The Use Of Conceptual Models In Designing And Implementing Long-Term Ecological Monitoring

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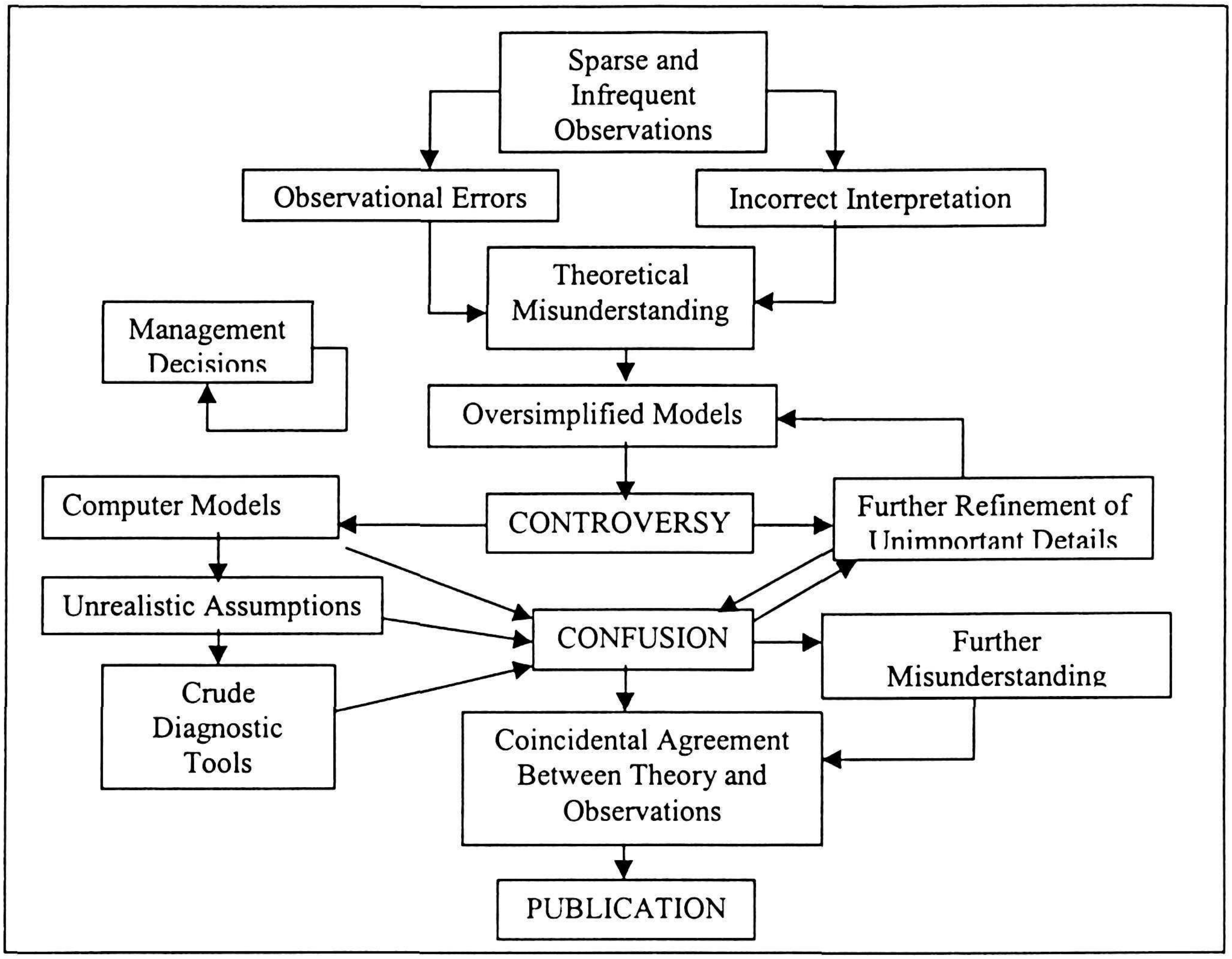
Models are useful tools to use throughout the process of ecological monitoring. Conceptual models depicting key structural components, and system drivers assist us in thinking about the context and scope of the processes that effect ecological integrity (Karr 1991). They also provide a heuristic device to expand our consideration across traditional discipline boundaries (Allen and Hoekstra 1992). As we begin monitoring, smaller, more focused conceptual models can be similarly employed to develop and refine monitoring questions concerning communities and populations. Once a few years of data have been collected, we can begin constructing mathematical models to quantify relationships. Our final aim is to develop predictive models that are sufficiently precise to provide early warning of biologically meaningful change. Throughout the monitoring process clear, simple models may facilitate communication 1) between scientists from different disciplines, 2) between researchers and managers, and 3) between managers and the public.

Why is it then, that conceptual models are not more widely employed to develop ecological monitoring? One reason may stem from the tension between pure and applied research. Hobbs (1998) describes the cynic's view of the interface between ecological research and management in a diagramatic model (Figure 1). "Academic ecologists enjoy developing models that are internally elegant but frequently bear no relation to the real world. The aim of the research is to produce papers in scientific journals, rather than find answers to particular problems or aid in the understanding of complex natural systems." Note in the model that meanwhile, management decisions are made in a closed circuit without input from research or empirical observation.

Another reason for reluctance may be our recognition that we don't know enough about the system in question to compose an intelligent model. And while this is often the case, it reveals a common misconception that models are intended as a faithful representation of the "truth". It may be more useful to think of a model as a hypothesis or a problem-solving tool, "a purposeful representation of reality" (Starfield 1994). Geissler (1997) uses a car analogy to illustrate the point that a conceptual model does not need to completely describe a system to be useful. It is not necessary to fully understand automotive engineering to construct a model that relates an action (pressing the brake pedal) to certain results (the car stops).

Several conceptual models of the inventory and monitoring process have been developed (NRC 1990; NPS 1992; Davis et al.1994; Barber 1994; Mulder et al. 1999) and are summarized by Geissler (1997). The purpose of this discussion is rather to introduce the use of conceptual ecosystem models, small focused models, and holistic program models to the process of developing vital signs monitoring.

Figure 1. Cynic's conceptual model of the interface between ecological research and management. (Hobbs 1998, original idea by Sue Briggs)



Types of Models

Hall and Day (1977) describe four types of models that may also be viewed as stages in the model-building process.

Conceptual Model: Synthesis of current scientific understanding, field observation and professional judgment concerning the species, or ecological system

Diagramatic Model: Explicitly indicates interrelationships between structural components, environmental attributes and ecological processes

Mathematical Model: Quantifies relationships by applying coefficients of change, formulae of correlation/causation

Computational Model: Aids in exploring or solving the mathematical relationships by analyzing the formulae on computers.

A number of authors have variously described two competing approaches to modeling (Levins 1966; Holling 1966, May 1973; Maynard Smith 1974) that are summarized by Gillman and Hails (1997). At the tactical end of the spectrum, all relevant factors are measured to determine if and how they interact with the target population or community. From the strategic perspective, modeling is used as a way of formalizing generalizations about the ecological system of interest. Starfield (1997) describes a similar dichotomy as bottom-up versus top-down model construction.

Conceptual Ecosystem Models

Barber (1994) describes three essential aspects to consider as conceptual ecosystem models are developed:

1) Identify the structural components of the resource, interactions between components, inputs and outputs to surrounding resources, and important factors and stressors that determine the resource's ecological operation and sustainability

2) Consider the temporal and spatial dynamics of the resource at multiple scales because information from different scales can result in different conclusions about resource condition .

3) Identify how major stressors of resource are expected to impact its structure and function.

Noon et al. (1999) follow a similar process, developing conceptual models that demonstrate how the system works with emphasis on anticipated system responses to stressor input.

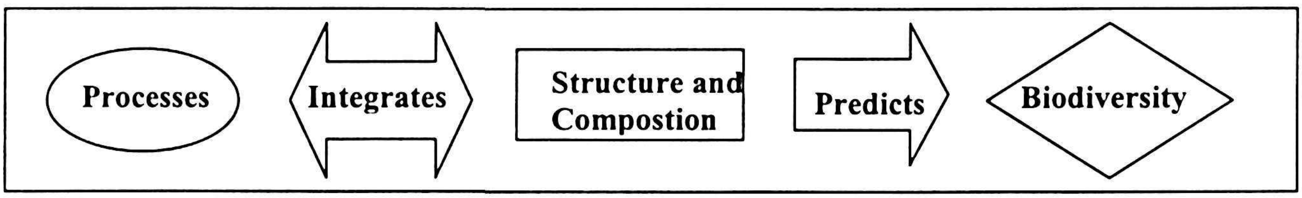
Less Is More. It is often assumed that since ecosystem dynamics are complex, it follows that models of those systems must be similarly complex. Sage advice councils otherwise. Levins (1966) asserts that precision in models has a cost. Models dense with complex relationships may only apply in very limited circumstances. And if a complex model contains erroneously modeled relationships, they may be difficult to discern among the model's thicket of equations. Allen and Hoekstra (1992) emphasize that "we do not wish to show that everything is connected, but rather to show which minimal number of connections that we can measure may be used as a surrogate for the whole system in a predictive model". Starfield (1997) suggests that simple, top-down models that capture the broad, essential aspects of ecosystem dynamics provide a more pragmatic approach. Noon et al. (1999) concur, summing up the difficulty and importance of using ecosystem models to select monitoring indicators in this way:

> Despite the complexity of ecosystems and the limited knowledge of their functions, to begin monitoring, we must first simplify our view of the system. The usual method has been to take a species-centric approach, focusing on a few

> high-profile species; that is those of economic, social, or legal interest. Because of the current wide (and justified) interest in all components of biological diversity, however, the species-centric approach is no longer sufficient. **This wide interest creates a conundrum; we acknowledge the need to simplify our view of ecosystems to begin the process of monitoring, and at the same time we recognize that monitoring needs to be broadened beyond its usual focus to consider additional ecosystem components.** (*my emphasis*)

The simplifying approach developed for the Northwest Forest Plan was to focus on structural and composition elements of the landscape, assuming they reflect underlying process and function (Figure 2) (Noon et al. 1999).

Figure 2. Conceptual model that is the basis for identifying indicators from structural and compositional landscape elements (Noon et al. 1999).

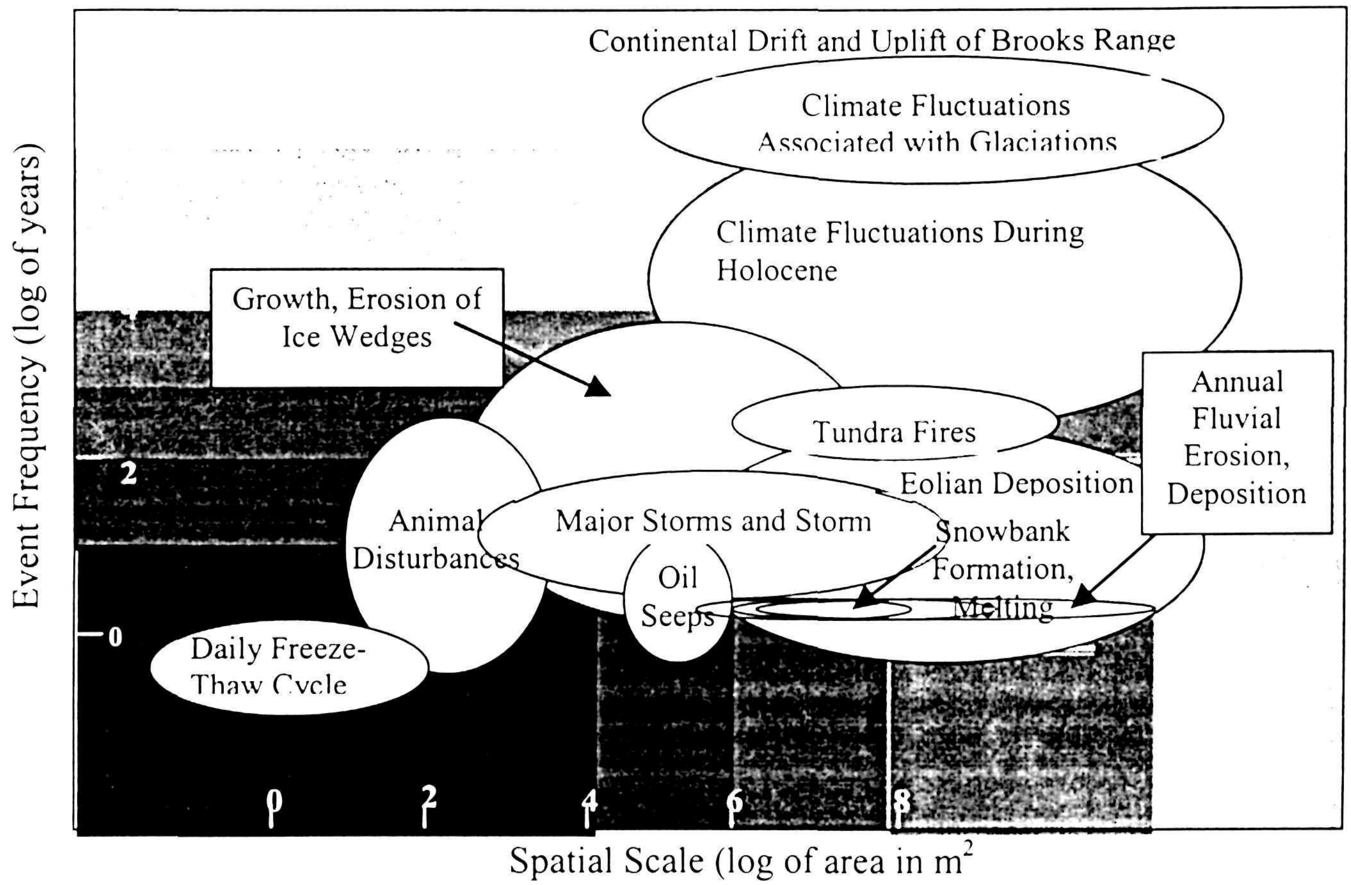


In developing conceptual models for the Prairie Cluster LTEM Program, we have followed a similar approach. We relied on several recent literature syntheses to build conceptual models of the natural drivers of terrestrial and aquatic prairie ecosystem (Figure A1). We then developed tables of the most significant anthropogenic stressors, the resources they influenced, and their known or hypothesized effects (Table A1). We used these tables to build a diagrammatic model of the most significant stressor effects Figure A2).

A Consideration Of Scale. Lee (1993) has proposed that most environmental problems are driven by mismatches of scale between human responsibility and natural interactions. Hobbs (1998) notes the need to incorporate scale considerations into conservation and resource management planning. He asserts that collecting information at the relevant scale is an essential first step toward informed management decision making. A number of authors have recognized the importance of scale considerations in conceptual model construction (Noon 1999, Barber 1994). One criticism of EPA's EMAP program has been inadequate consideration of the "domains of usefulness" of its indicators (NRC 1995). At what spatial and temporal scales are indicators reliable and at what scales are they less reliable?

Obviously models should include all components and interactions that affect the process of interest and operate on the same spatial and temporal scales. O'Neill et al. (1986) have used hierarchy theory to suggest that processes operating at three orders of magnitude larger or smaller than the process of interest may be aggregated. In other words, processes operating at much larger scales act as constraints on the system, while those operating at much finer scales occur so rapidly that they are perceived as static. Walker and Walker (1991), in a study of Arctic tundra systems, provide a good example of processes and disturbances occurring at numerous temporal and spatial scales (Figure 3).

Figure 3. An assessment of the spatial and temporal scales of natural disturbances in an Arctic tundra ecosystem (Walker and Walker 1991).



Turner and O'Neill (1995) suggest the following steps toward determining what can and cannot be aggregated in an ecological study.

1. Ask the question. Both the spatial /temporal scale and the level of abstraction change with the question.
2. Specify the spatial/temporal scales of interest, both in terms of grain and extent.
3. Aggregate the processes that occur much more slowly than the process of interest -- consider these to be the constraints on the process of interest.
4. Aggregate the processes that occur much more quickly than the process of interest -- consider these as 'noise'.

5. Identify the interacting factors that influence the process of interest. Can more aggregation be done at this scale?
   a) Is there functional redundancy at the particular spatial and temporal scale of interest?
   b) Are there feedbacks at the particular spatial and temporal scale of interest? If not the processes may be aggregated or ignored.
   c) Are there nonlinearities or threshold dynamics? If so it may be possible to aggregate below and above a threshold but not across it.

Multiple Points of View. Allen and Hoekstra (1992) stress that ecology is in many ways a soft-system science, one in which point of view (ecological level of inqury, temporal/spatial scale) is accepted as the substance of discourse. They suggest there are enough decision points in an ecological investigation (or in the design of a monitoring program) to require some formalization of the decision-making protocol. They propose using a protocol called 'soft-systems methodology' (developed by Peter Checkland, Lancaster University) for problem solving in messy situations where there are too many points of view for simple trial and error to prevail. The first steps of Checkland's scheme (Table 1) may be useful as we attempt to incorporate multiple ecological disciplines and scales into ecosystem conceptual models.

Table 1. Checkland's "Soft-systems Methodology" from Allen and Hoekstra (1992)

1) Recognize that there is a problem, 'a real mess'
   - troubled feeling an ecosystem, community or population ecologist may have that some other sort of specialist could better solve the problem at hand
   - trying to manage water, vegetation and wildlife in a unit of particular size but realizing the temporal or spatial scales don't mesh with natural process scales

2) Actively generate as many points of view for the system as possible -- 'painting the rich picture'
   - community ecologist consider physiological aspects of the problem, population biologist to consider nutrient cycling, etc.

3) Find the root definitions - develop abstractions that restrict the rich picture in hopes of finding solution.
   - (key system attributes will change as scale of the system and point of view (ecological discipline) is altered

4) Build the model

Thus far, the discussion has focused on conceptual ecosystem models. Two other types of models are equally important to designing a long term monitoring program.

Small, Focused Models

As we begin specific monitoring projects, smaller, more focused conceptual models (Starfield 1997) may be useful to formulate hypotheses concerning particular communities or populations, identifying for instance, key life history stages or limiting factors. At this stage, conceptual models are also helpful in selecting important ancillary environmental attributes to monitor. Figures A3 and A4 illustrate focused models drawn at two different scales for examining the biotic and abiotic effects on population dynamics of a rare plant. Once a few years of data have been collected, we can begin constructing mathematical models, quantifying relationships with coefficients of change and formulae of correlation. Comparisons between the model and data often lead to either a revision of the hypothesis or a reinterpretation of the data. Eventually focused models should capture adequate interaction between important stressors, environmental limitations and the species or community of interest to predict future responses.

Holistic Program Models

When assessing the overall effectiveness of an ecological monitoring program, perhaps the most important question is, Taken as a whole, are we monitoring the right things? NPS/USGS reviews of the prototype programs (1995, 1996) emphasized the importance of balancing short-term management issues and long-term ecological trends in the design of a monitoring program. The reviewers stressed that consensus must be reached between scientists and managers to achieve an appropriate balance of monitoring objectives. The reviewers also recommended improving integration within monitoring programs. A major value of an environmental monitoring program is the ability to relate trends across protocol areas. One program review suggested that none of the projects encompassed monitoring to better understand ecosystem dynamics or to attempt to correlate or support the findings of one area of study with another. The reviewers recommended instituting a formal process that encourages and ensures the cross-linking of protocols. Improving our performance in these two areas requires close communication between 1) scientists and managers, and 2) scientists within different ecological disciplines. One way of initiating dialog may be through the use of simple conceptual models that describe the links between monitoring questions and selected indicators (Figure A5). Conceptual models may also be useful as we begin to formalize how monitoring data from multiple projects will feed back into the management decision-making process (Figure A6).

Summary: Why Do We Need Conceptual Models?

1. Ecosystems (communities, populations) are 'messy' ; our ability to provide early warning of resource decline is uncertain. We need a roadmap.

2. Long-term monitoring is an iterative process (i.e. we may not get it right the first time); modeling will help ensure that mistakes are instructive and not repeated.

3. A balanced monitoring program should consider multiple spatial/temporal scales and integrate monitoring across ecological disciplines. Models serve as a heuristic device to foster better communication and clarify scaling issues.

4. A balanced monitoring program should address short-term management questions and long-term ecological integrity. Clear models serve as a heuristic device to foster better communication between managers and scientists, and between managers and the general public.

5. Modeling is like owning a bike. The important thing is not that you own a bike, but that you go bike-riding. Develop conceptual models to formalize your thinking, and refine monitoring objectives -- not to hang on the wall.

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Appendix A. Examples of conceptual models from the Prairie Cluster LTEM Program.

Figure A1. **Conceptual model of core biotic and abiotic relationships of terrestrial prairie ecosytems. Modified from Hartnett and Fay (1998), the model has been adopted by the Prairie Cluster LTEM Program. Arrows indicate known and hypothesized interactions among components.**

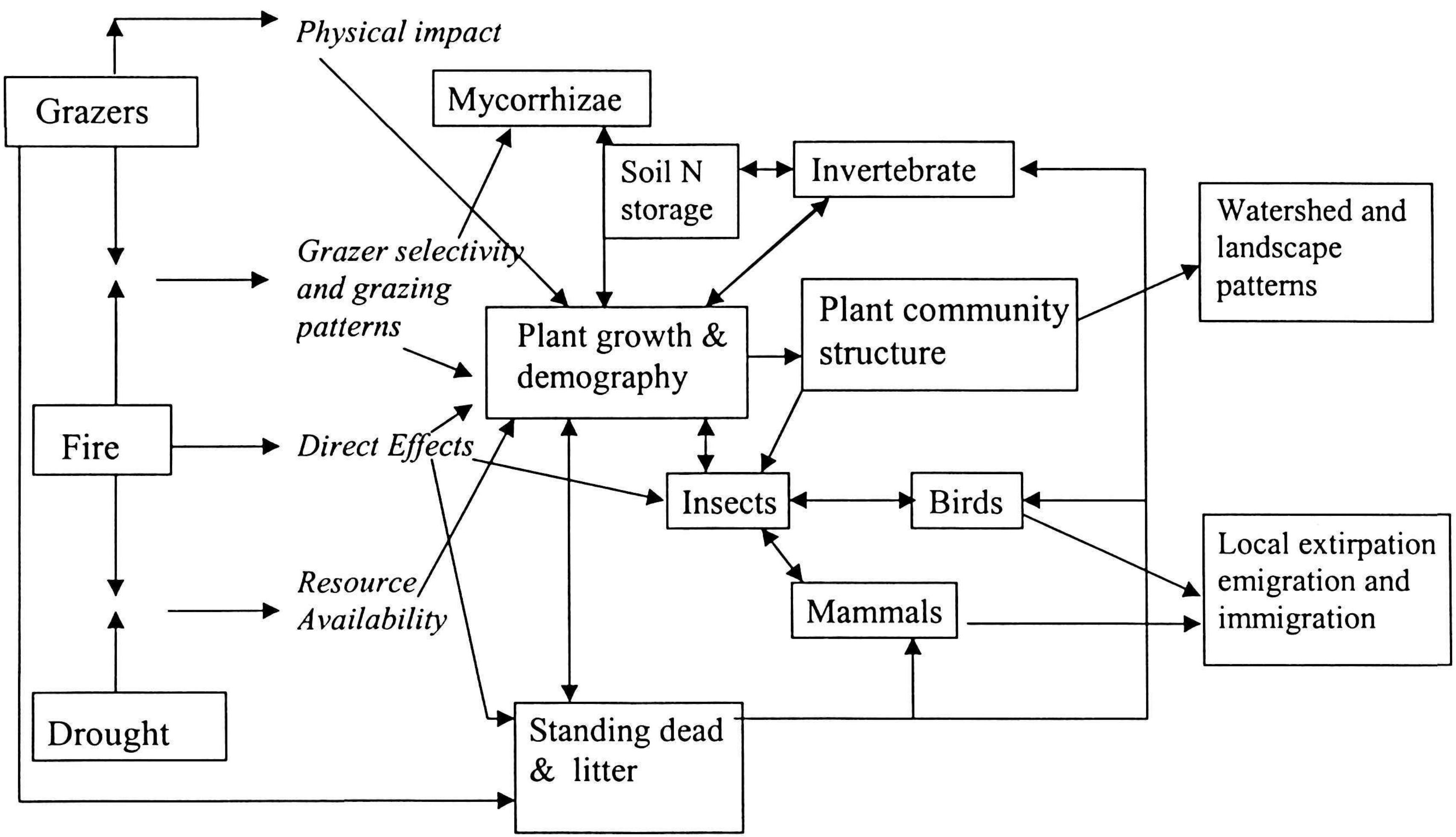

Table A1. Current anthropogenic stressors of terrestrial prairie ecosystems -- development and use impacts. Prairie Cluster LTEM Program.

Stressor	*Resource*	*Effect*	*Indicator*
Adjacent Habitat Loss & Fragmentation			Land use change maps
Isolation of native plant populations	Grassland plant communities	Loss of colonization and pollination sources, resulting in reduced abundance or loss of native species	Plant community composition; pollinator abundance
Fire suppression	Grassland plant communities	Woody invasion of prairie; conversion of savanna to woodland	Woody seedling/sapling density
Reduced wildlife habitat	Woodland plant communities	Deer over-abundance resulting in selective browsing pressure, loss of forb species	Plant community composition using exclosures
Reduced wildlife habitat	Grassland birds communities	Increase in edge and ruderal species resulting in displacement of grassland species	Bird community composition, relative abundance
Isolation of rare populations	Rare species populations	Loss of re-colonization sources following local extinction; reduced gene flow between populations	Decreased population persistence; reduced genetic diversity
Exotic Species Invasion	Grassland plant communities	Displacement of native species, alteration in community composition, structure and diversity	Plant community composition; distribution, abundance of exotics
Elevated CO_2 levels	Grassland plant communities	Shifts in species' range	Changes in persistence/abundance of edge-of-range populations
Cultural Use			
Trail Development/Use	Grassland plant communities, unique habitats	Further fragmentation of remnant communities, corridors for exotic invasion, soil compaction	Plant community composition
Fencing for cattle, watering points,		Disrupt spatial distribution of grazing, reducing landscape heterogeneity, high-impact zones adjacent to water, shade	Reduced Beta diversity, compositional changes in high-impact zones
Over-grazing	Grassland plant communities	Increased allocation to foliar production, resulting in reduced root mass; more rapid N-cycling results in increased soil N availability -- reduces dominance of prairie grasses. Reduced root mass & soil compaction reduce soil moisture retention.	Plant community composition, dominance; increased abundance of exotic species; soil nitrogen availability, soil compaction
Over-grazing	Grassland bird communities	Changes in vegetation structure result in poorer habitat quality for grassland birds	Bird community composition, abundance, diversity;

Figure A2. Conceptual model of core biotic and abiotic relationships of terrestrial prairie ecosytems, including anthropogenic stressors affecting Prairie Cluster parks. Arrows indicate known and hypothesized interactions among components.

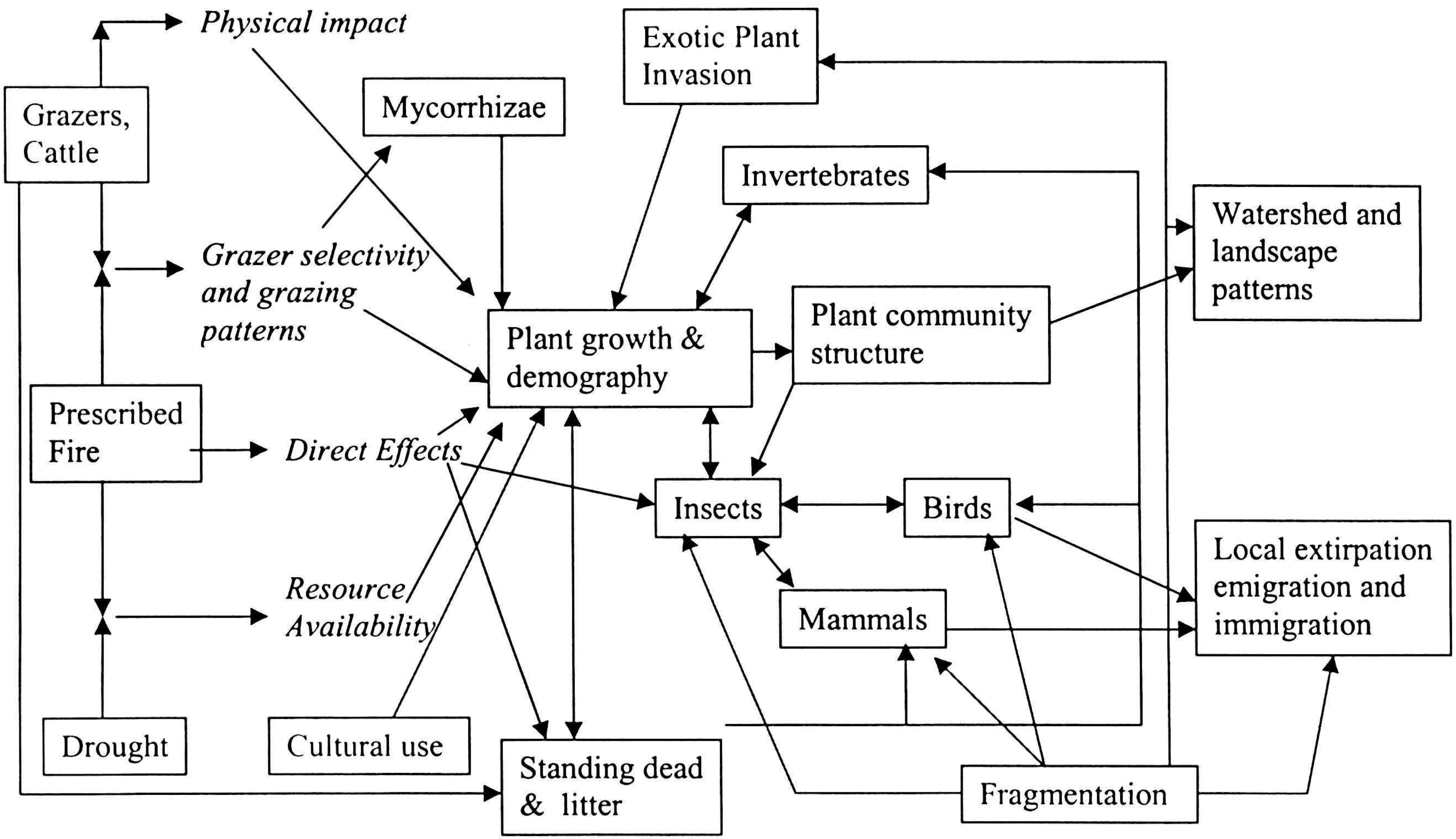

Figure A3. Focused conceptual model examining community-level interactions that may effect population dynamics of Missouri bladderpod (*Lesquerella filiformis*) by altering the quality and availability of habitat.
John Boetsch, Prairie Cluster LTEM Program.

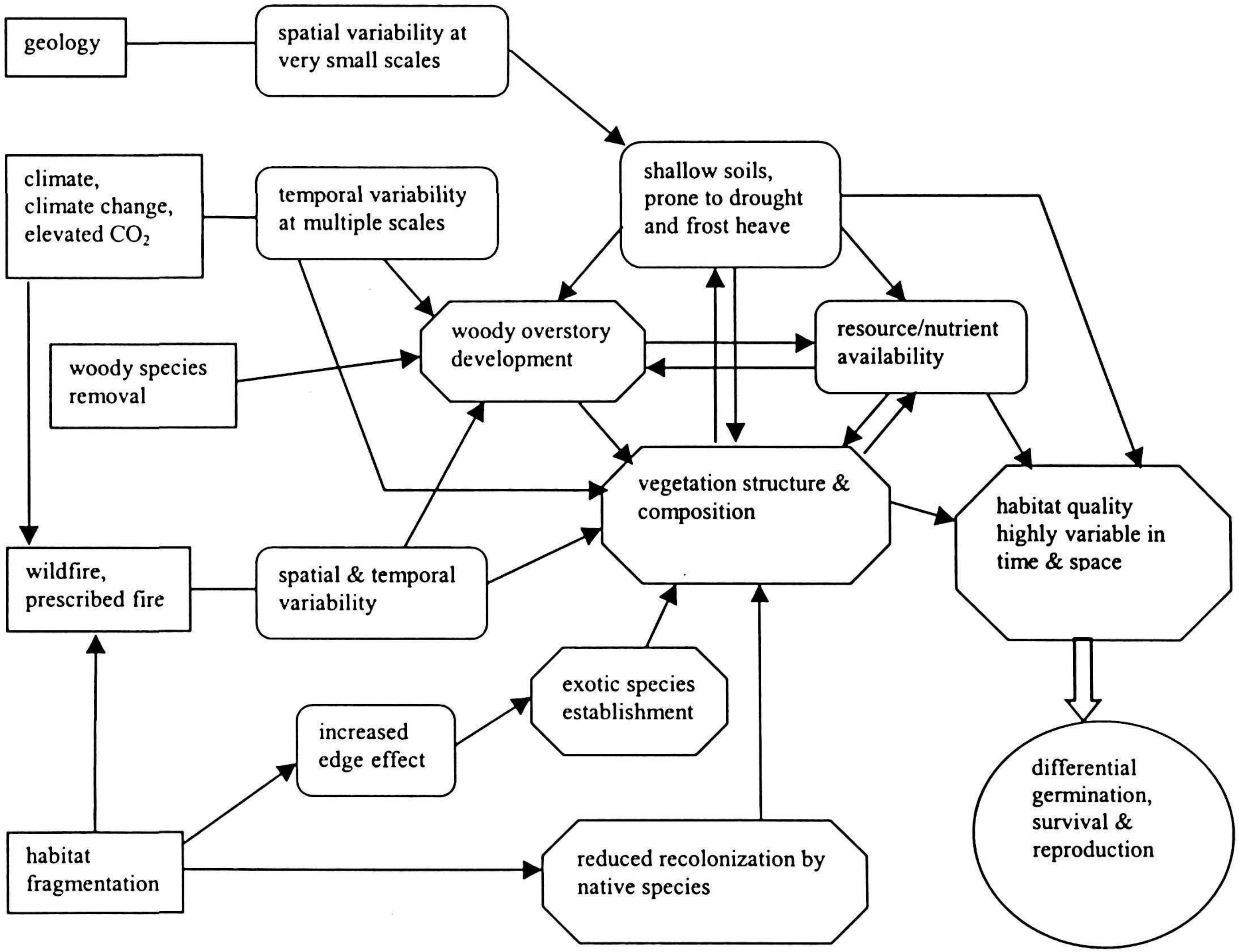

Figure A4. Focused population model examining biotic and abiotic factors influencing population dynamics of Missouri bladderpod (*Lesquerella filiformis*). John Boetsch, Prairie Cluster LTEM Program.

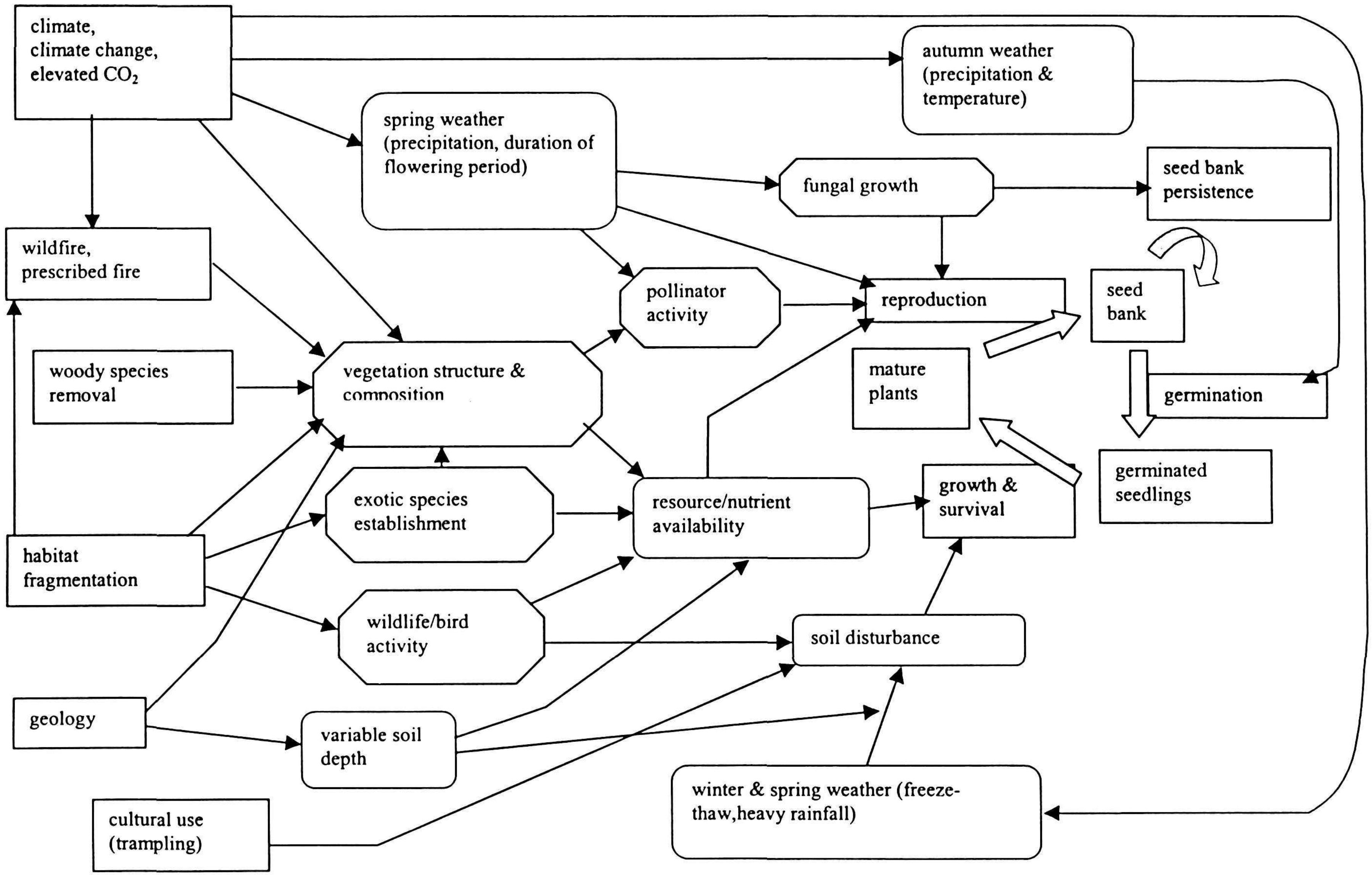

Figure A5. Holistic program model for the Prairie Cluster LTEM Program. The model illustrates key ecosystem threats and management actions affecting indicators of ecosystem health. The selected indicators provide a balanced approach that includes landscape, community and population level monitoring.

Are prairie remnants sustainable within small parks?

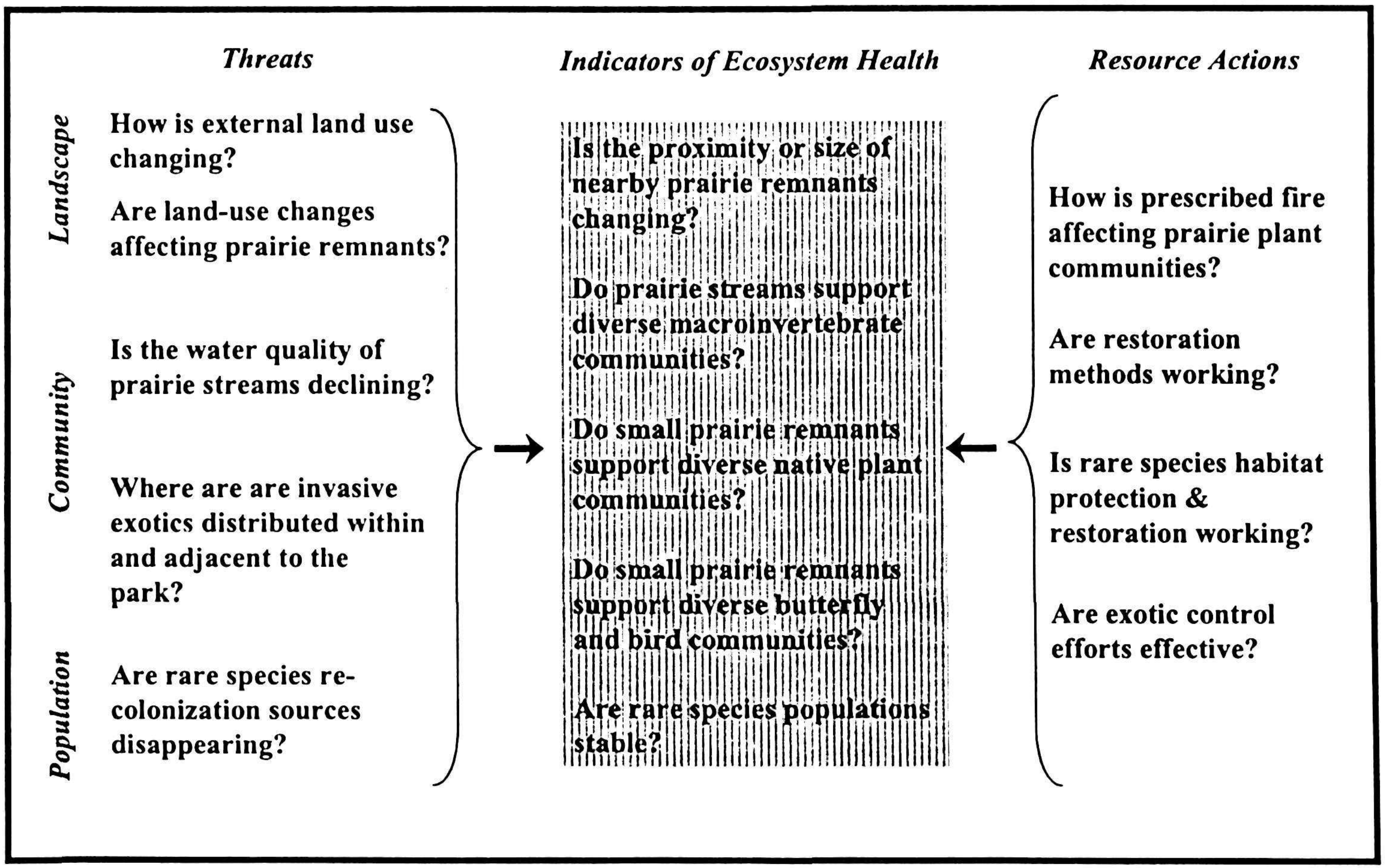

Figure A6. Conceptual model illustrating how data from several monitoring projects will be synthesized to provide management feedback.