Guiding principles for developing an indicator and monitoring framework

by Robert S. Rempel[1], David W. Andison[2], and Susan J. Hannon[3]

Sustainable forest management ideally involves five elements: 1) establishing a clear set of values, goals and objectives and, 2) planning actions that are most likely to meet desired goals and objectives, 3) implementing appropriate management activities, 4) monitoring the outcomes to check on predictions, effectiveness, and assumptions, and 5) evaluating and adjusting management depending on the outcome of monitoring. Within this framework, indicators are used to determine whether the outcome of management has met the intended goals. In this paper we provide general guidance for developing an integrated and logical monitoring system, define and differentiate between "evaluative" and "prescriptive" indicators, provide more specific advice on choosing evaluative indicators (including a comparison of types of ecological indicators), and provide specific advice on defining prescriptive indicators. Our guidelines for developing an indicator and monitoring framework are based on three principles. The first principle is to develop a logical framework, including 1) establishing clear values and goals before setting indicators and objectives, and 2) linking prescriptive and evaluative indicators directly to plan objectives, and to each other. The second principal is to use the framework to learn adaptively by: 1) designing management activities to address specific questions, 2) learning about thresholds, and 3) testing assumptions. The third principal is to create a formal plan for learning.

Key words: biodiversity, indicators, focal species, adaptive learning, sustainable forest management

L'aménagement forestier durable comprend idéalement cinq éléments: 1) la mise en place d'un ensemble défini de valeurs, de buts et d'objectifs; 2) la planification des actions qui permettront le plus vraisemblablement d'atteindre les buts et les objectifs; 3) la mise en place des activités appropriées d'aménagement; 4) le suivi des retombées afin de vérifier les prédictions, l'efficacité et les hypothèses et 5) l'évaluation et l'ajustement de l'aménagement en fonction de l'analyse du suivi. Au sein du cadre de travail, les indicateurs sont utilisés pour déterminer si les retombées de l'aménagement ont rencontré les buts envisagés. Dans cet article, nous établissons une direction générale pour élaborer un système intégré et logique de suivi, nous définissons et faisons la différence entre les indicateurs « d'évaluation » et de « prescription », nous formulons des conseils plus spécifiques pour le choix d'indicateurs d'évaluation (comprenant une comparaison des types d'indicateurs écologiques) et nous formulons des conseils plus spécifiques relativement à la définition des indicateurs de prescription. Nos directives concernant l'élaboration d'un indicateur et du cadre de suivi reposent sur trois principes. Le premier principe touche l'élaboration d'un cadre de travail logique comprenant 1) l'identification précise des valeurs et des buts avant de mettre en place des indicateurs et des objectifs et 2) le rattachement des indicateurs de prescription et d'évaluation directement aux objectifs du plan et également entre eux. Le second principe est d'utiliser le cadre pour apprendre par adaptation : 1) en concevant des activités d'aménagement qui répondent à des questions spécifiques, 2) en identifiant les limites et 3) en évaluant les hypothèses. Le troisième principe vise à créer un plan formel d'apprentissage.

Mots-clés: biodiversité, indicateurs, espèces principales, apprentissage par adaptation, aménagement forestier durable

Introduction

The ultimate goal of sustainable forest management is to maintain the ecological integrity of forest landscapes so they will continue to provide the social, cultural and economic needs of people. The process requires projecting forest conditions, natural disturbance threats, and market and technology trends more than 100 years into the future using imperfect knowledge of the biological system being managed and the response of current and future societies to forest management. Effective sustainable forest management must make sound decisions and constantly assess how good those decisions were, allowing for the incorporation of new knowledge.

Robert S. Rempel

David W. Andison

Susan J. Hannon

Towards that overarching goal, forest management should involve 5 elements: 1) establishing a clear set of values and goals, 2) planning actions that are most likely to meet those goals, 3) implementing appropriate management activities, 4) monitoring the outcomes of management to check on predictions, effectiveness, and assumptions, and 5) evaluating monitoring outcomes and adjusting management if goals were not met (Fig. 1).

[1]Centre for Northern Forest Ecosystem Research, Lakehead University, Thunder Bay, Ontario P7B 5E1. E-mail: rob.rempel@mnr.gov.on.ca
[2]Bandaloop Landscape-Ecosystem Services, 3426 Main Ave., Belcarra, B.C. V3H 4R3.
[3]Department of Biological Sciences, University of Alberta, Edmonton, Alberta T6G 2E9.

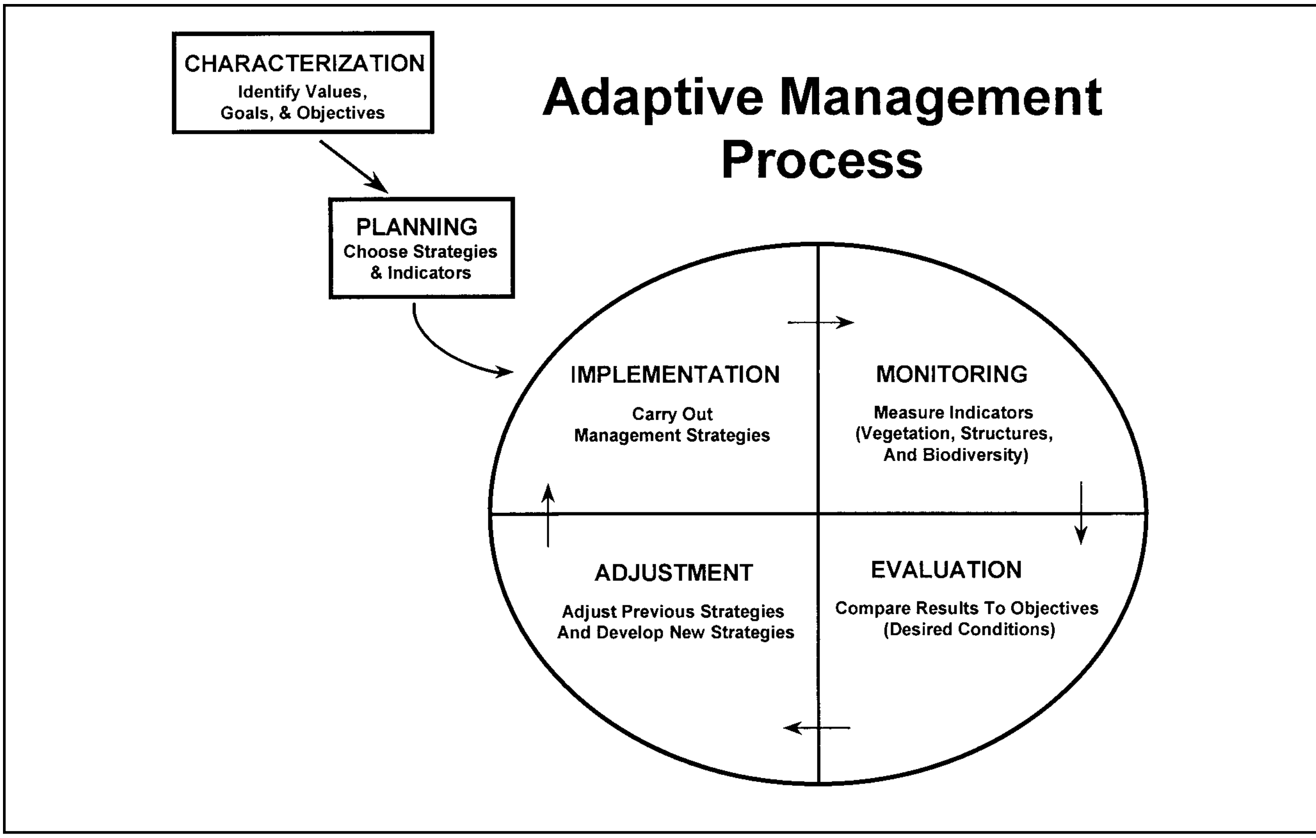

Fig. 1. Key components of the adaptive management process (figure courtesy of Jim Schieck).

These five elements ideally function in a continuous cycle, with monitoring supplying constructive feedback on the effectiveness of decisions and the status of uncertainties to the other phases. This cycle is the essential foundation of what is known as adaptive management. Thus, the key to a robust sustainable forest management system is successful adaptive management, which is largely achieved through an effective monitoring program.

Unfortunately, few examples of robust monitoring systems (within this larger context) exist today. We propose this is the case for at least three reasons. First, there has been a lack of appreciation that monitoring is part of a larger goal, and not merely an end unto itself. Evidence of this is prevalent in both provincial biodiversity monitoring programs and formal certification programs that create deliberately disconnected monitoring cycles, which are only peripherally linked to management activities. The second reason that monitoring systems have been so troublesome is our inability to see indicators as more than simple monitoring measurements. In fact, indicators are a tool with which many of the five elements listed above are connected to each other. If we do not think of them in such terms, they will never function as such. The third and final failure has been insufficient thought given to the classification of indicators. Indicators tend to be lumped together as simple lists, suggesting they should also be measured and reported together, with little hierarchical structure.

Through an examination of indicators as one of the most critical linking tools for adaptive management, we will demonstrate in this paper how an integrated management planning and monitoring cycle can become a reality by considering an expanded role for indictors. The purpose of this paper is to identify the kinds of indicators that can be used to support and test management actions in a realistic manner, to define the underlying logic for the indicators and illustrate their use, and through this, provide guidance for developing an integrated and logical monitoring system.

Definitions Used in This Paper

Too often, differences in the meaning of terms are the reason for our failure to communicate, critically discuss, reach agreement, and move forward. This paper is a case in point. If we hope to help mature the ideas and use of indicators in forest management, we must ensure that readers have the same mental model of the technical terms most commonly used. Our brief definitions are given below, not as being right, but rather as they are used in the discussion to follow.

Indicators

One way to test whether management actions have met management goals is to monitor indicators (Carlsson 1999, Failing and Gregory 2003). Indicators are measurements representing specific issues or concerns. If they do not specifically represent an issue, they are simply measurements, and of no concern to a monitoring program. For example, if access is identified as an important management issue, then indicators of this may include road density, road quality, and/or the number of road closures and gates. If conservation of woodland caribou (*Rangifer tarandus caribou*) is an issue, then indicators might be measures of caribou habitat quantity and quality and/or direct counts of caribou herds. To be effective, an indicator must be measurable within a reasonable period of time, relevant to the issue in question, informative, understandable, and cost-efficient (Ferris and Humphrey 1999).

Prescriptive versus evaluative indicators

Two main types of indicators exist in forest management: prescriptive and evaluative (Kneeshaw *et al.* 2000). Prescriptive indicators are used in harvest planning to stipulate the future condition of the forest. Evaluative indicators test whether the future forest condition achieved the ultimate objective. For example, assume that the goal of forest management is to maintain current levels of biodiversity (i.e., no net loss of species, no declines in abundance of species). The management strategy to meet this goal might be to harvest the forest to emulate natural disturbance patterns. In this case, prescriptive indicators are used in harvest planning to describe the future condition of the forest. These indicators would include such things as the amount, severity, spatial pattern, and frequency of harvest specified to mimic natural disturbance activities. Evaluative indicators are then used to test whether the resulting forest condition achieved the desired objective: maintaining biodiversity. These evaluative indicators could be measures of species richness and abundance, for example.

For reference, note that prescriptive indicators are often referred to as compliance indicators since they are really nothing more than a check on what activities were promised. Evaluative indicators measure the response of the system to the management activities, and are often referred to as effectiveness indicators.

Coarse-filter versus fine-filter management

A filter is a means by which a system is simplified for the purposes of understanding and decision-making. A fine filter is a very specific piece of knowledge, and a coarse filter is a more generalized one. In the context of forest management, fine-filter refers to management of individual species or specific ecological functions. Coarse-filter management relies on creating the conditions under which those species and functions exist (Hunter 1990). For example, coarse-filter management might attempt to use harvesting to emulate patterns and structures left after a natural disturbance, with the hope that the habitat created would attract the same biota as habitat created by the natural disturbance. Fine-filter management is designed to protect those species whose habitat requirements are not met by coarse-filter management. These may include rare, threatened and endangered species. Both fine-filter and coarse-filter management strategies are necessary, and work best in concert. Consider that one of the weaknesses of a coarse-filter management strategy is the assumption that by creating the conditions we hope are suitable for species and functions, those species and functions will exist. This is largely an unproven hypothesis that must be continually verified also by managing and monitoring key fine-filter issues.

Values, goals and objectives

Values are statements of socially accepted states or flows of resources from the forest. For example, "healthy" state of biodiversity, natural forest patterns, and a viable forest industry are all values. Associated with values are goals that indicate the direction in which we want these values to develop over the long-term. No change in endemic levels of biodiversity, maintenance or restoration of natural forest patterns, and the long term sustainability of the forest industry are goals associated with the above list of values, respectively. Goals are implemented through planning objectives, which are measurable, tangible, and functional predictions of the future, designed to achieve the goal in question. At least thirty caribou per 1000 square km, 5–10% of all disturbance patches over 1000 ha in size, and a critically reviewed long-term wood supply analysis might be objectives that achieve the three goals outlined above, respectively.

Note that the definition of an objective is similar to that of an indicator. In fact, indicators are nothing more than the units of measure used by objectives. Thus, the terms evaluative and prescriptive can apply to objectives as well.

Adaptive management

Adaptive management is a process of hypothesis testing at the scale of whole ecosystems (Fig. 1) (Walters 1997). In forestry, adaptive management is meant as a means of attaining longer-term goals sooner, through shorter-term testing of hypotheses. This is done by recording the reactions of an imperfectly known, stochastic system to perturbations. The hypotheses in this case are predictive links between management prescriptions and outcomes. Ideally, such prescriptions should follow basic rules of experimental design such as controls, replicates and treatments. However, in reality, this is rarely feasible or desirable.

On the other hand, the concept of being actively and openly adaptive in planning and management is not only possible, but extremely relevant in the context of this paper. One of the basic tenets of adaptive management is that one should be making predictions of the impact of management decisions. Another is that learning becomes a regular part of the management cycle rather than a separate activity. These are powerful ideas of which we have yet to take full advantage.

Guiding Principles for Developing and Applying Indicators

The following outlines a series of rules that can be used to help design a set of indicators that meets the requirement of both providing efficient, effective, and timely measurements from a monitoring perspective, as well as robust links between planning, management and monitoring systems. It is organized into three sub-sections or principles.

Principle #1: Develop a logical framework

An overarching framework for developing indicators that serve the greater needs of planning, management, and monitoring includes three rules.

1. *Establish clear values and goals before setting objectives*

Without a clear understanding of values and goals, it is impossible to establish meaningful management objectives (Noss 1999). Care must be taken in the phrasing of goals as they define the scope and flexibility of management objectives. For example, consider "maintaining natural forest patterns" versus "maintaining endemic levels of biodiversity" as alternative goals. With "maintaining natural disturbance pattern" as the goal, any management activity that results in forest patterns that might be considered "unnatural" would be rejected. Shoreline buffer strips along lakes and rivers may be such an example in fire-dominated landscapes. With "maintaining biodiversity" as the goal, natural disturbance patterns may be one of several reference systems used as guides for management prescriptions.

2. *Link prescriptive and evaluative indicators directly to plan objectives, and to each other*

Because indicators are used via monitoring to determine whether we have met our objectives, they must be stated in the same terms as the planning objectives. Not only does this association force indicators to be more realistic, but it also forces us to phrase objectives in measurable, meaningful terms. If plan objectives are not phrased in quantitative, concrete terms, then they are probably either unattainable or irrelevant. For example, a goal might be to "provide hunting opportunities for game animals." In this case, prescriptive indicators would be things like edge density or forest age composition, and an evaluative indicator would be the number of moose per unit area. The corresponding objectives might be: "No more than 400m of edge/ha," "at least 40% of the landscape greater than 100 years of age," and "a density of at least 1 moose/km^2." Only when the link to the plan objectives is made do measurements become indicators. Monitoring without any traceable link back to goals and values is simply an accounting exercise. Indicators must be stated explicitly and quantitatively to become useful measures, and the reference scale or extent for the measurement must be identified.

Further more, evaluative indicators are closely related to the original goals, but represent essentially unproven hypotheses that must be continually tested (i.e., if we do x, y will result). In this example, the evaluative indicator is the number of moose/km^2, but only by linking a prescriptive indicator to this do we create an hypothesised cause and effect linkage. By doing this we have two meaningful, measurable objectives that are also robust indicators of achieving the original goal. The prescriptive indicator allows the plan to be compared directly to the outcome, while the evaluative indicator allows the effectiveness of the prescription itself to be assessed, i.e., did the change in edge density and forest age structure result in an increased moose density (Rempel *et al.* 1997)? Thus, linking the outcomes of the evaluative indicators to the prescriptions allows us to move on to other, new hypotheses that are hopefully more successful at achieving our objectives.

Summarizing these two rules, we envision the following series of decisions being made in the following order for a biodiversity example:

Step 1: Value = "Healthy" state of biodiversity

Step 2: Goal = Maintain current diversity and relative density of old-growth-dependent vertebrates.

Step 3: Evaluative indicator = Abundance of American marten (*Martes americana)* per unit area; selected because marten respond to the condition of mature and older forest at the landscape scale).

Step 4: Evaluative objective = Forest will have at least 250 marten per unit area (minimum viable population + 15%).

Step 5: Prescriptive indicator = Amount of mature and late seral stage forest per unit area.

Step 6: Prescriptive objective = Ensure at least 48 000 ha of mature and late seral stage forest per unit area (15% of a 320 000 ha forest management unit).

Principle #2: Use the framework to learn adaptively

As discussed, evaluative outcomes from prescriptive objectives are in most cases untested hypotheses. One of the advantages of deliberately differentiating between evaluative and prescriptive indicators while establishing the framework is that they can be used to essentially pose and answer critical questions. This can take several forms.

1. *Design management activities to address specific questions*

The most literal adoption of the adaptive management model would be to design a landscape-scale experiment using prescribed management activities to address very specific and important questions. This is known as active adaptive management (Walters 1986, Sinclair 1991). For example, the question of whether or not terrestrial disturbance in riparian zones is necessary or desirable in the boreal forest is a critical issue that may warrant large-scale prescriptions of various treatments that may include various levels of mechanical and prescribed burn severity (captured by prescriptive indicators), as well as appropriate control or representative areas. Evaluative indicators may include key aquatic biotic and abiotic measurements such as water temperature, large woody debris recruitment, or macro-invertebrate species diversity. The actual monitoring activities in this case would take place on the treatments as well as the designated control or background areas.

This option involves a high level of commitment, planning, and resource allocation to do well. However, it remains a viable possibility since it is the best way to address some of the more critical questions definitively. In such instances, the framework suggested above at least provides a scientifically-consistent context for such experiments since the indicators are already phrased in terms of cause and effect that relate back to relevant goals and objectives. Thus, as envisioned by the originators of the adaptive management concept, monitoring systems become an integral part of gaining new knowledge.

2. *Learn about thresholds*

A less drastic application of the monitoring framework is to explore thresholds. Species can react to changing amounts of habitat in different ways (Fig. 2). For example, as the amount of forest cover decreases, the abundance of open-country species might increase (Fig. 2a), whereas forest-dependent species might decline in a linear way (Fig. 2b). Alternatively, some habitat generalist species might reach their highest abundance at intermediate amounts of forest cover (Fig. 2c). Finally, some forest-dependent species might initially decline in a linear way, but at a certain level of forest cover, their rate of decline might increase (Fig. 2d). The inflection point in Fig. 2d is called a critical threshold. Critical thresholds are levels of a resource below which small changes in the configuration or amount of that resource produce abrupt shifts in ecological responses (With and Crist 1995).

Despite the importance of identifying species thresholds, most of our knowledge on this subject is theoretical (With and Crist 1995, Fahrig 1997). The relationships between potentially prescriptive indicators such as patch size, connectivity, or edge density and evaluative indicators of species responses are largely unknown. Exploring these important relationships is facilitated through the monitoring framework outlined above due to the deliberate connection between cause and effect. The planning effort and resources required to tackle threshold questions is far less than that of a full-on experiment, but still requires the involvement of scientists.

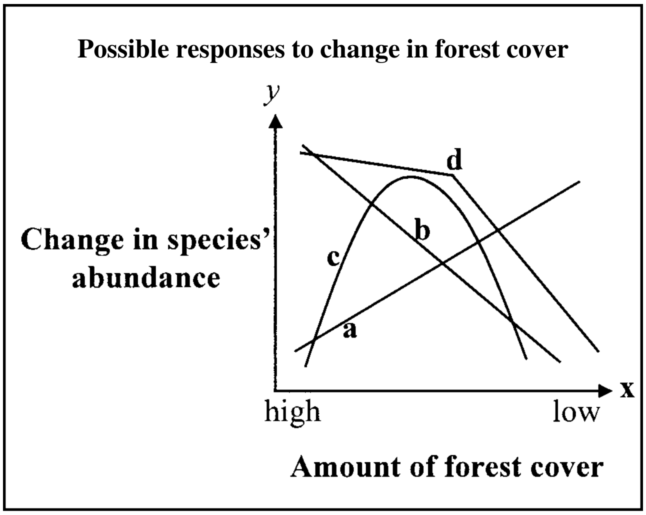

Fig. 2. Four theoretical responses of wildlife to changes in forest cover: (a) wildlife abundance increases linearly with amount of forest cover, (b) decreases linearly, (c) displays local optimum at the midway point, and (d) displays break in rate of change at the midway point (i.e., at the critical threshold).

3. *Test assumptions*

The third and most passive level of adaptive monitoring involves no more than a commitment to making, and reporting on, specific predictions of the relationship between prescriptive and evaluative indicators. Regardless of the basis of such predictions, as long as the represent our best estimate, we cannot help but learn something. There is no shortage of dogma and untested assumptions in certain forest management decisions, and at the very least, this will allow those assumptions to be tested. However, it is important to keep in mind that our capacity to learn relies on how specific our predictions are.

Principle #3: Create a formal plan for learning

A critical component of a successful monitoring framework is a formal mechanism to respond to new knowledge. Monitoring reports should include several sections on compliance outcomes (for prescriptive indicators), a critique of evaluative indicator outcomes, a review of new fine-filter knowledge gained (including thresholds and other pattern-process relationships), identified research gaps, policy and practice conflicts, and recommended changes to indicators, targets, and objectives. If the evaluative indicators inform us that our changes to forest pattern are doing more harm than good, then management and stakeholders must be informed of the problem and be prepared to respond to this knowledge. Similarly, governments must have a mechanism to review and approve changes to management plans resulting from this knowledge. Without such mechanisms, the sustainable forest management system cannot adapt to new knowledge, or does so very slowly.

If management targets are not met, managers must determine why. For example, the provincial planning and monitoring framework in Saskatchewan identifies the following 12 possible reasons why an expected or predicted target may not be met (from Andison *et al*. 2002). These are, briefly: 1) measurement methods/tools inappropriate; 2) external influences; 3) target inappropriate; 4) indicator inappropriate / too vague; 5) poor implementation of (forest-level) plan; 6) poor planning (at the forest level); 7) unforeseen conflict with non-ecological considerations; 8) unforeseen conflict with other ecological needs; 9) relevant objective wrong / inappropriate / too vague; 10) Provincial-level objectives inappropriate / too vague; 11) poor models (of understanding / prediction); and 12) baseline was lacking (as with a baseline indicator). Such a success/failure could be part of a formal feedback system and monitoring report.

This discussion illustrates the need for links between policy, planning, management, and research to create an effective monitoring program. Indeed, the number and strength of such links would be excellent indicators of the success of a monitoring program overall.

Choosing Evaluative Indicators

The number and composition of evaluative indicators chosen depends on the complexity of the goals. For example, if the objective for a particular area was simply to increase the number of woodland caribou by 20% and to maintain this density in perpetuity, then the evaluative indicators would include the density and age and sex structure of caribou on the area. If the goal was to ensure that populations of all species on the forest management unit persist in perpetuity, then choosing evaluative indicators becomes more difficult because it will be impossible to monitor all populations of all species on the area. In this case, one must resort to choosing a set of focal species that will represent all other species in the system (Table 1). Below, we define terms used to describe different types of indicators and then outline approaches for choosing suites of evaluative indicators when one of the goals of management is to maintain populations of all species on the management unit in perpetuity—which we presume to be a goal common to most forested areas of Canada.

Choice of evaluative indictors for forest management

The various types of focal species that are used in environmental impact assessment or protected areas planning are defined in Table 1. This proliferation of terms has not helped to clarify the process of indicator selection. Below, we outline a template for indicator selection that is based on linking the indicators to important processes, structures and compositions in the forest that might be altered by forest management activities. In general, forest management alters natural disturbance regimes and successional patterns resulting in changes in stand species composition, age structure of the forest, stand size and shape, and structures within stands (i.e., snags, coarse woody material). Hence, if our goal is to maintain populations of all species on the management unit in perpetuity and our strategy to achieve this goal is to pattern our harvest after fire patterns, then our choice of evaluative indicators will be linked to prescriptive indicators. Prescriptive indicators are chosen to represent structural, functional, or compositional elements that are likely to be different after harvest when compared with post-fire, such as amount of snags and downed woody debris, patch size distribution, connectedness of patches, amount of old growth and so on (Table 2).

For example, if a specified amount of snags and downed woody material per hectare (vertical structure) was the prescriptive indicator, then our evaluative indicator must be a species or set of species that are dependent on these elements (what Lambeck (1997) calls resource-limited species). We might choose

Table 1. Focal species synonyms and definitions[a]

Type	Synonyms	Definition
Focal	Surrogate	• small number of species whose requirements for persistence represent the requirements of other species in the landscape; subsumes indicators, umbrella and keystone species
Indicator species	Management indicators	• groups of species or species habitat elements that focus management attention on resource production, population recovery, population viability or ecosystem diversity
a) population indicators		• species that reflect the dynamics or presence/absence of other species e.g., species x is always associated with species y and z and population dynamics of species x is the same as in y and z.
b) guild indicators	Biological, taxon-based	• species that represent other species in the guild e.g., downy woodpecker (*Picoides pubescens*) chosen to represent all primary cavity nesters
c) condition indicators	health indicators, bio-indicators, sensitive species, sentinel species	• species that are sensitive to stressors in the environment or that have habitat requirements that might be threatened by management activities • sometimes invasive species are used as indicators of anthropogenic stress (e.g., exotic plant species)
d) composition indicators	Ecological, environmental, structure-based	• species that represent particular habitat types or elements e.g., spotted owl (*Strix occidentalis*) representing old growth forest
e) biodiversity indicators		• species or taxal groups that represent areas of high species richness of other taxal groups e.g., hot spots of bird species richness overlapping centers of butterfly species richness
Umbrella species	Coarse-filter species	• area-limited, resource-limited, dispersal-limited or process-limited species (Lambeck 1997). Conservation of these species should automatically conserve a host of other species e.g., grizzly bear (*Ursus arctos*)
Keystone species		• species that have an effect on many other species in an ecosystem disproportionate to their abundance or biomass • can be predators, prey, plants, mutualists and habitat modifiers (e.g., beaver, *Castor canadensis*)
Species-at-risk e.g., woodland caribou	Recovery species	• species that are threatened, endangered or rare
Featured species e.g., moose	Special management species	• species with social or economic value
Flagship species		• charismatic species, usually threatened, used to rally public support for conservation e.g., peregrine falcon (*Falco peregrinus*), woodland caribou

[a]Compiled from: Landres *et al*. (1988), Mills *et al*. (1993), Simberloff (1998), Caro and O'Doherty (1999), Andelman and Fagan (2000), Lindenmayer *et al*. (2000) and Zacharias and Roff (2001).

the red-backed vole and the marten as two species that operate at different spatial scales, but both require downed woody material, and we might choose two primary cavity nesting birds, such as the Pileated woodpecker (*Dryocopus pileatus*) and Yellow-bellied Sapsucker *(Sphyrapicus varius*), that are keystone cavity producers for an array of secondary cavity users (Martin and Eadie 1999). This could be supplemented by choosing a larger species, such as the Barred Owl, that uses cavities in old, large-diameter deciduous trees, and that operates over a larger spatial scale than the woodpeckers. At a larger scale, a prescriptive indicator might be the amount of connectedness between mature forest patches on the landscape. In this case, we would choose evaluative indicators that were dispersal-limited (Lambeck 1997) such as plants with poor seed dispersal abilities or animals with low vagility.

We would also choose indicators to evaluate the impact of removing or reducing a natural disturbance (function), in this case fire. Here we would choose indicators that are burn-associates (i.e., found at highest density in burns) or specialists such as Black-backed Woodpeckers or a vascular plant such as *Geranium bicknelli*. These have been called process-limited species by Lambeck (1997). Finally, we would choose evaluative indicators that might reflect changes in forest composition. For example, if mixedwood forests become "unmixed" due to harvesting and silvicultural treatments, then evaluative indicators would be species found at highest abundance in mixedwood forests (e.g., black-throated green warbler). Finally, as a precaution, we might add to our list of indicators any species-at risk that might be found in our management area. A single indicator is generally not sufficient and suites of indicator species should be chosen (Landres *et al*. 1988, McLaren *et al*. 1998).

In refining our list of evaluative indicators we might also wish to consider the following points:

1. Include species indicative of rare habitats that might not be conserved with coarse-filter management.
2. Include species from all trophic levels (McLaren *et al*. 1998) and from different nesting and foraging guilds.
3. Include species that operate at different spatial scales. Small species with limited movement will reflect within-

Table 2. Example of management goals, prescriptive indicators and some potential evaluative indicators for the value of maintaining current biodiversity on a management unit. We present the hypotheses tested by each of the evaluative indicators to emphasize the adaptive monitoring process

Management goal is to preserve:	Prescriptive indicator	Example Hypotheses/ Questions	Possible evaluative indicator
Stand			
Stand vertical structure	Snags and downed woody debris	If species is present, then the snags and downed woody debris are above the minimum threshold.	Red-backed vole (*Clethrionymus rutilus*), marten, woodpeckers, Barred Owl (*Strix varia*)
Stand composition	Amount of mature deciduous	If the species is present, then conditions are appropriate for other species that also require mature deciduous.	Barred Owl, old-growth lichen species (e.g., *Usnea* spp)
Stand condition	Fire origin versus harvest origin	If the species is present, then for a given stand age, there is no difference between fire versus harvest origin of the stand.	Black-backed woodpecker (*Picoides arctus*), post-fire vascular plant (e.g., *Geranium bicknelli*)
Landscape			
Fragmentation	Low interspersion of young and old age classes	If the species is present, then other species that require low fragmentation will also be present	Brown creeper (*Certhia americana*), Barred Owl
Connectivity	Corridor connecting two landscapes	If species are detected moving between landscapes, then the corridor is functioning properly.	Species with low vagility (e.g., *Ambystoma tigrinum*) or plant with poor seed dispersal

and between-stand changes. Species that are mobile and hence can integrate disturbance over larger areas should make good indictors of processes that occur over larger spatial scales (Landres *et al*. 1988, Caro and O'Doherty 1999).

4. Include exotic species. The presence of exotic species may be indicative of large-scale changes in the ecological integrity of your management unit (see Karr 1991 for an example from fisheries management).

Good evaluative indicators should be sufficiently abundant and widespread within specific habitats to monitor, be in the core of their range, and exhibit low temporal and spatial variability to enable ease of census (Dufrêne and Legendre 1997). Finally, in the forestry context, indicator species should have the potential to be used at operational or planning scales used by foresters and should reflect environmental conditions that can be controlled by foresters (Pearson 1994, Noss 1999, Caro and O'Doherty 1999, Kneeshaw *et al*. 2000).

Research needs

The selection and validation of good indicators species requires more research (e.g., Fleishman *et al*. 2000, 2001). In particular, more work is needed on demonstrating that the presence of a particular indicator species does indeed indicate that biodiversity in general is being conserved, or alternatively, determining the group of species for which the indicator functions (Simberloff 1999). The manner in which community structure can be used as an indicator also requires more research (e.g., Bryce *et al*. 2002). In particular, how can community structure be summarized quantitatively to provide a useful and meaningful indicator of biodiversity?

Choosing Prescriptive Indicators

At the largest scale, coarse-filter management means maintaining a representative set of ecosystems. Depending on the defined goals, this may mean maintaining a representative array of age classes, species and structures across the landscape, within management units and on cutblocks. The assumption is that if this heterogeneity is maintained, the full complement of species-level biodiversity will also be retained (i.e., if you build it, they will come). An example of this approach is to harvest in a way that emulates the patterns produced by natural disturbance processes. Lindenmayer *et al*. (2000), for example, proposed that prescriptive indicators such as stand complexity and plant species composition, level of connectivity, and landscape heterogeneity patterned after natural disturbances be used in harvest planning (e.g., Hunter 1993). Lindenmayer and Franklin (1997) advocated a variety of approaches, implemented at different spatial scales, in order to spread risk of species loss. They emphasized the need for protected areas and, within the managed landscape, the protection of sensitive habitats. At the stand scale they advocated leaving elements such as snags, logs, large live trees, and understory plants.

The habitat requirements of focal species (see below) can also be used to guide selection of prescriptive indicators and associated objectives. Lambeck (1997) suggested that these species be selected from those that are most limited (e.g., dispersal-limited, element-limited, area-limited, seral stage-limited). For example, the species with the largest area requirements would define the minimum patch size; the species that was the poorest disperser would define the isolation of patches or the level of connectedness; species that were resource-limited would define stand-level retention of those resources (e.g., snags, large diameter trees); and species that were the most process-limited would define silvicultural treatments (e.g., burn-dependent species might require prescribed burns) (Lambeck 1997).

Without heavy-handed legislation, a monitoring program can only be sustained if it is cost-effective. To the degree that prescriptive indicators can be linked to operational planning activities, the monitoring system will survive long after the issue-of-the-day has passed. For example, if vegetative and disturbance pattern indicators are based on the same forest inventories used for operational planning, and not on a specific inventory developed only for monitoring or research purposes, then the collection, analysis, and reporting of that data becomes cost-effective. In this context, it is important that researchers develop their predictive models using the operational inventory, even if it means losing some resolution, and certainly not developing models based on data too expensive to obtain if a less-expensive, coarser-level proxy is available. These issues force a thorough discussion of the costs and benefits of filling these data and knowledge gaps, and are a legitimate outcome from a successful monitoring cycle.

Research needs

Relationships between prescriptive and evaluative indicators are hypotheses of form and function, and require further research and validation (e.g., Lindenmayer *et al*. 2000, 2002; McAlpine and Eyre 2002). This will remain one of the focal points for research activities for many years.

Summary

We have described in this paper principles that can be applied to the development of indicators for any monitoring program, and some guidance on choosing and defining good indicators. While we are not suggesting that this is the only way of generating indicators that are effective, our intent is to make the process less overwhelming and more meaningful by providing structure.

However, in the bigger picture what we have outlined conceptually is a framework that goes beyond the expectations of most monitoring programs. We argue that there has been minimal effort to go beyond a stand-alone isolated program largely limited to compliance issues, and that we need to create a fully integrated framework that allows us to actively learn and improve. For the most part, it requires more substantial planning, coordination and communication but we do not foresee its implementation and operation being more expensive or time-consuming.

Our conceptual model of monitoring also considers monitoring activities in a slightly different light. We recognize that regulators and certification programs require a strong compliance program to evaluate the performance of land management organizations. However, it is hardly fair to judge the performance of these organizations based on evaluative predictions generated largely through independent research, and in some cases policy and public opinion. In other words, while prescriptive indicators are largely a forest management company responsibility, the evaluative indicators, and the degree to which we learn and move forward, is very much a shared responsibility. Thus, a monitoring framework should be designed to have meaning to a wide range of audiences, and be careful not to pass judgment beyond simple compliance issues. Companies may be the agents of change, but we all participate in the decision-making process.

While monitoring is not new to forest management, it remains a tool with tremendous untapped potential. We hope we have revealed some of that potential, and provided some suggestions as to how to make it work better for everyone.

References

Andelman, S.J. and W.F. Fagan. 2000. Umbrellas and flagships: efficient conservation surrogates or expensive mistakes? Proc. Natl. Acad. Sci. 97: 5954–5959.

Andison, D.W., R. Wright, R. Rempel, D. Dye, R. Nesdoly, B. Christiansen, D. Ens, P. Mackasey, P. Maczek and R. Fincati. 2002. Vegetation pattern indicators V 6.0. Saskatchewan Environment and Resource Management. Prince Albert, Saskatchewan.

Andren, H. 1994. Effects of habitat fragmentation on birds and mammals in landscapes with different proportions of suitable habitat: a review. Oikos 71: 355–366.

Bryce, S.A., R.M. Hughes and P.R. Kaufmann. 2002. Development of a bird integrity index: Using bird assemblages as indicators of riparian condition. Environ. Manage. 30: 294–310.

Caro, T.M. and G. O'Doherty. 1999. On the use of surrogate species in conservation biology. Cons. Biol. 13: 805–814.

Carlsson, M. 1999. A method for integrated planning of timber production and biodiversity: a case study. Can. J. For. Res. 29: 1183–1191.

Dufrêne, M. and P. Legendre. 1997. Species assemblages and indicator species: the need for a flexible asymmetrical approach. Ecol. Mon. 67: 345–366.

Fahrig, L. 1997. Relative effects of habitat loss and fragmentation on population extinction. J. Wildl. Manage. 61: 603–610.

Failing, L. and R. Gregory. 2003. Ten common mistakes in designing biodiversity indicators for forest policy. J. Environ. Manage. 68: 121–132.

Ferris, R. and J.W. Humphrey. 1999. A review of potential biodiversity indicators for application in British forests. Forestry 72: 313–328.

Fleishman, E., R.B. Blair and D.D. Murphy. 2001. Empirical validation of a method for umbrella species selection. Ecol. Appl. 11: 1489–1501.

Fleishman, E., D.D. Murphy and P.F. Brussard. 2000. A new method for selection of umbrella species for conservation planning. Ecol. Appl. 10: 569–579.

Hunter, M.L. Jr. 1990. Wildlife forests, and forestry principles of managing forests for biological diversity. Prentice Hall, Englewood Cliffs, New Jersey.

Hunter, M.L. Jr. 1993. Natural fire regimes as spatial models for managing boreal forests. Biol. Cons. 65: 115–120.

Karr, J.R. 1991. Biological integrity: a long-neglected aspect of water resource management. Ecol. Appl. 1: 66–84.

Kneeshaw, D.D., A. Leduc, P. Drapeau, S. Gauthier, D. Paré, R. Carignan, R. Doucet, L. Bouthillier and C. Messier. 2000. Development of integrated ecological standards of sustainable forest management at an operational scale. For. Chron. 76: 481–493.

Lambeck, R.J. 1997. Focal species: a multi-species umbrella for nature conservation. Cons. Biol. 11: 849–856.

Landres, P.B., J. Verner and J.W. Thomas. 1988. Ecological uses of vertebrate indicator species: a critique. Cons. Biol. 2: 316–328.

Lindenmayer, D.B. and J.F. Franklin. 1997. Managing stand structure as part of ecologically sustainable forest management in Australian mountain ash forests. Cons. Biol. 11: 1053–1068.

Lindenmayer, D.B., R.B. Cunningham, R.B., C.F. Donnelly and R. Lesslie. 2002. On the use of landscape surrogates as ecological indicators in fragmented forests. For. Ecol. Manag. 159: 203–216.

Lindenmayer, D.B., C.R. Margules and D.B. Botkin. 2000. Indicators of biodiversity for ecologically sustainable forest management. Cons. Biol. 14: 941–950.

Martin, K. and J.M. Eadie. 1999. Nest webs: a community-wide approach to the management and conservation of cavity-nesting forest birds. For. Ecol. Manag. 115: 243–257.

McAlpine, C.A. and T.J. Eyre. 2002. Testing landscape metrics as indicators of habitat loss and fragmentation in continuous eucalypt forests (Queensland, Australia). Landscape Ecology 17: 711-728.

McLaren, M.A., I.D. Thompson and J.A. Baker. 1998. Selection of vertebrate wildlife indicators for monitoring sustainable forest management in Ontario. For. Chron. 74: 241–548.

Mills, L.S., M.E. Soule and D.F. Doak. 1993. The keystone-species concept in ecology and conservation. BioScience 43: 219–224.

Noss, R.F. 1999. Assessing and monitoring forest biodiversity: a suggested framework and indicators. For. Ecol. Manage. 115: 135–146.

Pearson, D.L. 1994. Selecting indicator taxa for the quantitative assessment of biodiversity. Phil. Trans. R. Soc. Lond. B. 345: 75–79.

Rempel, R.S., P.C. Elkie, A.R. Rodgers and M.J. Gluck. 1997. Timber-management and natural-disturbance effects on moose habitat: landscape evaluation. J. Wildl. Manage. 61: 517–524.

Simberloff, D. 1998. Flagships, umbrellas, and keystones: is single-species management passé in the landscape era? Biol. Cons. 83: 247–257.

Simberloff, D. 1999. The role of science in the preservation of forest biodiversity. For. Ecol. Manage. 115: 101–111.

Sinclair, A.R.E. 1991. Science and the practice of wildlife management. J. Wildl. Manage. 55: 767–773.

Walters, C. J. 1986. Adaptive management of renewable resources. Macmillan Publishing Company, NY. 374 p.

Walters, C.J. 1997. Adaptive policy design: thinking at larger spatial scales. Bissonette, J. A. Wildlife and Landscape Ecology. pp. 386–394. Springer-Verlag Inc., New York, NY.

With, K.A., and T.O. Crist. 1995. Critical thresholds in species' responses to landscape structure. Ecology 76: 2446–2459.

Zacharias, M.A. and J.C. Roff. 2001. Use of focal species in marine conservation and management: a review and critique. Aquatic Conserv: Mar. Freshw. Ecosyst. 11: 59–76.