MONITORING ECOSYSTEMS IN THE SIERRA NEVADA: THE CONCEPTUAL MODEL FOUNDATION

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Abstract. Monitoring at large geographic scales requires a framework for understanding relationships between components and processes of an ecosystem and the human activities that affect them. We created a conceptual model that is centered on ecosystem processes, considers humans as part of ecosystems, and serves as a framework for selecting attributes for monitoring ecosystems in the Sierra Nevada. The model has three levels: 1) an ecosystem model that identifies five spheres (Atmosphere, Biosphere, Hydrosphere, Lithosphere, Sociocultural), 2) sphere models that identify key ecosystem processes (e.g., photosynthesis), and 3) key process models that identify the *"essential elements"* that are required for the process to operate (e.g., solar radiation), the human activities (*"affectors*") that have negative and positive effects on the elements (e.g., air pollution), and the *"consequences* "of affectors acting on essential elements (e.g., change in primary productivity). We discuss use of the model to select attributes that best reflect the operation and integrity of the ecosystem processes. Model details can be viewed on the web at *http://www.r5.fs.fed.us/sncf/spam_report/index.htm* (Appendix section).

Keywords: monitoring, ecosystem processes, conceptual modeling, indicators, human impacts

1. Introduction

Monitoring is a critical tool for dealing with uncertainty in the management of large-scale systems (Hellawell 1991, Noon et al. 1999). Monitoring is intended to provide information on: 1) the success of implementing management direction, 2) the achievement of desired conditions, 3) the effectiveness of management direction in meeting resource objectives, and 4) the validity of assumptions made about desired conditions and cause-effect relationships during the development of management direction.

Monitoring at large geographic scales presents many challenges, including identifying clear goals and selecting attributes to monitor based on a thorough evaluation of theory and concepts. Recent reviews of large-scale monitoring plans have identified failures in both process and content. Frequently, monitoring efforts have had poor foundations in ecological theory, little consideration of cause-effect relationships, and inadequate or uninformed approaches to selecting, justifying,

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and evaluating the specific indicators to monitor (Bricker and Ruggiero 1998, Hellawell 1991, National Research Council 1995, Noon et al. 1999). Monitoring plans are required by the National Forest Management Act (NFMA) (1976), guiding legislation for National Forest System (NFS) lands. Monitoring plans developed for Land and Resource Management Plans for National Forests, in compliance with NFMA, are typically confounded by many shortcomings in process and content which have contributed to their unsuccessful implementation.

A monitoring plan must also be responsive to changing information needs. Responsiveness can be achieved by providing: 1) a clear set of questions to answer, 2) a specified time period to answer each question, and 3) the ability to add and delete questions without redesigning the conceptual foundation or experimental design. Few monitoring strategies are created with growth or change as an integral part of their design. However, in light of current high public involvement and the correspondingly rapid rate of policy changes, it is prudent to consider adaptability as the core of any effort that strives for enduring utility.

The development of a conceptual model has been touted as a key component of a scientifically based, ecologically founded monitoring plan (Barber 1994, National Research Council 1995, Noon et al. 1999). 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 knowledge - they are working hypotheses about system form and function (de Wit 1993, Huggett 1993, Walters 1986).

We built a conceptual model to serve as the scientific foundation of a monitoring plan. The conceptual model serves as a foundation by providing all members of the multidisciplinary scientific team with a common view of the facets and dynamics of ecosystems across scales. The model also provides an objective, broad-based, and structured framework by which we can select specific attributes (indicators) to monitor and adjust monitoring needs over time. The objective of this paper is to describe the conceptual model and to discuss considerations for applying it to the development of a large-scale monitoring plan. Our geographic area of application represents a broad geographic area of management consideration within and proximate to the greater Sierra Nevada study area, as defined by the Sierra Nevada Ecosystem Project (1996) (Figure 1).

2. Unique Features of the Ecosystem Process Conceptual Model

2.1 PROCESS-CENTRIC STRUCTURE

Franklin et al. (1981) identified three primary attributes of forest ecosystems: composition, structure, and function. Composition is the array of components present in the ecosystem (e.g., species, roads, water); structure refers to the spatial arrangement of various components of the ecosystem (e.g., tree canopy layering,

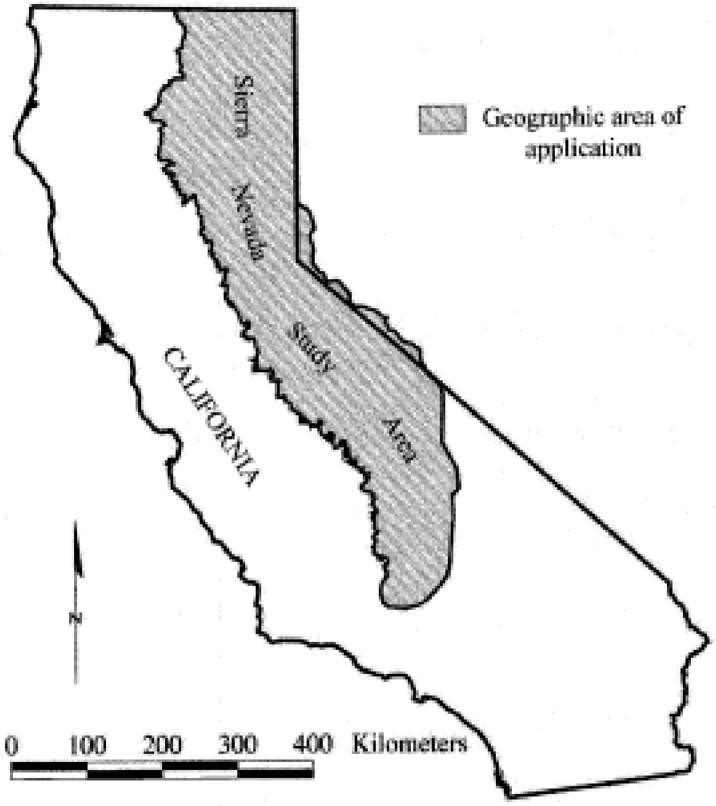


Figure 1. *Geographic area of application for the conceptual model, adopted from the Sierra Nevada Ecosystem Project (1996).*

transportation corridors); and function refers to how various processes (e.g., nutrient cycling, erosion) are accomplished and the rates at which they occur. We chose to center our model on the concept of ecosystem processes, as opposed to components or structures. Processes integrate the components through space and time by transferring energy, matter, and information. Processes are central to the maintenance of ecosystem structure and function, and as such are key features for managers to preserve (Pickett and 0stfeld 1995). Processes have been fundamental to previous conceptual models as well (e.g., Boyden 1992, Noon et al. 1999, Noss 1990). Monitoring processes directly is ideal, and some processes (e.g., water flow, commerce) can be measured directly. However, other processes (e.g., chemical reactions, gene flow) are difficult, if not impossible, to measure directly and must be monitored through indirect measures of related conditions. In either case, by centering our conceptual model on processes, the focus of monitoring stays on processes, both in terms of what to measure and how to interpret monitoring data once it is collected.

2.2 HUMANS AS PART OF THE ECOSYSTEM

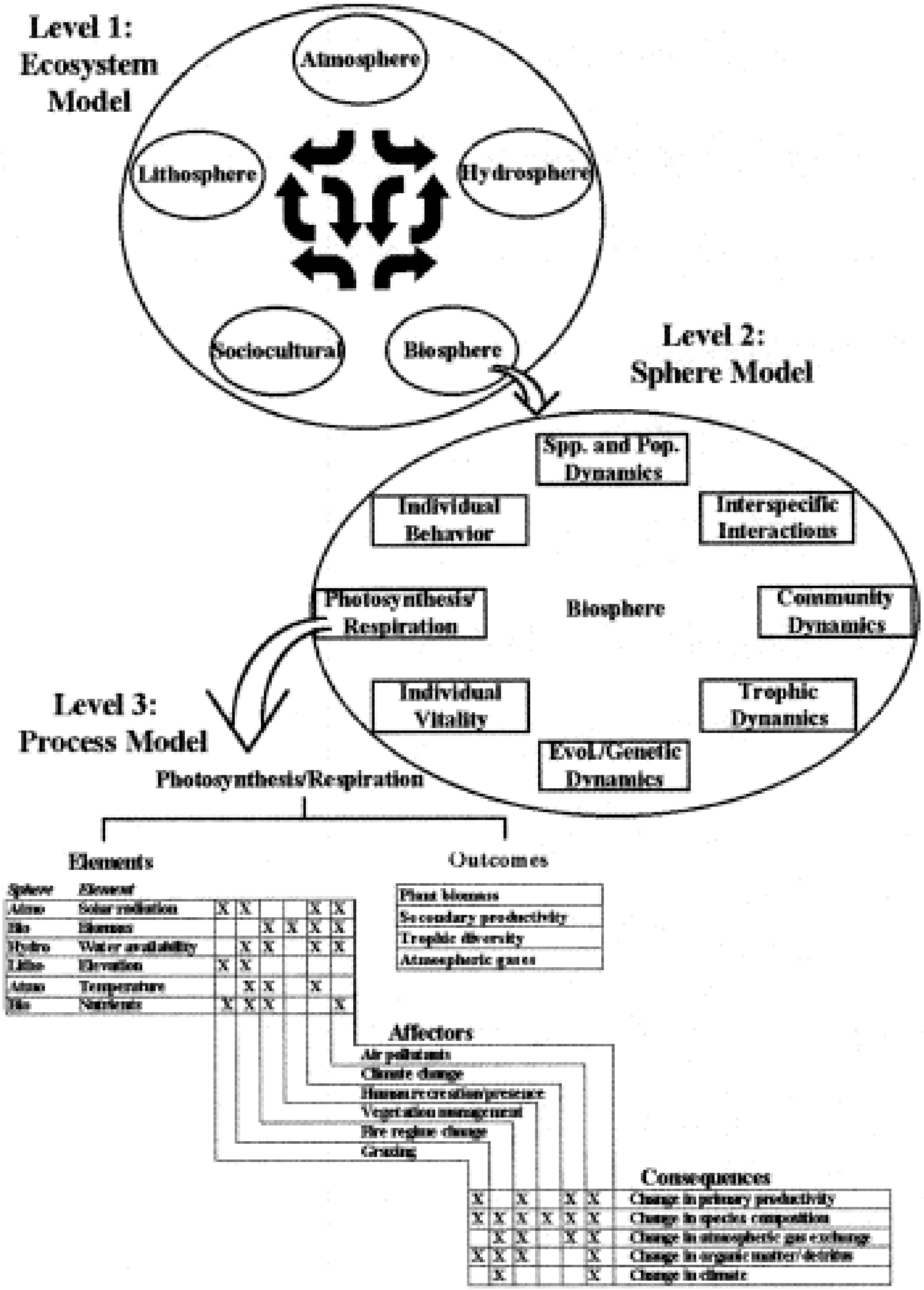
Most ecosystem management literature assumes that a scientific understanding of ecosystems is solely the purview of biological and physical scientists (Endter-Wada et al. 1998). Few existing models are based on the entire range of biological, physical, and sociocultural processes, or adequately represent feedback links between and among human and environmental systems (e.g., DeAngelis 1996). The need for such a model is critical for environmental management, where law (e.g., National Environmental Policy Act of 1969) requires agencies to consider the interrelationships of human and biophysical elements. Acknowledging that humans are part of ecosystems (Christensen 1997, Meyer 1997) complicates the task of understanding ecosystem dynamics. However, as human values, culture, and activities are more explicitly represented, the models should better represent the true breadth of interactions among biological, physical, and sociocultural processes and conditions (Endter-Wada et al. 1998, Keddy 1991). Our conceptual model represents an attempt to bridge the gap between socio-centric and bio-centric approaches, and improve our ability to address the potential range of environmental impacts of humans, effects of environmental conditions and services on social systems, and interrelationships among biological, physical, and sociocultural processes.

3. Structure of the Ecosystem Process Conceptual Model

Our Ecosystem Process Conceptual Model (the Conceptual Model) is hierarchical, and consists of three levels: ecosystem, sphere, and process models (Figure 2). The first two levels of the model are not specific to any spatial scale or geographic location. The third level consists of process models which address specific considerations of the Sierra Nevada and NFS land management. The Conceptual Model, as presented here, is the generic version of the mode 1- it is not tailored to a particular project or type of use. In application, various levels and parts of the model would be more relevant than others, and would be further developed. The model is intended to serve as a map of processes, components, and their interactions. It is not intended, nor does it function, as a predictive tool.

3.1 LEVEL 1: ECOSYSTEM MODEL

The first level of the model consists of five spheres: atmosphere, lithosphere, hydrosphere, biosphere, and sociocultural sphere (Figure 2). The five spheres are defined by a unique set of processes, components, and structures which are highly interactive, as represented by the myriad of arrows located between the spheres. The processes belonging to a given sphere may use components from more than one sphere, but each process is still a member of only one sphere (see Level 2 be-



Sphere	*Element*						
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

Plant biomass
Secondary productivity
Trophic diversity
Atmospheric gases

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 2. *Levels of the ecosystem process conceptual model as displayed by means of an example from the Photosynthesis/Respiration process within the Biosphere model.*

low). For example, erosion is a lithosphere process, but the process frequently involves the interaction of lithosphere (rocks and soil) with atmosphere (wind) and hydrosphere (water) components.

The one biological sphere (biosphere) and three physical spheres (hydrosphere, lithosphere, atmosphere) are derived from a long-held classification of major components of the global ecosystem (Begon et al. 1990). The Sociocultural Sphere builds upon concepts present in human cultural ecology, sociology, and environmental impact modeling (e.g., Dietz and Rosa 1994, Ehrlich and Holdren 1971, Forester and Machlis 1996, Stern et al. 1992).

3.2 LEVEL 2: SPHERES

The second level of the hierarchy consists of a model of each sphere that identifies the *key processes* that perform major material, energy, and information transfers (Figure 2). The key processes identified for each sphere are not scale or location specific and typically represent many sub-processes. Some key processes in our model are readily identifiable as classic ecosystem processes, such as nutrient cycling (Odum 1971), while others are identified by the outcomes of sub-processes grouped by familiar categories or bodies of science on the subject (Table 1). For example, the Biosphere and Hydrosphere include traditional processes (e.g., photosynthesis and respiration, and evapotranspiration, respectively), as well as processes that encompass the dynamics of ecosystem components (e.g., species and population dynamics, and cryologic dynamics, respectively).

3.3 LEVEL 3: PROCESSES

The third level of the hierarchy consists of submodels depicting the mechanics of each process, and their two parts: 1) the *essential elements* (i.e., inputs) and *outcomes* (i.e., outputs) of each process and 2) the influence of *affectors* on the process (Figure 2). *Essential elements* are those components that are required for a process to occur or that significantly influence the rate at which a process occurs. For example, solar radiation is required for photosynthesis to occur, but the rate of photosynthesis is also influenced by essential elements such as water availability and temperature. *Outcomes* simply represent what the process produces or creates. For example, photosynthesis is a process that is not readily visible, however one of the tangible outcomes of photosynthesis is primary productivity.

The influence of *affectors* on a process comprises the second component of the Level 3 models. We define affectors as actions, consisting primarily of human activities, that generate a change in the value of state variables (e.g., elements, outcomes, or process operation). The term "affector" is a broad term that encompasses other terms used in the literature such as "stressor" (e.g., Honing, 1992; Noon et al. 1999), "stress" (e.g., Rapport et al. 1985, Seyle 1973), and "ecosystem subsidy" (Honing 1986). Those affectors viewed as having negative effects can be

Table I

Key processes identified in the Ecosystem Process Conceptual model.

Sphere	Key Processes
Atmosphere	Hydrodynamics
	Radiative Transfer
	Transport and Dispersion
	Chemical Reactions
Biosphere	Photosynthesis and Respiration
	Individual Vitality
	Individual Behavior
	Species and Population Dynamics
	Interspecific Interactions
	Community Dynamics
	Trophic Dynamics
	Evolution and Genetic Dynamics
Hydrosphere	Infiltration
	Evapotranspiration
	Surface Water Movement and Storage
	Surface Water Chemical Reactions
	Surface Water Thermal Dynamics
	Subsurface Movement and Storage
	Subsurface Chemical Reactions
	Cryologic Dynamics
Lithosphere	Physical and Chemical Weathering
	Erosion and Sediment Dynamics
	Volcanism
	Tectonics
Sociocultural Sphere	Human Population Dynamics
	Land and Resource Transactions
	Economic Activity
	Human Social Structure Dynamics
	Technological Innovation and Diffusion
	Human Communication
	Dynamics of Attitudes, Beliefs, Values, and Behaviors
(Metaprocesses)	Nutrient Cycling
	Hydrologic Cycling

considered stressors (e.g., air pollutants, introduction of exotic species), whereas those viewed as having positive effects can be considered ecosystem subsidies (e.g., restoration of physical features, education/training). We use the term affector because it is a broad term that is value-free and is applicable across all spheres, including the Sociocultural Sphere.

Affectors identified in all our process models are specific to the Sierra Nevada and NFS lands. Thus, it is at the step of identifying affectors that the Conceptual Model becomes geographically explicit and relevant to the specific area for which a monitoring plan is being developed. Affectors in all but the Sociocultural Sphere consist of both human activities (e.g., urbanization, vegetation management) and three natural processes which are commonly altered as a result of human activities (i.e., flooding, fire, and climate). In the Sociocultural Sphere, a broader array of affectors are recognized, including additional biological and physical processes that have the potential to rapidly alter sociocultural processes.

Consequenees are the result of affectors acting on the process. Consequences reflect state changes in essential elements, the process outcomes, or the character of the process itself. For example, affectors acting on the photosynthesis and respiration process may result in changes in gas exchange, primary productivity, or species composition, among other consequences. Consequences reflect potential changes on NFS lands in the Sierra Nevada and represent potential focal areas for assessment and monitoring. The consequences identified in the model are a potential subset, limited by our desire to keep the model concise. The influence of affectors on different processes can produce the same consequence. This serves to further illustrate the difficulty in assigning potential causal relationships to specific consequences or conditions.

In all spheres, except the biosphere, the consequences represent direct effects related to the process and its elements. In the biosphere, we added a category of indirect consequences related to the habitat of biota. Habitat is defined as an area with the combination of resources (i.e., food, cover, water) and environmental conditions (e.g., temperature, predators) that promotes occupancy by individuals of a given species or population (Morrison et al. 1992). In the Hydrosphere, consequences are all direct, but they are divided into lotic and lentic because these systems differ in their structure and response to affectors.

The relationships among the process, affectors, and consequences are complex, but for the purposes of our conceptual model, we simply indicate where a relationship exists ("x"s in Figure 2). These relationships document the logic and assumptions used to develop the model and can be expanded to address specific monitoring questions using techniques such as envirograms (Andrewartha and Birch 1984, James et al. 1997) and influence diagrams (Howard and Matheson 1981, Ellison 1996).

3.4 THE SPHERES AND THEIR PROCESSES

The number of processes identified for each sphere varies from four in the atmosphere model to eight in the biosphere model (Table I). The processes each aggregate a number of sub-processes. For example the Interspecific Interaction process in the Biosphere model is assumed to consist of predation, competition, and mutualism. We also simplified ecosystem complexity by placing particular processes in particular spheres (e.g., evapotranspiration resides in the hydrosphere), even though we realized that processes may influence other spheres. However, two processes interacted so strongly with multiple spheres that they were designated as *metaprocesses* and were modeled separately. We describe the processes ineach sphere briefly below. Additional detail on the rationale for the choice of individual processes and their essential elements, affectors, and consequences are available from the U.S. Forest Service Pacific Southwest Region (U.S. Forest Service, Ecosystem Conservation Staff, 1323 Club Dr., Vallejo, CA, 94592, or *www.r5.fs.fed.us/sncf/spam_report/index.htm*, Appendix section).

The Atmosphere model follows the classic division of atmospheric phenomena into either the physical or chemical realm (Cole 1975, Seinfeld and Pandis 1998, Wayne 1985). We identified one chemical key process and three physical key processes (Table I).

The biosphere has classically has been organized into cells, organs, organisms, individuals, populations, communities, ecosystems, landscapes, and biomes (Allen and Hoekstra 1992, Odum 1971, O'Neill 1989). Our biosphere model reflects this by the identification of eight processes, but does not reflect levels above the community because this invokes multiple spheres that, together with the Biosphere, represent ecosystems, landscapes, and biomes. With the exception of the affectors, we do not consider humans in the biosphere model - they are considered in the sociocultural sphere. We identified eight biosphere processes pertaining to seven facets of the biosphere: a fundamental pair of biochemical reactions, individuals, populations and species, interspecific interactions, community interactions, energy organization and transfer, and evolution (Table 1).

The hydrosphere model includes stages of the hydrologic cycle that occur on or below the Earth's surface (Gordon et al. 1992), and the chemical and thermal dynamics of water. We differentiated surface and subsurface systems because they differ fundamentally in their temporal and spatial dynamics, and response to affectors. We identified a total of seven processes, four processes relating to the hydrologic cycle, two chemical processes, and two thermal processes (Table 1).

The lithosphere is classically partitioned into subsurface (endogenic) and surface (exogenic) processes (Ritter 1984). Two surface and two subsurface processes were identified (Table I). All four processes contribute to the development of geomorphic features such as landforms and soils, and represent key soil and geologic processes.

We identified two metaprocesses, processes that were directly associated with multiple spheres. Nutrient cycling and hydrologic cycling relate to the cycling of two elemental forms of matter-water and nutrient compounds (Table I). Essential elements of each metaprocess consist of key processes and their sub-processes from associated spheres.

The sociocultural sphere model encompasses all behavioral and structural manifestations of human culture and society, including customs, lifestyles, social organization, beliefs, and economic activity. Within the sociocultural sphere, we organized seven key processes along a gradient from human interactions with the biophysical environment, through functions involving human subsistence, material culture, and commerce, to increasingly intangible dynamics of social ordering, communication, and human value formation (Table I).

4. Use of the Ecosystem Process Conceptual Model in Monitoring Plan Development

Use of a conceptual model is not enough to avoid the common pitfalls of large-scale monitoring efforts. Rather it is the approach taken in applying the model that determines its efficiency and effectiveness.

4.1 RETROSPECTIVE AND PREDICTIVE MONITORING

For large-scale monitoring efforts, two general approaches have been defined: retrospective and predictive. Retrospective monitoring seeks to detect changes in status or condition. It is based on detecting an effect after it has occurred as the result of including a wide array of attributes in the monitoring program (National Research Council 1995). This inductive approach is valuable for a variety of management and conservation uses, but is not helpful in understanding why observed changes are occurring. The weakness of retrospective monitoring is that the potential cause of observed changes is often unknown.

Predictive monitoring seeks to detect indications of undesirable effects before they have a chance to occur or become serious (National Research Council 1995). It focuses on detecting changes expected to result from actions or activities. It assumes a cause-effect relationship between affectors and expected changes, and it is an efficient monitoring approach where there is a high level of confidence in regard to particular cause-effect relationships. The weakness of this approach is that assumptions about cause-effect relationships may be inaccurate, effects may have multiple causes, or unforeseen changes may go undetected.

We consider retrospective and predictive monitoring as complementary so that a balance of these two approaches, combined with affector monitoring, constitutes the best approach to monitoring large-scale systems. Affector monitoring consists of identifying the *key affectors* that are expected to have the greatest influence on ecosystem condition, and monitoring their attributes. Integrating predictive, retrospective, and affector monitoring increases the probability of detecting and interpreting important ecosystem changes.

4.2 ATTRIBUTE SELECTION

The Conceptual Model was developed to serve as a tool to assist the user in considering the array of interactions that may be affecting a condition of interest, and to facilitate the selection of *attributes* to answer monitoring questions. We define attributes broadly, in the sense of Noon et al. (1999), as "any biotic or abiotic feature of the environment that can be measured or estimated". We recognize the history of referring to attributes in this sense as indicators (Hunsaker and Carpenter 1990, Noss and Cooperrider 1994). However, because many attributes may be species, and the indicator concept has been challenged with regard to species (e.g., Landres et al. 1988), we have avoided the term "indicator".

Candidate attributes consist of all attributes that are determined to be an information rich reflection of ecosystem condition. Identifying candidate attributes for each process requires a detailed inquiry into the mechanisms of each key process. The Conceptual Model explicitly documents our views and assumptions about these mechanisms, and serves as a guide to the attributes of processes, essential elements, outcomes, and consequences of affectors we should consider in a monitoring plan. Attributes generally consist of a set of specific measures that reflect one or more aspects of the process through direct measures or measures of its elements, outcomes, or affector consequences. We recommend a review of the relevant literature to explore all possible attributes and identify the strongest candidate attributes to represent each process.

In developing our monitoring plan, we seek to identify candidate attributes that address three complementary approaches to monitoring: 1) attributes that reflect the *general condition* of the process over time (retrospective approach), 2) attributes that reflect *expected changes* resulting from *key affectors* operating in the ecosystem (predictive approach), and 3) attributes that reflect the key affectors. Criteria for identifying candidate attributes differ for general condition, expected change, and key affector attributes. General condition attributes are ideally direct measures of the process, but are often measures of the outcomes and essential elements of the process model. Expected change attributes are primarily measures of the consequences identified in the process model. Affector attributes are derived by careful consideration of the cause-effect relationships of greatest interest.

We propose that the final set of attributes to monitor would be selected from the list of candidate attributes based on practical considerations partitioned here into three categories: technical, operational, and administrative. Technical criteria pertain to the science of monitoring, such as responsiveness and specificity. Operational criteria pertain to the physical implementation of monitoring, such as the ability to directly measure the attribute and the skill level required to collect the data. Administrative criteria pertain to institutional needs, desires, requirements, and barriers for implementation.

An example of the path we describe to select attributes to monitor processes may be beneficial here. Attributes for the photosynthesis/respiration key process include a wide array of potential features, ranging from bioregional estimates of net primary productivity, to within stand estimates of carbon dynamics, to below ground details of root formation and distribution. Candidate attributes should consist of tractable measures of the photosynthesis process at one or more of these geographic scales. The final selection of attributes would be largely dictated by the level of funding and the theoretical and empirical bases for identifying a suite of attributes that together can describe photosynthesis and respiration at the bioregional scale. The selected attributes should be accompanied by documentation that demonstrates the scientific basis of the selection. More detailed, conceptual or quantitative models may be necessary to illustrate and link attributes and the processes they represent.

5. Summary and Conclusion

The Conceptual Model provides an essential foundation for the development of our large-scale monitoring plan. The model alone does not solve all the problems that typically beset such monitoring efforts. However, a strong conceptual model provides an ecosystem foundation which, when used in concert with a balanced approach of retrospective, predictive, and affector monitoring, can serve as a framework to identify appropriate and informative attributes for monitoring. The process of selecting strong attributes that can be accurately measured and easily interpreted requires information not provided by the Conceptual Model presented here. Rather the model is the framework within which to include more refined information and models, and is the foundation for interpreting the results of monitoring and its implications for management.

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