The Process of Indicator Selection

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Abstract—*Of all the steps in monitoring, choosing the correct indicators is arguably the most important. The challenge is obvious: among all the possible attributes of an ecosystem that can be measured, select a small number whose measurement will tell you something about all of the unmeasured attributes and processes. Even if a monitoring program is fully funded and implemented for many years, it will fail if the wrong indicators were selected. Yet establishing a strong logical basis for indicator selection is often overlooked. It is not unusual to discover that great thought and deliberation have gone into how, when, and where to measure a given indicator, but little discussion of why that particular attribute is being measured, what magnitude of change needs to be detected, and what the indicator tells you about unmeasured components of the ecosystem. Further adding to the challenge is the fact that there is no prior reason to expect agreement between scientists, managers, and the public on those attributes of ecological systems most logical and important to measure. How can one narrow down the field of all possible attributes and reach agreement on what to measure? Unfortunately, science provides limited guidance because no body of ecological theory or empiricism exists to precisely guide indicator selection. We therefore contend that partnerships are critically important to the development of prior agreements between multiple parties. Critical to this process is the collaborative development of common paradigms concerning how ecosystems are conceptualized. We believe this is best accomplished if scientists and managers collaborate in the following steps: 1) develop a conceptual model which reflects the hierarchial structure of the ecological system to be managed; 2) view the environmental hierarchy as a set of filters which constrain the plant and animal species observed on the ground; 3) identify the collection of traits of a set of focal species that reflect the desired states of the environmental filters; 4) focus on the factors that adversely affect the state of the environmental filters (in other words, take a stressor-based approach to monitoring). These steps should lead to a logical group of focal species and stressors to be monitored.*

Introduction

Compliance with environmental laws and the practice of adaptive management require ecological systems to be closely monitored to assess the effects of different management practices and various land uses. However, few examples exist of successful environmental monitoring programs and the essential components of such programs have only recently been articulated (NRC 1995, Noon 2002; table 1). All steps in the development of a successful monitoring program are important (table1), but perhaps none is as important as the selection of what to measure. Even if a monitoring program is fully funded and implemented for many years, it will fail if the wrong attributes were selected for measurement. Thus, the ultimate success or failure of the monitoring program may be determined by this one step.

We consider an indicator to be any measurable attribute that provides insights into environmental conditions that extend beyond its own measurement. Indicators are usually surrogates for properties or system responses that are too difficult or costly to measure directly (Leibowitz and Hyman 1999), and indicators differ from estimators in that functional relationships between the indicator and the various ecological attributes are generally unknown (McKelvey and Pearson 2001). Not all indicators are equally informative—one of the key challenges to a monitoring program is to select for measurement those attributes whose values (or trends) provide insights into ecological integrity at the scale of the ecosystem. Pragmatic considerations alone dictate

Table 1. Steps in the design of a prospective environmental monitoring program (from Noon 2002).

1. Characterize the anticipated stressors and disturbances according to the attributes of frequency, magnitude, and selectivity.
2. List the ecological processes, resources and species affected by the stressors or disturbances and the spatial scale at which they operate.
3. Ordinally rank the stressors according to their degree of impact and/or degree of irreversible consequences.
4. Develop conceptual models of the ecological system—outline the pathways from stressors to ecological effects at the appropriate spatial scale of the ecosystem.
5. Select an "optimal" set of condition indicators that reflect the action of the stressors prior to irreversible change.
6. Determine detection limits for the ecological indicators.
7. Establish critical decision values for the indicators (values that 'trigger' a management response).
8. Establish clear connection to the management decision making process.

that only a small number of indicators can possibly be measured. However, strategies and processes for selecting ecological indicators are complex and poorly developed (Barber 1994, NRC 1995).

On way to think of indicator selection is as a filtering process. The goal is to subject all the potential measurement variables to a logic filter that allows passage of only those attributes which provide comprehensive and reliable inference to the status of the managed ecosystem. Candidate attributes include measures of ecological processes (for example, primary productivity, rates of nutrient cycling), structural and compositional elements of ecosystems (for example, distribution and abundance of vegetation community types and seral stages), and species. What these sets of attributes have in common is that information on their status and trends provide insights into the status and trend of the larger ecological system to which they belong.

Developing the criteria that constitute the fabric of the filter is difficult—the scientific knowledge needed to guide this process has generally not been synthesized with monitoring questions in mind. It is clear, however, that the nature of the criteria will vary according the types of indicators considered. For example, the criteria for indicators of physical processes will differ from those for biological processes. Further, within the class of biological indicators, the criteria for indicator species selection will differ from those for indicators that reflect scale-dependent structural and compositional aspects of the environment.

Most of the relational information collected in the biological sciences is based on correlation. While often very practical and useful, dependence on correlational relationships is dangerous in the development of indicators. There are a number of pitfalls associated with such analyses. First, it is very difficult to infer causal relationships from empirical correlations. The fact that many ecological attributes co-vary, a property which forms the logical basis for an indicator-based approach, requires additional logical structures beyond simple correlation to determine those elements that are mechanistically linked to specific ecological attributes of interest. As an example, plethodontid salamanders have been shown to be strongly correlated to canopy closure (Welsh and Lind 1995) but, mechanistically, they are linked to cool moist understory conditions (Welsh and Droege 2001). Thus, in coastal redwood forests, where moisture stress is limited, correlations to canopy closure disappear (Diller and Wallace 1994). Because the relationship between salamander densities and canopy closure is correlational rather than mechanistic, it would only work sporatically as a salamander indicator. Secondly, even those elements that are mechanistically important must be evaluated within the context of the systems in which they exist. Whether a certain density of an organism is considered beneficial or problematic is entirely dependent on the context in which it exists.

Selecting indicators that reflect meaningful ecological change is further complicated by the dynamic, stochastic, and spatially heterogeneous nature of natural systems. Further, many changes that occur in space and time are not a consequence of human-induced impacts, and many are not amenable to management intervention. For example, at least three kinds of changes are intrinsic to natural systems: stochastic variation, successional trends following natural disturbance, and cyclic variation (Noon 2002). Potential indicators that vary by orders of magnitude, due either to cyclic or stochastic dynamics will likely make poor indicators even if they have strong mechanistic ties to the larger ecosystem. As an example, snowshoe hare are the only common winter prey species in the 1 kg weight range in many boreal forests, and therefore are essential to the larger predator community. However, 10-year population oscillations (Elton and Nicholson 1942, Keith and Brand 1979, Boutin and others 1995) mean that several decades are required to characterize these oscillations such that trend could be computed.

Of most interest to monitoring programs are extrinsically driven changes to ecological indicators that arise as a consequence of some human action. Concern arises

when extrinsic factors, acting singly or in combination with intrinsic factors, drive ecosystems outside the bounds of sustainable variation. Thus, one goal of a monitoring program is to select indicators that discriminate between extrinsic and intrinsic drivers of change. That is, we seek indicators that allow us to filter out the effects of intrinsic variation or cycles (background noise) from the effects of additive, human-induced patterns of change (the signal we want to detect).

If the purpose of the monitoring program is to provide an early warning of ecosystem decline (or signs of improvement), then its success depends upon having selected an appropriate indicator or indicators, and knowledge of how much change in the value of the indicator signals a significant biological change. By itself, however, a monitoring program cannot (1) unambiguously ascertain the cause of a change (2) help decide on how much change is acceptable (in other words, is the observed change still within the range of acceptable variation?), (3) decide on threshold values of the indicator that trigger specific management actions or, (4) avoid false alarms. Specifically, because indicator activity cannot be expected to translate into precise understandings of most unmeasured elements, the simple idea of triggering specific management response based on the measured level of an indicator likely will likely prove ineffective.

Given the need to choose elements that are mechanistically linked to complex stochastic processes and structures, indicators cannot be selected without the logical rigor of carefully conceived ecological models of the system to be monitored. However, such models should reflect the fact that sustained ecosystems maintain the dynamic variations of key state variables with stable bounds (Chapin and others 1996). Unfortunately, the best state variables to monitor and their 'normal' bounds of variation are poorly known for most systems. As a result, monitoring should be an adaptive process designed to obtain accurate and precise estimates of the indicators and at the same time testing the validity of the conceptual model that lead to the current indicator choices.

Here we provide details concerning the four steps to effective indicator choice: 1) develop a conceptual model which reflects the hierarchical structure of the ecological system to be managed; 2) view the environmental hierarchy as a set of filters which constrain the plant and animal species observed on the ground; 3) identify the collection of traits of a set of focal species that reflect the desired states of the environmental filters; 4) focus on the factors that adversely affect the state of the environmental filters (in other words, take a stressor-based approach to monitoring). We focus on species to provide guidance to indicator selection for both pragmatic and scientific reasons. Pragmatically, we want to take advantage of all the species abundance/distribution data that are already available and continue to be collected. Scientifically, we want to build on the importance of the evolutionary connections between species traits and environmental attributes (Kolasa 1989 and Poff 1997).

Methods

Developing Conceptual Models

To select indicators that reflect the key elements of ecological systems—composition, structure and function—requires well-developed conceptual models of the managed ecosystem (Barber 1994, NRC 1995, 2000, Manley and others 2000, Noon 2002). The conceptual model(s) outlines the interconnections among ecosystem components, the strength, and direction of those linkages, and the attributes that characterize the state of the system. The model should demonstrate how the system "works," with particular emphasis on anticipated system responses to human-induced stresses. The model should also indicate the pathways by which the system accommodates natural disturbances and what system attributes provide resilience to disturbance. These processes could be portrayed by illustrating the acceptable bounds of variation of system components, and normal patterns of variation in input and output among the model elements.

To address all the factors mentioned above, the conceptual model must explicitly incorporate the nested, spatial structure of ecosystems (Allen and Hoekstra 1999, Pickett and Candenasso 2002). Each level of the hierarchy is defined by a set of state variables which yield scale-defined criteria based on the principle of constraint (Allen and Hoekstra 1992). By state variables we mean those habitat conditions expressed at multiple scales that influence the distribution and abundance of species. The upper levels of the hierarchy define the boundary conditions, and thus constrain, the levels below. Constraint arises because the hierarchial levels, or filters, determine the type of ecological community that will be observed. This occurs via a process of filtering out those species whose traits are incompatible with the state of the environmental filters.

Because of uncertainty over the structure and dynamics of ecosystems, reaching agreement on a single conceptual model to guide indicator selection is unlikely. Therefore, competing models are likely but not undesirable. Multiple competing models provide a formal expression of ecological uncertainty. As data accumulate from the monitoring program, they can be used to discriminate among competing models and the pool of

potential models will decline over time. This will also lead to convergence on a 'best' indicator set.

Viewing the Environment as a Set of Hierarchial Filters

We build off of two well-established facts in ecology: 1) species are deterministically linked to environmental factors (in other words, suitable habitat), and 2) the mechanism for this deterministic linkage is the presence of specific behavior, life-history, and morphological adaptations. In addition, we assert that the environment is hierarchically structured in terms of physical, chemical, and biological elements and processes (Allen and Hoekstra 1992). Because these elements and processes provide the context for the adaptative relationships between organism and environment, the organism-environment linkage is also scale dependent (Poff 1997).

An ecological hierarchy is a system of interconnected elements and processes wherein the higher levels in the hierarchy constrain lower levels (Allen and Starr 1982, O'Neill and others 1986). Within a hierarchically structured ecosystem, levels are distinguished by differences in their characteristic process rates or spatial scales. Once position in the hierarchy is identified, it is necessary to look both to larger scales to understand the context and to smaller scales to understand the mechanism that give rise to the observed patterns (Allen and Hoekstra 1992). The most well-known ecological hierarchy describes the levels of biological organization—that is, the top-down progression from biomes to genes within individual organisms. However, in this paper we refer to a hierarchy of landscape scales ranging from microhabitats to entire watersheds or basins. Following Keddy (1992) and Poff (1997), we refer to the different spatial scales as habitat filters that constrain the expression of species composition and relative abundance at lower scales. Each scale in the hierarchy is defined by a combination of physical and biotic variables that act as constraints on the regional species pool (fig. 1).

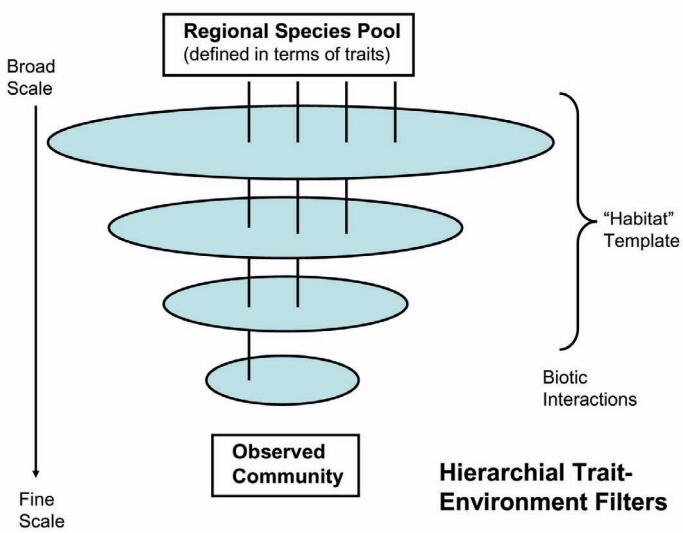

Figure 1. The trait-environment filter model developed by Poff (1997). The environment acts as a multi-scale habitat filter that ultimately determines the species composition of local communities. Species that lack traits suitable for passage through the are limited in abundance (or absence) at smaller spatial scales.

The relationship between a species adaptive traits and environmental factors provides the basis of the landscape filter theory of Poff (1997). Each level within the spatial hierarchy effectively eliminates any species whose functional attributes do not allow it to pass through the filter. Biotic interactions are also a potential filter that operates at the lower levels of the hierarchy (Poff 1997). Only species which pass through all the nested filters will be observed as a member of the local ecological community. This model is the basis on which to predict how changes in environmental conditions at different spatial scales will select against combinations of species traits (functional groups) and modify community composition (Poff 1997).

The linkage between species traits and the environment requires a characterization of the environment in terms of a specific set of state variables. These variables form the fabric of the filter—if the functional characteristics of the species fail to match the selective characteristics of the filter, the species will not occur in the community. To achieve the goal of indicator selection requires that both the functional traits of species and the environmental state variables to which they are linked be identified.

We believe the relations described above provide a framework for indicator selection based on hierarchy theory and the evolution of species trait-environment linkages. Both these topics have an extensive literature, much of it theoretical. What we find most relevant is the literature on species environment linkages that specifically incorporate the hierarchal structure of the environment and the role it has played in the evolution of species traits. What may be novel in our paper is the merging of these two areas of theoretical ecology to address the challenge of indicator selection for environmental monitoring programs. In adopting this approach we are emphasizing species composition at local and regional scales as the proximate measure of management success. If the expected complement and relative abundance of species is retained on the landscape then management is providing successful. If the expected values are not observed, then this suggests that one or more of the defining elements of the hierarchal environmental filter is missing. The focus is on functional groups as indicators of the state of the

environment—that is, environmental state is the ultimate measure of management success.

Identifying Species Traits Consistent With Environmental Filters

To operationalize the process of defining species-environment linkages it is necessary to: 1) assign each species a trait strength that identifies its tolerance to different environmental filters at each hierarchal level; 2) assign each environmental filter a strength that determines the likelihood that a species with a given trait strength will pass through the filter. Based on these two sources of information, Parsons (19??) proposed a method of predicting local species composition and abundance patterns by multiplying indices of trait strength and filter selectivity to estimate a likelihood of occurrence. Occurrence likelihoods are subsequently associated with different abundance categories (for example, abundant, common, uncommon, rare). Coupling information from the regional species pool with desired environmental states yields an expected species abundance distribution. A comparison of the expected species composition and abundance patterns with that observed will identify "breaks" in the occurrence patterns (Kolasa 1989). Lack of agreement between an expected pattern and what is observed on the ground indicate that current environmental conditions are restricting the occurrence of (in other words, filtering out) specific species or functional groups. Information from trait-environment linkages of the missing species can then be used to identify those components of the environment that need to be changed.

The Use of Species Population Dynamics as Indicators

Species are common components of comprehensive indicator sets for several reasons. Pragmatically, species are often a good choice because they have value to the public. Even if they are not the best choice based on ecological criteria, public interest along suggests their inclusion in an indicator set. Fortunately, however, there are strong ecological arguments for the inclusion of species because their population status is often indicative of disturbance and stressors events that span a range of temporal and spatial scales. For example, changes in stream macro-invertebrate communities are good indicators of acute stressor events that may go unrecorded by infrequent water chemistry measurements. Indicators species may also provide insights to the status and trends of unmeasured species. For example, multi-species conservation issues in Africa and Australia have been addressed by concentrating on "focal species" (Davis 1996, Lambeck 1997). Often these species are simply those with large area requirements in habitats experiencing loss and fragmentation. By sustaining the populations of species with large area requirements, presumably those species with similar habitat requirements, but requiring less area, will also be conserved.

The Committee of Scientists (COS 1999) in their report to Secretary of Agriculture Daniel Glickman proposed the use of focal species as an integral part of the monitoring of Forest Service lands. The key characteristic of a focal species that make it particularly relevant to monitoring was that its status and trend were hypothesized to provide insights to the integrity of the larger ecological system to which it belongs. "Focal species serve an umbrella function in terms of encompassing habitats needed for many other species, play a key role in maintaining community structure or processes, are sensitive to changes likely to occur in the area, or otherwise serve as an indicator of ecological sustainability" (COS 1999). In this paper we have extended the focal species concept by emphasizing those species with strong trait-environment linkages.

The focal species concept differs subtly, but significantly, from the previous "management indicator species" concept. Rather than acting as an indicator of a specific management prescription or an indicator to the abundance of less easily survey species and their associated habitats, focal species allow induction to the state of the ecological system to which they belong. In this sense, the focal species concept is more closely aligned with the concept of a condition indicator (see discussion in Zacharias and Roff 2001). Even though species are key components of the indicator set, they are judiciously chosen so that inference is at the ecosystem level.

For pragmatic reasons it may be necessary to limit the set of trait-species to a manageable number of focal species. For example, in its recommendations for changes to the National Forest Management Act, a Committee of Scientists (COS 1999) proposed a focal species approach to monitoring on Forest Service lands where focal species where largely defined on the basis of their functional role in ecological systems. Others classifications of focal species can be derived by varying the selection criteria including one based on the possession of traits strongly linked to environmental filters. Other researchers have successfully defined functional species groups on the basis of evolved trait-environment linkages (Keddy 1992) and we propose a similar process with an objective of indicator identification.

A Stressor-based Approach to Indicator Selection

To be most meaningful, a monitoring program should provide insights into cause and effect relations between environmental stressors or specific management practices and anticipated ecosystem responses. Prior knowledge of the factors likely to stress an ecological system or the expected outcomes from management should be incorporated into the indicator selection process (NRC 1995, 2000). Narrowing down the list of candidate indicators is aided by an appropriate conceptual model that clearly links stressors (for example, pollutants, landscape change, management practices) to specific levels in the hierarchy of environmental filters (fig. 1). This process enables the monitoring program to investigate the relations between anticipated stressors and environmental consequences prior to irreversible change. Such predictive or stress-oriented monitoring seeks to detect the known or suspected cause of an undesirable effect before the effect has had a chance to occur or to become serious. The design chosen for effectiveness monitoring of the Northwest Forest Plan (USDA 1993 and others) was an attempt to incorporate effects-oriented and stressor-oriented thinking into the indicator selection process (Mulder and others 1999).

Indicator Selection

Figure 1 could be interpreted as either a top-down or bottom-up set of relationships. We have so far emphasized the top-down aspect of figure 1—that is, the environment acting as an hierarchal filter that constrains the species composition and abundance of a community at a given site. It is equally useful to view figure 1 from the bottom-up. In this case, it is the missing species or unexpected abundance patterns that indicate an undesired state for one or more of the environmental filters. Identifying the spatial scale of absence of a focal species or functional group identifies where an undesired environmental state resides in the spatial hierarchy. Thus, the linkage between species traits and environmental filters provides a model for the selection of both environmental and species indicators.

Given the significance of trait environment linkages, it is possible to outline a process of indicator selection. The procedure entails the identification of a set of species based on criteria such as their functional importance to the ecosystem (for example, keystone species, ecological engineers, competitive dominants), their role as an umbrella species, or their legal status (in other words, a listed species under the Endangered Species Act). Because they represent more general categories than species, several authors (Poff, 1997, Poff and Allan 1995, Weiher and Keddy 1995, and Statzner and others 2004) have argued for the identification of functional trait groups defined on the basis of trophic guild, habitat specialization, body size, and vagility, for example. Whatever criteria are used to select focal species, to be useful indicators they must possess traits that are strongly linked to the environment and collectively include the entire hierarchy. Each of the focal species has an expected distribution and abundance pattern based on the desired states of the environmental filters. The distribution and abundance patterns of the focal species then become the species-level indicators.

The process for selecting environment indicators is essentially the flip-side of selecting focal species. Those environmental state variables most frequently associated with the occurrence of the focal species (or functional trait groups) become candidate indicator variables. That is, the strongest trait-environment linkages help define the environmental indicators to be measured. For a given focal species these might include factors such as the abundance and spatial pattern of habitat at the landscape scale, the structure and composition of habitat at the home range scale, patches of food resources within the home range, and the presence of a suitable nest site within a resource patch. Alternatively, specific spatial scales for the environmental filters can be defined a priori. This was the approach used by Poff (1997) and Jensen and others (2001) in their hierarchial classification of drainage basins. Prior to identifying environmental state variables, Poff (1997) proposed the following nested scales: basin/watershed, valley/reach, channel unit, and microhabitat. Within each of these scales he identified measurable landscape attributes (state variables) that could be related to species presence/absence or abundance patterns.

Collectively, the trait-environment model helps identify two types of indicator variables: 1) focal species whose traits (for example, trophic position, behavior, body size, habitat specialization) are linked to environmental state variables, and 2) environmental variables that represent those habitat attributes that must be present to allow the focal species to occur. In addition, the environmental indicators are scale-specific—that is, coarse scale attributes are necessary, but not sufficient, to explain species occurrence patterns in local communities (fig. 1).

Discussion

A comprehensive monitoring program should include indicators that collectively measure compositional, structural, and functional attributes of ecological systems at a variety of spatial scales (Lindenmayer and others 2000, Noon and Dale 2002). Composition indicators usually are species-based measurements where the species measured

provide insights to the status of trend of the unmeasured species. Concepts such as guild indicators species would apply here (Verner 1984). Function-based indicators include direct measures of processes and their rates. Examples include primary productivity, rates of nutrient cycling, and water flows. Structure-based indicators, measured at local and landscape scales, include elements such as vegetation structural complexity, among-patch vegetation heterogeneity, landscape connectivity and landscape pattern (in other words, the distribution and abundance of different patch types). These metrics are often assumed to constitute a "coarse filter" because of their ability to predict broad-scale patterns of biological diversity (Hunter and others 1989, Haufler and others 1996).

Both function- and structure-based indicators can be measured at multiple spatial scales ranging from local, to landscape, to regional. In addition, there are composition-based indicators that include the direct measurement of some aspects of a species' life history, demography, or behavior. These are often referred to as "fine filter" assessments because they evaluate the effects of management practices on individual species (Haufler and others 1996).

What we propose in this paper is consistent with these previous perspectives on indicator selection—it is multi-scale and based on composition, structure, and function indicators. What is novel is the emphasis on species traits and their linkage to environmental state variables to facilitate indicator identification. It is based on the understanding that the scaled habitat features of the environment influence the probability that individual species with specific traits will occur as members of local communities (Poff 1997). Viewing the observed biological community as a set of species traits enables two types of inference: 1) from species data to the state of the environment at multiple spatial scales, and 2) from the state of environment to the expected species composition. A missing species or an unexpected composition or abundance distribution is indicative of an undesired environmental state(s). Knowledge of the links between traits and environment state variables thus allows one to identify what in the environment needs to changed and helps guide an appropriate management response.

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