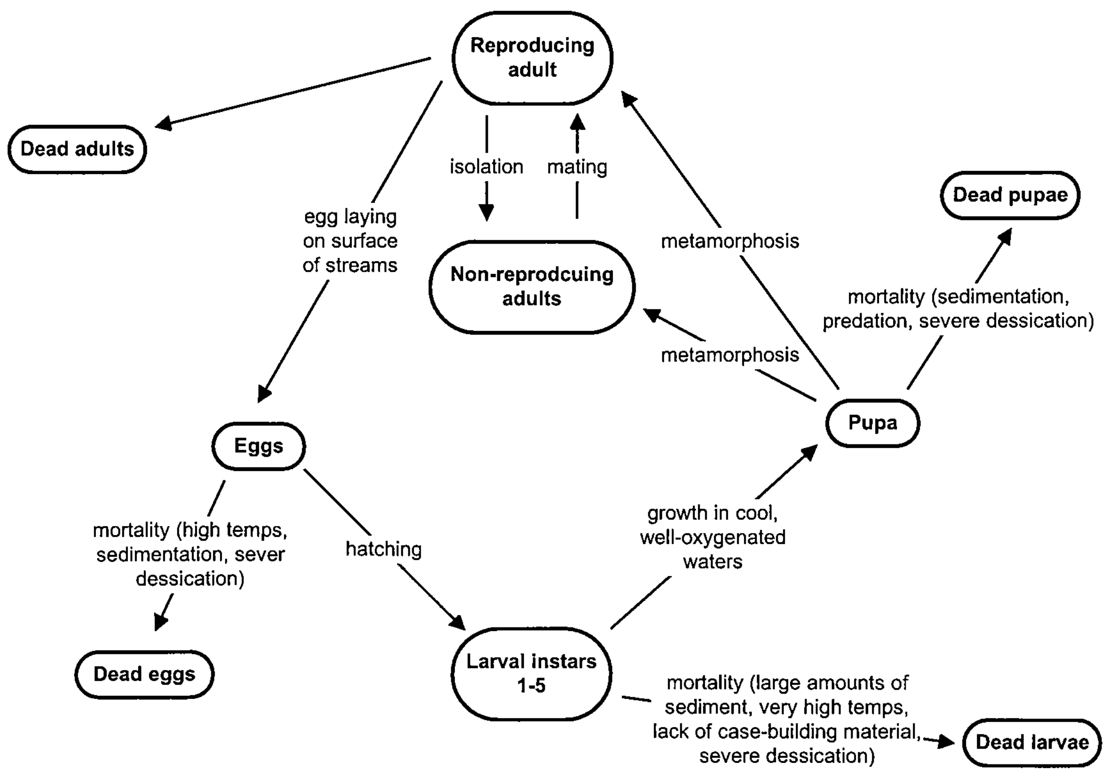

Fig. 5. Life cycle of aquatic insect model.

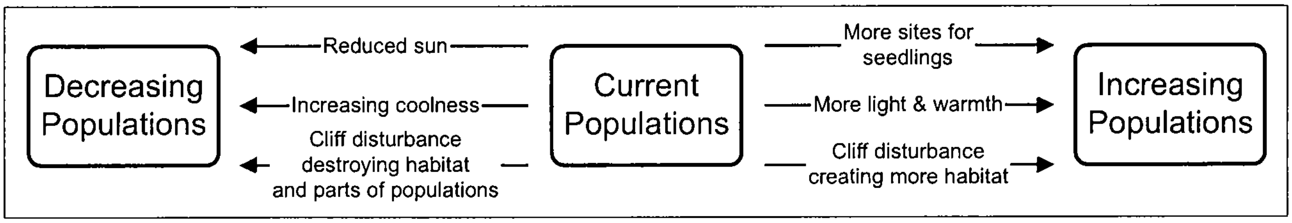

Fig. 6. Northern monkshood model. Model development by R. Sutter (pers. comm.).

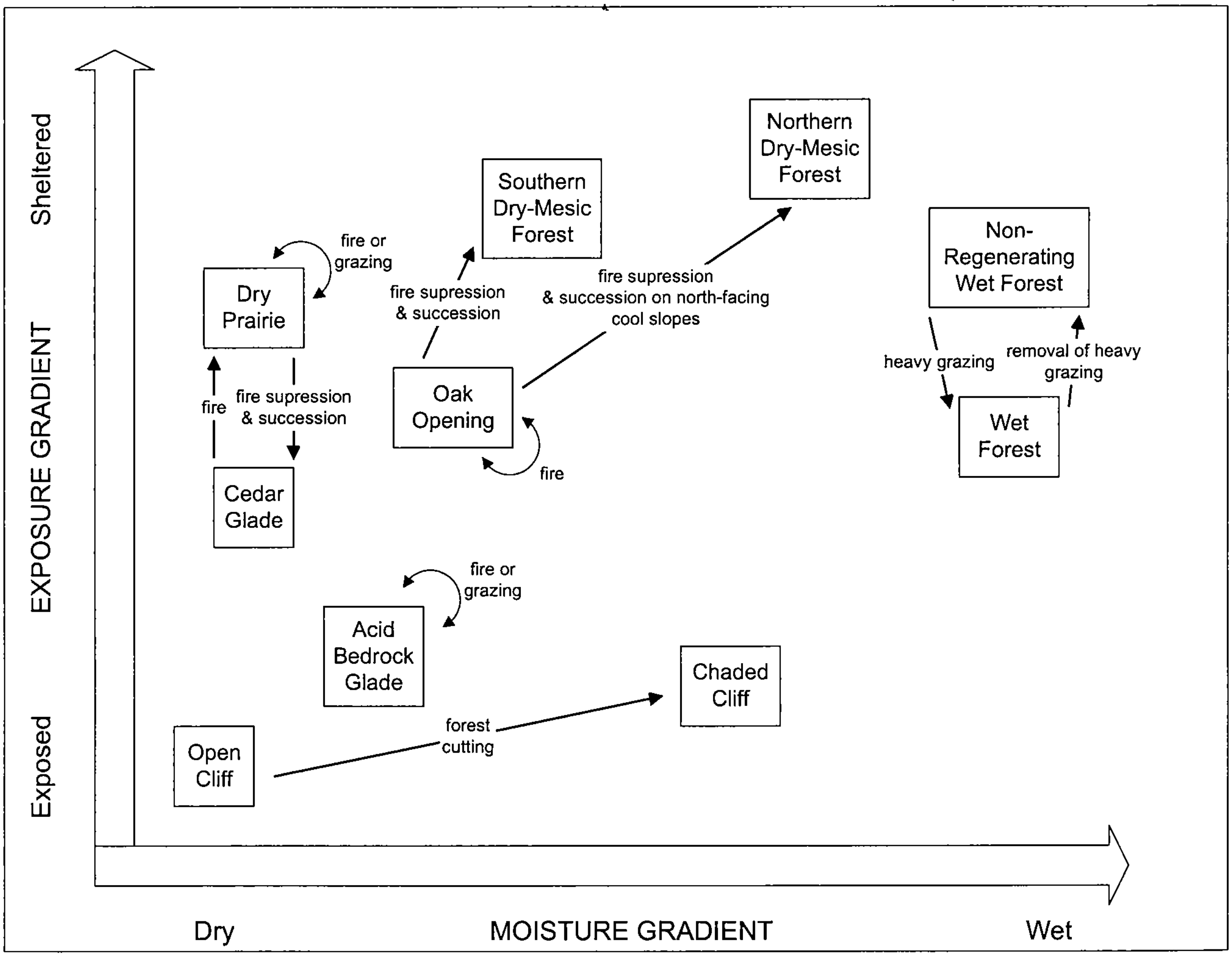

Fig. 7. Vegetation mosaic model for natural community types in midwestern United States.

of the ecological system or systems being managed. Models are flexible tools that are most helpful when they are designed to help solve specific problems.

3.2 Divining Essential Properties, Understanding Pattern and Process

To manage well we strive to understand ecosystem pattern and process. A causally ordered ecological model will eventually articulate state-of-the-art understanding of the ecosystem. Two sequential steps prior to this are development of a general appreciation of ecosystem character and articulation of a specific set of the ecosystem's essential properties. Table 1 lists a variety of questions pertinent to the development of ecological understanding and eventually a monitoring study. These questions were modified from Quattrochi and Pelletier (1991), who discussed uses of remote sensing data and analysis in landscape ecology. The questions form a good starting point for thought about ecosystems. They emphasize pattern, process, and scale, focusing thought on the links between ecosystem attributes and management. What should be clear is that relevant questions can (and probably should) be

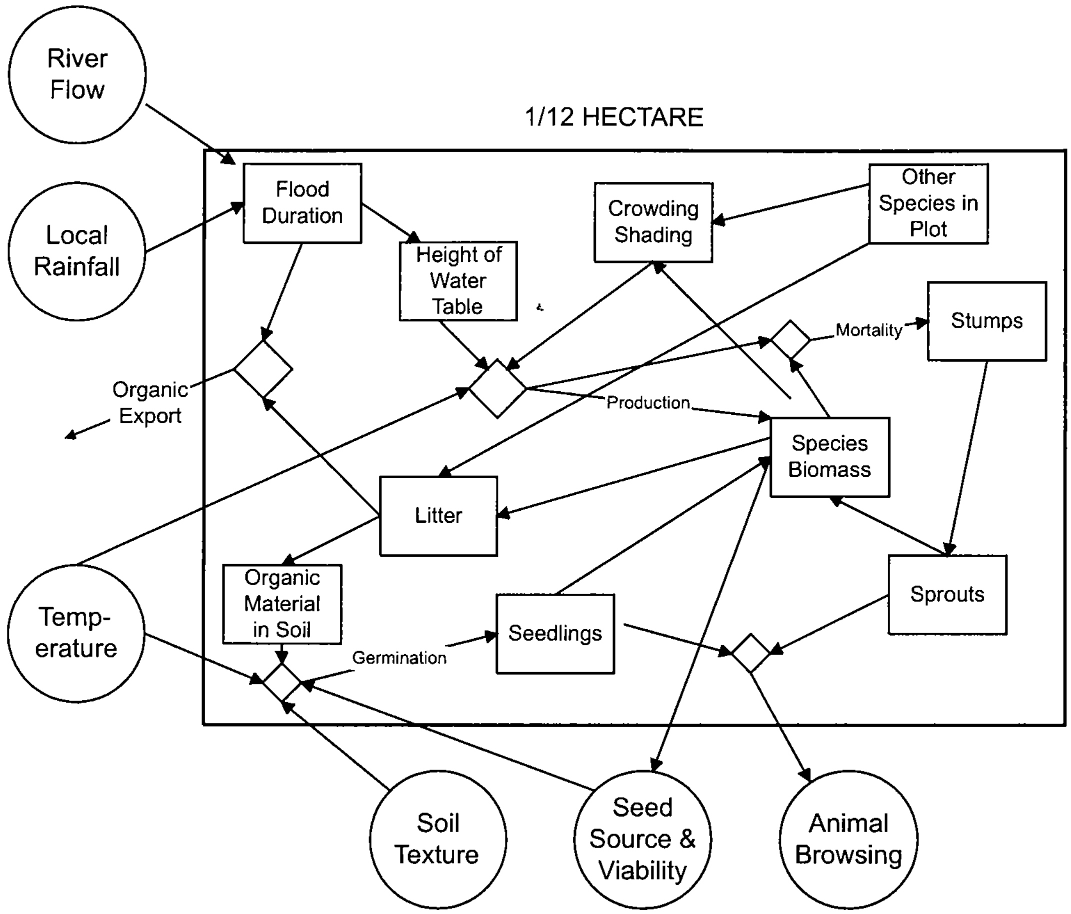

Fig. 8. Whole ecosystem model, FORFLO, a forest succession simulation model (from Pearlstine et al. 1985).

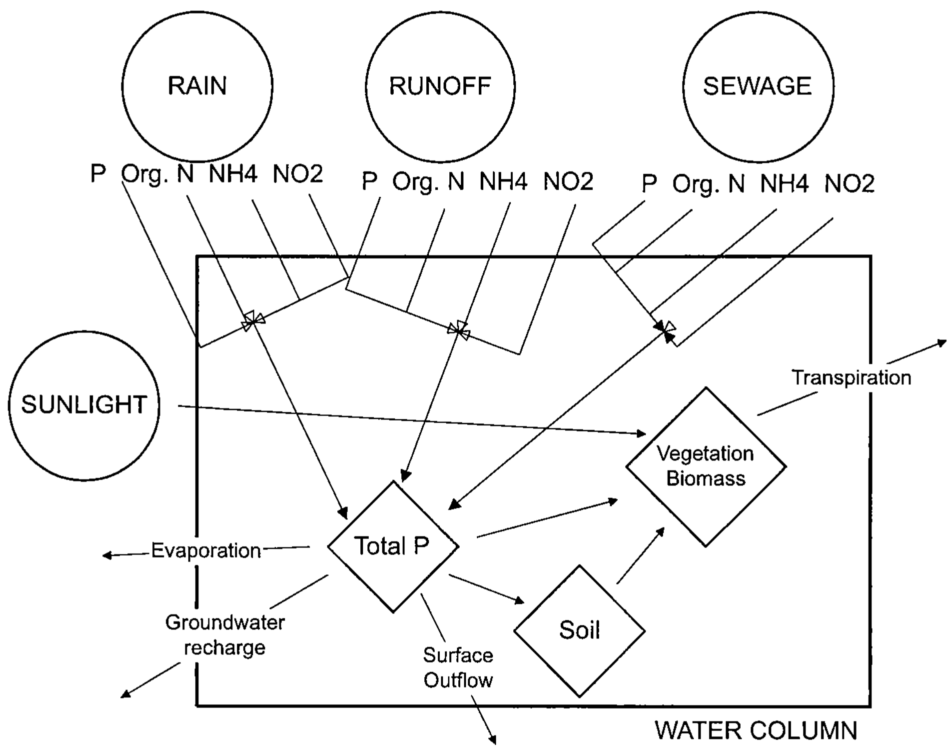

Fig. 9. Nutrient simulation model for wetlands typical of Florida (from Brown 1988).

Table 1. Pertinent questions in the development of an ecosystem monitoring plan (modified from Quattrochi and Pelletier 1991).

Questions of Space	What is there? Species composition (presence of abundance of significant alien species, keystone, dominant, or economic species) Community types present; their absolute and relative abundance Land cover attribute (e.g., forest, field, urban) Terrain attributes (e.g., topography)
	What is the pattern of ecosystem attributes?
	What is the spatial scale required for management and policy decisions?
Questions of Time	What are the temporal dynamics of ecosystem components? What are the temporal scales of changes in ecosystem components? What are the temporal scales of the effects of management?
Questions of Dynamics	What kinds of processes shape the ecosystem? Explicit (i.e., easily observable) Implicit (i.e., not easily observable) Natural (i.e., undisturbed) Uncontrolled disturbances (e.g., exotic species) Controlled disturbances (e.g., resource harvest, controlled burning)
	Temporal occurrence of these processess Continuous Pulsed Chaotic or random
	Biological levels that reflect or indicate these processes Population dynamics Community composition Spatial arrangement Ecosystem process (e.g., nutrient cycling) Statistical index (e.g., "Index of Biological Integrity")
Quesitons of Management	What are the human uses? What are the management goals?
	What are the reporting requirements (i.e., what kind of information is known to be critical for policy making and reporting to the public)?

drawn from widely different ends of the biological spectrum. Also, there are a number of basic issues of spatial and temporal scale that must be appreciated.

To create effective monitoring programs, we must answer the questions in Table 1 and separate out those properties that help us understand, order, and ultimately measure important aspects of the ecosystem. That is, we must identify the critical, or essential features and processes. Keddy and Drummond (1996) provide an excellent example of this kind of analysis, describing a program of management and restoration in mature deciduous forests in eastern North America. They identify 10 properties that measure forest condition (Table 2), along with extensive citations of scientific support. They determine properties using historical and recent data from numerous primary forests within the geographic zone, preferring characteristics that reveal consistent patterns. For each property, Keddy and Drummond (1996) establish specific ranges, derived from the data, and propose them as "rules" or thresholds for three categories of forest status: "control," or characteristic of mature forest; "intermediate"; and "low," or characteristic of altered forest.

Of course we can debate the particular elements of Keddy and Drummond's list or the specific threshold values they propose. They wisely caution against taking the measures singly, rather recommending that they should be interpreted as a group. Nor do they propose a complete model in the sense that we advocate in this paper; it is not structured into a set of causal relations that would help us understand their interrelations. But such a list of essential properties for an ecosystem provides two things critical to adaptive management: a diverse set of integrated measures for

Table 2. List of essential properties proposed by Keddy and Drummond (1996). Modified from their table.

Property	Measurement	Control	Intermediate	Low
Stand Indicators				
1. Tree size	Basal area/ha	>29	20–29	<20
2. Canopy composition	Proportion of shade-tolerant species	>70%	30–70%	<30%
3. Coarse woody debris	Presence of large decaying logs (>8 logs per ha)	both firm and crumbling	either form or crumbling	no large logs
4. Herbaceous layer	Number of ephemeral species	~6	2–5	<2
5. Corticulous bryophytes	Number of species	~7	2–6	<2
6. Wildlike trees	Snags/10 ha	4	1–3	0
7. Fungi	No information			
Lanscape Indicators				
8. Avian community	Number of forest interior species	~5	2–4	<2
9. Large carnivores	Number of species	~6	2–5	<3
10. Forest area	Hectares	$>10^5$	10^2–10^5	$<10^2$

monitoring, and a quantitative framework, derived from data, for identifying threshold values of critical change.

Other basic information about the ecosystem is also of help. Knowing something about long-term natural variability in the system can assist greatly in evaluating the significance of changes, thus helping to avoid costly management errors. That is, if you know the extent of "natural" variation in the past, you are more capable of identifying out-of-the-ordinary variation in the future. Historical data on some ecosystems are available, and have been used in numerous studies of land-use change (e.g., Whitney and Somerlot 1985, Lowell and Astroth 1989, Richter 1997). We can use historical data in three general ways: (1) to suggest long-term trends that are cause for concern and that may suggest targets of monitoring; (2) to set critical thresholds based on natural variation (i.e., variation outside historical limits is deemed noteworthy); and (3) to identify radical changes resulting from specific events (e.g., dam construction, clear-cut, hurricane), which in turn may suggest vulnerable facets of the ecosystem.

Similarly, behavior of unmodified ecosystems can help us evaluate the effects of management and stress in focus sites. Such an approach is of course limited by the lack of experimental controls in the usual statistical sense. Nevertheless, the comparisons may lead to helpful hypotheses that can be pursued with more rigor. For example, Shearer et al. (1987) and Schindler (1995) describe a process they call "baseline drift," exemplified by a case in which acidification was thought to be increasing phytoplankton production. Later it was noticed that *all* lakes (including unmodified ones) were increasing in production. At the root, this is simply a statement that scientific care must be taken in the interpretation of patterns. Adequate controls are required to make clear conclusions about causative agents of ecosystem change.

3.3 A Process for Constructing Ecological Models

Constructing an ecological model is an interactive, iterative process (Box 6). Models are never complete. In some cases, we should gather data and information on the entire system, then develop models for key compo-

BOX 6
STEPS FOR CONSTRUCTING AN ECOLOGICAL MODEL

(1) Gather and assemble relevant data, information, and knowledge on system components and whole-system processes.
(2) Decide on structure of model.
(3) List all important states, transitions, entities, and threats.
(4) Illustrate known and record unknown relationships among system states.
(5) Discuss draft and revise as needed.
(6) Send out model for review.
(7) Update and improve model as new information becomes available.

nents or whole-system processes. In other circumstances, we should select focal species, communities, community complexes, or dominant processes (e.g., nutrient cycling) first, then gather information for a model. The order of events depends to some extent on the intended use of the model, how well the system is understood, and whether there are obvious targets or key components that represent the system adequately. Sometimes key components are mandated (e.g., endangered species) or obvious, in which case our initial modeling efforts can focus on these.

We must gather information for constructing an ecological model from many sources, including published papers, unpublished reports, and gray literature documents, comparison to other similar systems, expert knowledge, logic, and intuition. Expert knowledge is an excellent source of information and often underutilized. For example, informal "modeling workshops" with local biologists and land managers can provide a first-draft model in a relatively short time. Scientists and managers working in the field contribute knowledge and intuition typically not found in journal papers. In particular, they often know which ecosystem components and relationships are least understood.

We outline below a series of suggested steps for assembling conceptual ecological models. We suggest starting at the simplest level and progressing to more complex models as warranted. We emphasize assembling state-transition models, but the same general process can be applied to other types. We present the steps sequentially, but they may actually be performed simultaneously, and each may be revisited after completing subsequent steps.

1. *Gather and assemble relevant data, information, and knowledge* on system components and whole-system processes (see above).

2. *Decide on structure of model.* For example, is the system (or its components) best represented by a schematic diagram, a state-transition flowchart, or a written description? Who is the audience? How will we use the model (e.g., determine indicators, analyze threats, present information to stakeholders)? Can we build on something already started?

3. *List all important states, transitions, entities, and threats.* We can initially generate a written list of all important states and transitions before proceeding with a diagram. Then as the flowchart emerges, we can check it against the initial list to insure that no key components are omitted.

4. *Illustrate known and record unknown relationships among system states.* Draw states in boxes and show interactions among them using arrows. Indicate all known relationships as applicable, including successional processes, forcing functions, driving variables, human alterations, and biotic and abiotic processes. Indicate all unknown or suspected relationships in a manner that identifies their level of uncertainty. We can identify transitions as verbal descriptions (Fig. 7) and/or numerical relationships, if known (Fig. 10).

5. *Discuss draft and revise as needed.* Step back and view the model. Discuss, digest, and revise diagram as needed. Revisit and discuss more thoroughly uncertain or controversial components.

6. *Send out model for review.* Solicit feedback from ecologists and biologists working in similar systems or in other locations. Ask non-scientists to review results if the general public or other nontechnical persons will use them.

7. *Update and improve models as new information becomes available.* It is crucial to revisit and revise models periodically. We are always increasing our knowledge of ecosystems. Ongoing monitoring and research provide important feedback to model assumptions that may support or conflict with current understanding. Update models often. Review assumptions and key components. Adaptive management and monitoring depend on this feedback loop.

4 INDICATORS

A well-constructed ecological model depicts the central, critical, and driving processes of a system. The model, therefore, directly suggests components to monitor. In the language of the Monitoring Evaluation chapter (see Tolle and Powell, this volume), the model identifies information needs and monitoring objectives. What remains is to devise measures, or *indicators* for these processes and outcomes.

For example, Figure 4 depicts a model of the relationships among aspects of forest landscape structure and the abundance of three guilds of birds: forest interior, edge-loving, and birds of open habitats. Let us assume for argument that this model adequately reflects current understanding. The model explicitly shows patterns and processes that promote or discourage the three guilds. Thus, it suggests aspects of the ecosystem we can measure to track progress toward or away from management goals and the potential causes of these changes. In particular, the model recommends measures of landscape structure (e.g., fragmentation and the abundance of various habitat types) in

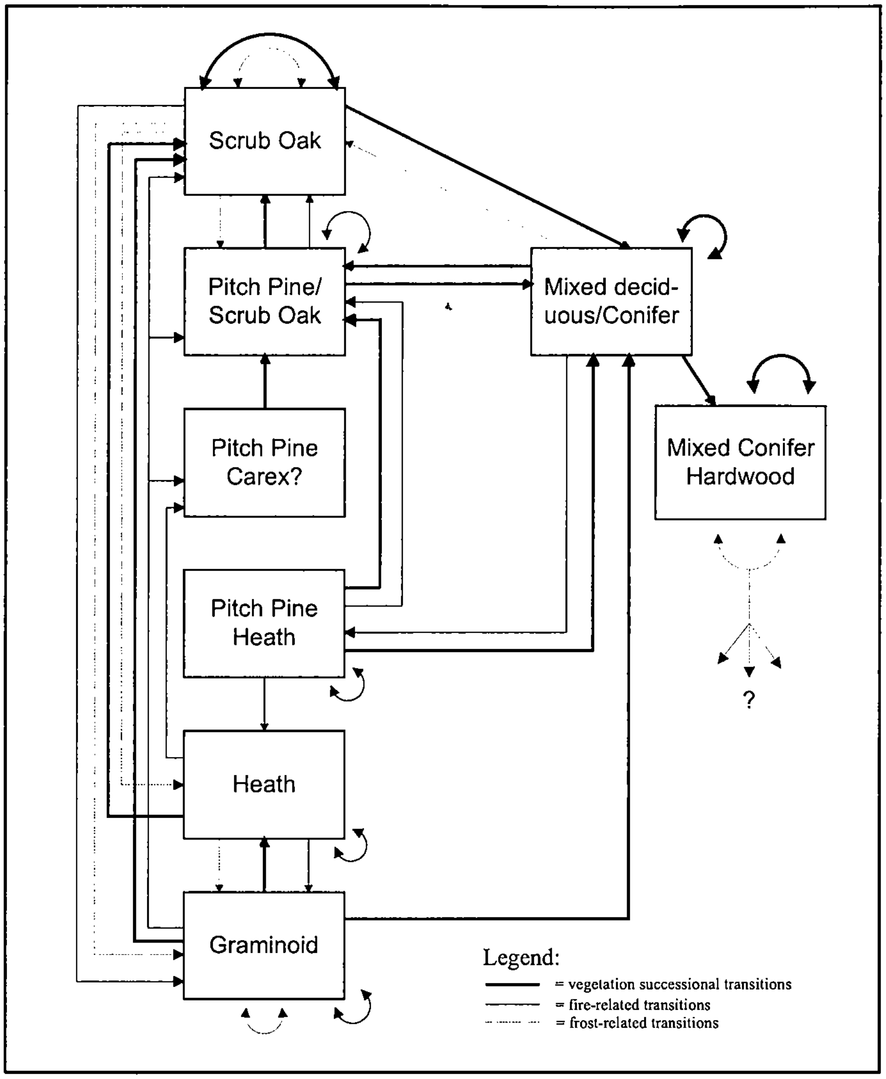

Fig. 10. State transition model for Waterboro Barrens, Maine.

addition to the abundance of the three guilds. Management actions that promote certain types of habitat should have measurable effects on guild abundance.

4.1 Good Indicators

The ecological model points the way toward appropriate indicators. Successful monitoring, and therefore successful evaluation and assessment of management, depends on appropriate and *well-crafted* indicators — good indicators. Precisely what good indicators are depends on the exact situation, reflecting the idiosyncrasies of the ecosystem and the management and policy goals. Good indicators have a number of general attributes (Cairns et al. 1993, also discussed in Tolle et al. in this volume). We require effective, repeatable, and hopefully unbiased measures, which in general means that they are *scientifically useful and defensible.* Cairns et al. (1993) provide an excellent summary of the various qualities of indicators and the purposes to which they are best put.

We emphasize three broad classes of indicators that have important scientific qualities and have complementary uses in monitoring programs (Box 7, Cairns et al. 1993).

BOX 7
THREE CLASSES OF INDICATORS USED IN MONITORING

- *Assessment indicators* allow simple temporal tracking of ecosystem character or comparisons of observed ecosystem attributes to expected or hoped-for values.
- *Predictive indicators* give warning of ecosystem stress.
- *Diagnostic indicators* enrich interpretation of the causes of ecosystem changes.

- *Assessment indicators* allow simple temporal tracking of ecosystem character or comparisons of observed ecosystem attributes to expected or hoped-for values; that is, whether management actions are having desired effects. (In the bird guild example, indicators of guild abundance and fragmentation are assessment indicators.)
- *Predictive indicators* give warning of ecosystem stress; that is, they facilitate detection of steady-state or problems before it is too late. (Again, from the guild example, forest fragmentation is also a predictive indicator.)
- *Diagnostic indicators* enrich interpretation of the causes of ecosystem changes; diagnosis is greatly aided by historical data or experimental controls that allow comparison of manipulated and unmanipulated areas. (There are no diagnostic indicators in the guild example because the relationship between fragmentation and bird guild abundance had been previously established.)

These types of indicators are interrelated, and it is probable that all three will be required even in simple ecosystem monitoring programs. However, no single indicator will be effective at all three functions. Thus, it is a truism that more indicators are better than fewer, and multiple indicators should have complementary functions. The larger and more complicated the ecosystem, the more indicators necessary for comprehensive monitoring, reflecting the complexity of the ecological model depicting the system. A relatively simple model like Barrows (1996) (Fig. 3) suggests a limited number of focused indicators. A more complicated situation, such as the riparian ecosystem described by Richter (1997) (Fig. 11) requires relatively more indicators (see the case studies in Section 6).

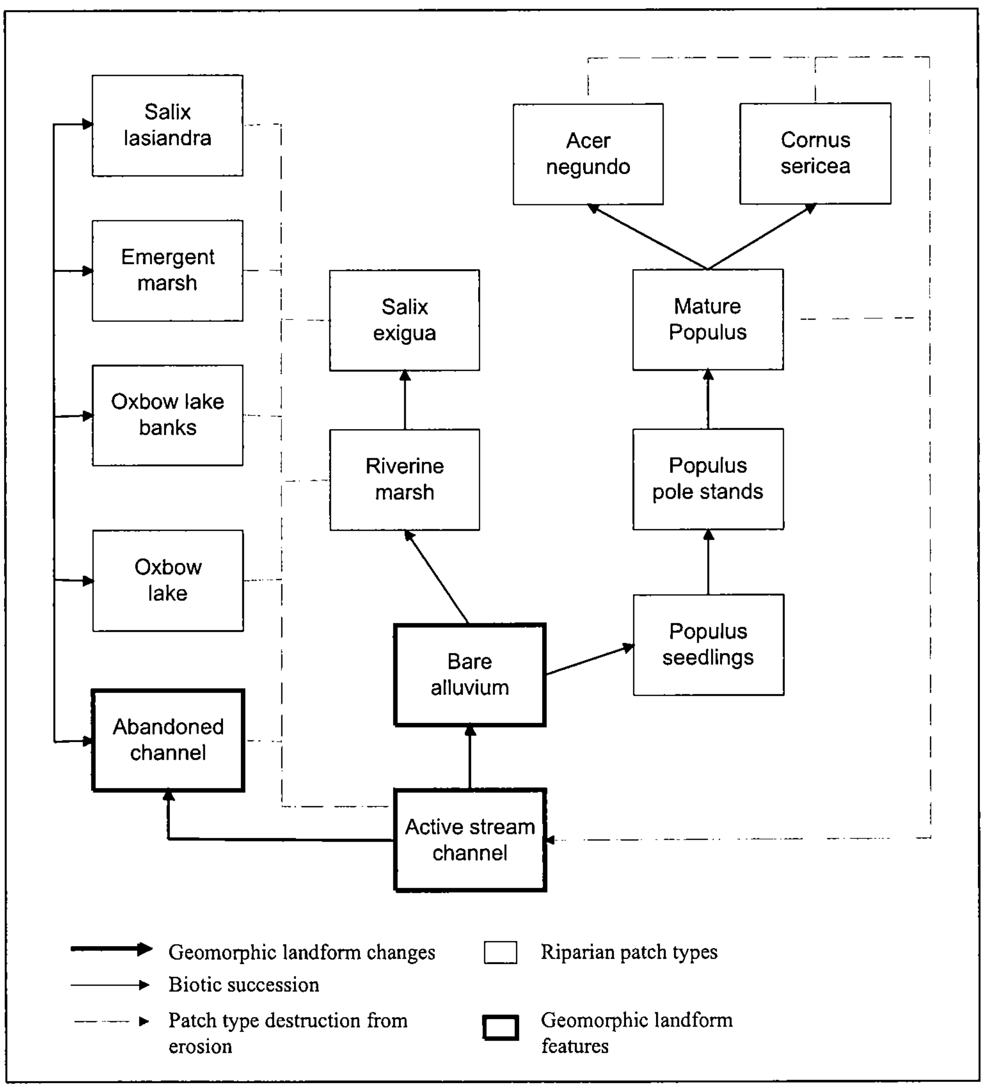

Fig. 11. Ecological model for riparian ecosystem at Yampa River, Colorado (from Richter 1997).

4.2 Seek Indicators at Lower Levels of Biological Organization

Monitoring typically involves two related activities: long-term tracking of ecosystem status, and evaluating the effectiveness of management (Fig. 1). For both activities we make a distinction between assessing ecosystem "health" in a descriptive way and monitoring ecological changes in a diagnostic way (Suter 1993). It is tempting to think that assessment of ecosystem condition and change must involve measures of the whole ecosystem (e.g., measures of "ecosystem health"), but this is often not the case. There are a variety of ecosystem and landscape-level measures that have been used as measures of overall ecosystem health (e.g., Karr 1991, Barbour et al. 1996, Roth et al. 1996, Wallace et al. 1996). However, while these measures can be synthetic measures for description, they typically are not specific enough to be used alone in monitoring programs. In particular, they often lack diagnostic and predictive ability because they tend to summarize many patterns and processes lower down the biological scale (Suter 1993). Makarewicz (1991) makes this point for photosynthetic rates as measures of limnological health. After two years of monitoring, it was determined that because many variables are correlated with variation in photosynthetic parameters, photosynthesis is a confusing indicator of ecosystem health.

Changes in communities and sensitive species — that is, ecosystem components at lower scales of organization — are typically much better, earlier, and more sensitive indicators of ecosystem stress (Schlinder 1987, 1990; Rapport 1992; Suter 1993). Thus, and perhaps counterintuitively, the most effective measures for monitoring ecosystems in a *diagnostic* way are usually not multidimensional or whole-ecosystem variables. Rather, the most effective measures illuminate *key processes and components*. Additionally, we can more easily interpret and communicate variation in components at smaller scales of biological organization. For example, Schindler (1987, 1990) reported that the most sensitive species in aquatic communities responded sooner to acidification and eutrophication than all but one ecosystem-level measure. Lake trout have been effectively used as indicators of the health of aquatic ecosystems (Ryder and Edwards 1985). Trout are conservative indicators because their populations are quick to respond to pollution and relatively slow to recover.

Still, we must always keep in mind the link between such components and the whole ecosystem, however poorly this link is understood. The ecological model provides a description of the ecosystem that helps us focus on particular elements of interest and importance. Once their relevance to ecosystem structure and function is made clear, the inherently more sensitive lower-scale indicators are much more effective instruments for ecosystem assessment and change detection. Such indicators vary in comprehensible ways, and the meaning of the variation can be interpreted and communicated in light of the model.

In sum, specific indicators can be drawn liberally, but should derive directly and explicitly from the ecological model. With this explicit link, it is possible to evaluate the efficacy of management as it affects the entire functioning ecosystem. It also facilitates reevaluation of the ecological model itself, and thus, the working understanding of the ecosystem.

5 EVALUATING MANAGEMENT SUCCESS

The classic role of monitoring is the routine assessment of the status of a resource and the success of management actions. These can take several forms (see Tolle et al., this volume). One is: "Are we performing the management we said we would?" In the language of the U.S. Forest Service, this is "implementation" monitoring. More relevant to this chapter is: "Are management actions producing a prescribed or desirable outcome?"

There are two critical points to be made about evaluation (Box 8). First, a steady drumbeat in this chapter has been that monitoring must be focused on specifically articulated questions. Stated another way, monitoring studies *must* be designed to evaluate something specific. Unfocused data collection that has no clear evaluative purpose is a waste of resources because there can be no benchmarks for success, failure, or most importantly, conclusion.

The second point follows directly: evaluation is more likely to be successful if the criteria of evaluation are worked out in advance as part of an overall concept of management and monitoring. Criteria for evaluation involve decisions about what variables to measure (i.e., study design) and also what results constitute management success or failure. In other words, after you have collected the data, how will you recognize success and failure of the management?

BOX 8
EVALUATING MANAGEMENT SUCCESS

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- Evaluation is more likely to be successful if the evaluation criteria are worked out in advance as part of an overall concept of management and monitoring.

5.1 Quantitative Standards

The most effective and direct way to evaluate management requires that management goals be stated in quantitative terms, with clear thresholds for achievement. Quantitative goals facilitate quantitative and (relatively) unambiguous evaluation. There are three primary reasons that quantitative goals and standards are helpful (Box 9). First, they are easy to communicate among biologists, policymakers, and the public, and thus are better for inspiring debate and discussion about their appropriateness. Vague goals are indefensible.

BOX 9
THREE REASONS TO DETERMINE QUANTITATIVE ECOSYSTEM MONITORING STANDARDS

- They are easy to communicate, and thus are better for inspiring debate and discussion about their appropriateness.
- They provide a clear benchmark for evaluation, either in the form of "success" (we have restored ecosystem values to some predetermined level) or concern (the ecosystem has changed by a significant degree).
- They routinize many difficult sampling and statistical issues, especially with regard to the sampling intensity required to adequately measure the biological changes and patterns expected.

Second, they provide a clear benchmark for evaluation, either in the form of "success" (e.g., we have restored ecosystem values to some predetermined level) or concern (e.g., the ecosystem has changed by a significant degree). Of course, one needs to have a vision of what success looks like. This is where previous research and experience, pilot data, and expert consultation, all embodied in an ecological model, come into significant play.

Third, they clarify many difficult sampling and statistical issues, especially with regard to the sampling intensity required to adequately measure the biological changes and patterns expected. With quantitatively stated goals we can plan rigorous monitoring studies and pay explicit attention to sampling methodology and statistical power (see the next subsection). In fact, once we define quantitative standards, many of the methodological and statistical issues follow routinely.

Consider the hypothetical ecosystem depicted in Fig. 1, in which we have historical data on "natural" levels of variability and a quantitative ecosystem goal or minimum threshold. It is relatively easy to determine the sample size needed to identify the statistical achievement of the threshold. This, in turn, clarifies monitoring costs and schedules — we know how much effort will be required to measure the variables of concern adequately. We must evaluate management in this quantitatively rigorous way or planning the monitoring program is mere guesswork.

A typical argument against the use of quantitative standards is that such numbers, in our ignorance of key processes, are at best meaningless chimeras; at worse, Sirens that will lure us into false and misleading senses of security. Certainly, quantitative standards must be periodically revisited in light of new data and understanding. Some management goals represent our best guesses, but typically data are available to devise quantitative benchmarks. Keddy and Drummond (1996) provide a comprehensive example of such quantitative standards or thresholds based on historical and new research.

5.2 Sampling, Levels of Precision, and Power

When designing a monitoring study, the goal is to detect relevant changes in the landscape. Thus there are generally two types of errors that can be made: false-change errors and missed-change errors (Fig. 12). These types of errors directly relate to standard statistical errors discussed in basic textbooks: the common "level of significance" (alpha) and "power" (c.f., Zar 1985, Sokal and Rohlf 1981).

Consider a simple example. A plant population (*Lomantium cookii*) is sampled in three consecutive years and we want to determine whether a change took place (Fig. 13). We analyze the data from the first and third years and make the statistical conclusion that no significant change occurred, despite the fact that we

Monitoring for change -- Possible Errors

	No change has taken place	There has been a real change
Monitoring system detects a change	False-change Error (Type I)	No Error (Power)
Monitoring system detects no change	No Error	Missed-change Error (Type II)

Fig. 12. Monitoring for change—possible errors of statistical interpretation.

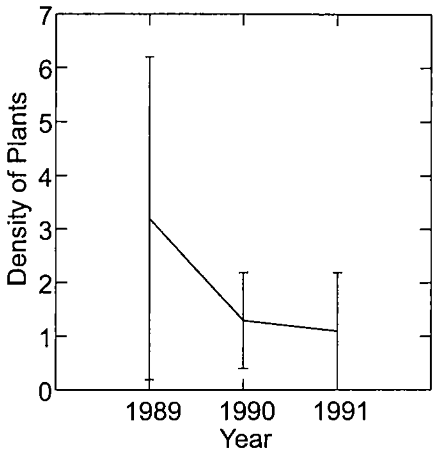

Fig. 13. Annual population size (± standard deviation) of *Lomatium cookii.*

observed a 63 percent decline in the sample mean. Because the statistical analysis failed to detect change, we reluctantly regard this as evidence that the population is stable. *Looking* at the sample means makes us uneasy, however, because there *appears* to be a problem. Unfortunately, interpretation of these data is complicated by the high variation in the sample means. We cannot clearly conclude that change has occurred, even though the sample means seem alarming.

This frustrating situation could have been avoided with some advance attention to sampling methodology. When we design a monitoring study with a scheme of sampling and data collection we are, to a large extent, fixing the level of detail that our data can discriminate. In the *Lomantium* example, the particular combination of sample size and large sample variation results in a 63 percent change that cannot be interpreted as statistically significant. The alternative is to collect some pilot data to estimate expected variance, state the amount of change we need to detect as significant (for biological or policy reasons), and then make simple calculations to determine the necessary sampling intensity (Zar 1985).

Sampling methodology and experimental design are huge topics we cannot adequately review here. Several excellent papers should be required reading, including Fairweather (1991), Kenkel et al. (1989), Green (1979) and Taylor and Gerrodette (1993). We make two general points.

First, the sampling and experimental design decisions made at the outset have enormous consequences. These include wasted resources resulting from monitoring efforts that are (a) more intense than required or (b) not intense enough to detect relevant or expected amounts of change. The construction of the ecological model is the logical first step for discussing and resolving these issues. It is at this step we identify the monitoring indicators that are central to the ecosystem. At this step, we must also identify the quantitative thresholds for management achievement, or minimum levels of change we want to detect. These quantities will determine the required sampling intensity.

Second, with any program of sampling there is the possibility of error (Fig. 12). Unfortunately, these errors are complementary — reducing our chance of missed-change increases our chance of making a false-change error, and *vice versa.* We could decide to sample so intensely that both types of errors are minimized, but this is usually too expensive. The better solution is to be aware of the types of errors we may make and their relevance to the particular monitoring problem at hand — that is, minimize the risk of the error we are most loath to make. Figure 14 shows monitoring problems and risks from four different fields. In each example, the scientist determines which type of error would be worse and minimizes it. The initial design phase of any monitoring study should include a candid discussion of what errors of interpretation are possible and which are most important to minimize.

6 CASE STUDIES

6.1 Fringe-Toed Lizard in a Dune Ecosystem, California

Barrows (1996) reported the development of a protection plan for a sand dune ecosystem in southern California. A target of this conservation was the Coachella Valley fringe-toed lizard, a threatened species that is restricted to the loose sand habitat found in the area.

An initial conceptual model of sand transport for the Thousand Palms natural area (Fig. 3) indicated two primary sand sources for dune construction: Thousand Palms Canyon and Indio Hills, originally thought to contribute equal amounts of sand. Subsequent investigations determined that over 90 percent of new sand originates in the Indio Hills and that important historic inputs of sand corresponded to two major rainfall events during the last 100 years. It also was determined that the existing dune field would migrate outside preserve boundaries without additional inputs of sand over a similar timeframe. Conservation goals and objectives then focused explicitly on protecting transport processes and source areas over the appropriate spatial and temporal scales (Barrows 1996).

The model sharpens focus on several aspects of management and monitoring of the lizard's ecosystem. It also exemplifies several major points in this chapter. First, the original model, suggesting equal contribu-

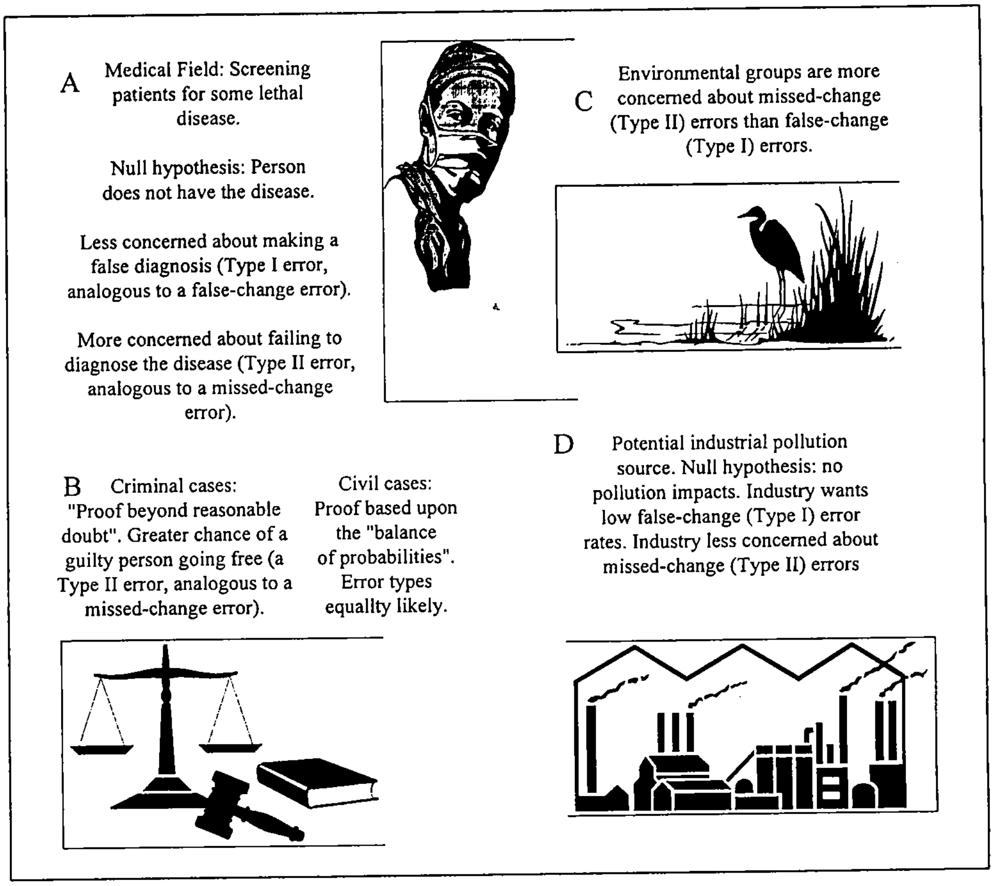

Fig. 14. Four examples of the relative weighting of possible statistical errors.

tions from the two sand sources, provided an explicit hypothesis for further study. Results indicating dramatically unequal contributions provoked an updated model that profoundly affected conservation strategy: where and what to protect.

Second, although lizard populations had been routinely monitored since 1986 (Barrows et al. 1995), the model suggested several whole-ecosystem processes that should be monitored. Monitoring the processes involved in dune construction and sand transport is critical because loss of these processes would portend decline of lizards long before they actually did so. Thus, processes of sand movement are predictive monitoring variables.

Third, the model provides diagnostic interpretations for major threats to lizard populations. Critical to this diagnostic function is the model's depiction of the link between lizard populations and dune processes. Thus, the monitoring program can do more than simply document change (e.g., the lizards are gone!). It can be a creative partner to the management process (e.g., why are the lizards going?), both evaluating current management strategies and suggesting new avenues. For example, certain large tracts of apparently suitable land have few or no lizards. The model clarifies why this is so; various human barriers have reduced the availability of loose sand. These areas, though free of development, do not help protect the lizard.

6.2 Riparian Stewardship in the Upper Yampa River Watershed, Colorado

The extensive work done by Richter (1997) in the Yampa River riparian ecosystem in Colorado is another illustration of the use of an ecological model as a powerful tool to direct and define conservation and stewardship activities. The flow regime of the Yampa remains relatively unaltered, supporting some of the best remaining examples of native riparian communities in the upper Colorado River watershed. In particular, protection of the globally rare *Acer negundo–Populus angustifolia/Cornus sericea* plant community is of highest priority. This rare community type exists as part of a mosaic of forested and emergent vegetated patches that, taken together, comprise the riparian system of interest. Patch types exist in various spatial and temporal configurations, dictated by dynamic alluvial processes including lateral channel migration that produces sand bars and abandoned river channels (Richter 1997).

A state-transition model of the system was constructed using historic data and current understanding (Fig. 11). This conceptual model formed the basis of a simulation model. State variables were vegetation patch types that comprise the riparian mosaic. Fluxes among states illustrated changes due to biotic succession, sand bar formation, and channel abandonment. The model integrated and summarized in a clear and concise manner knowledge and understanding of the interactions between dynamic river processes and natural vegetation states.

One of the primary goals of the model was to generate testable hypotheses for future research, monitoring, and experimental studies. A second goal was to help identify human influences that result in undesirable riparian conditions so that conservation activities could be directed at these threats. Interestingly, Richter (1997) states: "The formation of these new hypotheses regarding ecosystem dynamics may actually be thought of as the results of this study."

As we have stressed, one of the primary benefits of ecological models is their ability to dispute and clarify our current understanding of system behavior. Unexpected simulation results from the Yampa riparian model produced such an enlightenment. Aerial photographs showed a decline in riparian vegetation between 1938 and 1989, while model simulations predicted a slight increase (Richter 1997). This discrepancy revealed one of the most interesting and important shortcomings in their current understanding. On closer examination, they found that sand was being deposited more frequently along unstable, lateral channel bars and mid-channel islands instead of on point bars (located inside of meanders). Cottonwood seedling mortality rates were high on the unstable, shifting deposits compared to more stable conditions on point bars. These results alerted scientists to a potential shift in riverine geomorphological processes. Apparently, major deforestation along stream banks (50 percent of the original adjacent riparian forest was cleared for agriculture) is causing unstable movement of the channel rather than lateral migration and meandering typical of historic conditions, and necessary for cottonwood establishment. The river system appears to be moving from a meandering to a braided condition, indicated by decreased river sinuosity (ratio of channel length to valley length).

Thus, the model elegantly points out several key components and processes that should be monitored at this site. For example, measurements of just the rare community type will not likely indicate system integrity. Nor will monitoring established cottonwood stands, because re-establishment processes are in jeopardy. Monitoring should be focused at the landscape scale, on the entire vegetation mosaic, particularly the persistence and proportions of early vs. late successional types, and types that occur in abandoned channels vs. on point bars. In addition to measurement of patch types however, it is critical that riverine processes be monitored. The model clearly indicates that active channel movement (and in particular *lateral* channel meandering) is the *key* underlying mechanism that sustains the riparian system. Selected indicators for monitoring listed below stem directly from the model framework (H. Richter, written communication, 1996):

- Assess hydrologic variability from yearly USGS stream gage data. Determine if there are any significant changes in flow regime.
- Measure channel sinuosity and average channel width from aerial photographs at 5-year intervals. Values for sinuosity should be near 1.5 or greater to indicate meandering conditions (vs. braided).
- Monitor the proportion of stream banks devoid of native woody vegetation at 5-year intervals.
- Monitor the percent of the floodplain occupied by native vegetation from aerial photographs at 5-year intervals.

The modeling process and resulting models also helped biologists formulate specific protection goals for the system, restoration objectives, and recommendations for site design. Some of these directly illustrate the importance of the modeling process for focusing thought on critical patterns and processes that operate at different spatial and temporal scales (Richter 1997):

- Protect riparian habitat across the entire width of the active floodplain, not just along the present stream channel location, where riparian vegetation currently exists.
- In the short term, protect existing riparian vegetation that is stabilizing stream banks, especially if new sand bars are developing.
- Over the long term, restore vegetation on all segments of the stream channel where native vegetation was removed.
- Provide protection for sites in both narrow and wide valley settings.
- Strive for longitudinal connectivity between protected areas.

This study clearly demonstrates the usefulness of ecological models as a centerpiece to guide conservation, management, and monitoring activities. We believe strategies developed for the Yampa, for example, will be strongly tied to underlying ecological processes that sustain the riparian system. Hopefully, this link will ensure greater success and efficiency. In addition, the model provides a simple, yet flexible framework that documents assumptions and allows for easy updating as new information becomes available.

7 CONCLUSIONS

We believe that monitoring should not exist in a vacuum apart from all other activities. In fact, the ecological model, and its rendering of current ecological understanding, should be developed before plans for management and monitoring. Once management and monitoring have begun, the ecological model serves as the table around which management results are discussed in the light of monitoring data. These data serve as the raw materials of adaptive management by inspiring modifications to management actions, and perhaps even to the model itself (Fig. 2). Monitoring, management, and conceptual understanding, embodied in the ecological model, are one collective iterative process.

Ecosystems tend to be large and complicated, spanning wide areas and including a diversity of species, communities, and functions. We cannot measure everything, however, so we must focus monitoring programs on indicators that shed the most discriminating light on critical processes and management actions. Poor data, or faulty conclusions from data, can lead to incorrect choices and expensive management mistakes, or worse, misleading assessments of ecosystem threats (either falsely positive or falsely negative). It is a challenge to design an effective monitoring program within limited budgets, but the stakes are real. Nevertheless, mistakes of statistical interpretation are possible. It is important to be candid about them, and minimize the ones that would be most catastrophic.

How inclusive should ecosystem monitoring be? It should be limited to essential features of the ecological system, which include the central formative and preservative processes illustrated by the model. There is always a fundamental tension between (a) creating complete and comprehensive models of ecosystem behavior with fully estimated parameters, and (b) identifying a single key feature to monitor, a canary in the ecosystem's coal mine. At its extreme, this dichotomy is the choice between broad but shallow and detailed but hopelessly narrow. The former is represented by an expensive model that is too complicated to estimate or even specify, while the latter yields information on only a tiny fraction of the total ecosystem. We require indicators that are focused, but still representative of the breadth of the system, which typically means we require multiple indicators. A miner could monitor his coal mine with a canary because he referred to a clear conceptual model that identified problems (the bird is dead), diagnosed causes (the air is bad), and prescribed actions (get out of the mine). In complicated ecosystem monitoring, we should monitor multiple canaries and use a well-crafted ecological model to justify their selection.

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