SELECTING INDICATOR SPECIES TO MONITOR ECOLOGICAL INTEGRITY: A REVIEW

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Abstract. We review critical issues that must be considered when selecting indicator species for a monitoring program that aims to maintain or restore ecological integrity. First, we examine the pros and cons of different management approaches on which a conservation program can be based and conclude that ecosystem management is most appropriate. We then identify potential indicators of ecological integrity at various levels of the ecosystem, with a particular emphasis on the species level. We conclude that, although the use of indicator species remains contentious, it can be useful if (1) many species representing various taxa and life histories are included in the monitoring program, (2) their selection is primarily based on a sound quantitative database from the focal region, and (3) caution is applied when interpreting their population trends to distinguish actual signals from variations that may be unrelated to the deterioration of ecological integrity. Finally, we present and discuss different methods that have been used to select indicator species.

Keywords: birds, bogs, conservation, ecological integrity, ecosystem management, forest, indicator species

1. Introduction

Hall and Grinnell (1919) were among the first to use the indicator concept by associating plant and animal species to particular 'life zones' (i.e. large geographic areas with similar structural and compositional characteristics). Since then, the concept has evolved substantially and is now widely applied in situations ranging from the verification of the compliance of industries to specific anti-pollution laws (MacDonald and Smart, 1993) to the assessment of habitat quality (Powell and Powell, 1986; Canterbury *et al.*, 2000). Additionally, the use of indicators has frequently been incorporated into policies and regulations in order to monitor the ecological integrity of watersheds (Moyle and Randall, 1998), lakes (Karr, 1981; Harig and Bain, 1998), semi-natural pastures (Pärt and Söderström, 1999 a, b), rangelands (Bradford *et al.*, 1998), and forests (Brooks *et al.*, 1998). Indicators possess an undeniable appeal for conservationists, land managers, and governments as they provide a cost- and time-efficient mean to assess the impacts of environmental disturbances on an ecosystem.

This paper addresses many of the critical issues associated with the selection of indicator species in a monitoring program that aims to maintain or restore the eco-

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logical integrity of an ecosystem. We refer to ecological integrity as 'the capacity of an ecosystem to support and maintain a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of similar, undisturbed ecosystems in the region' (Karr and Dudley, 1981). Although many articles discussing the concept of indicator species have been published, our goal is to summarize the information scattered throughout the literature, both supportive and critical, in order to reassess the concept and identify criteria that may be used to select an appropriate set of indicator species for the purpose of monitoring ecological integrity. To achieve this goal, (1) we examine the problems that have been associated with indicator species in the past and discuss their implications, and (2) we present the characteristics desirable indicators should possess. We also evaluate different approaches that have been proposed to select indicator species. To set the stage, we compare the advantages and disadvantages of different management approaches in the development of a conservation program.

2. Management Approaches

There are three main types of management approaches available to natural resources managers: coarse-filter, fine-filter, and ecosystem management. Coarse-filter approaches generally aim to preserve entire communities of plants and animals by protecting large extents of habitat and, in certain cases, by maintaining the key ecological components and processes (e.g. snags, fires, etc.) that sustain them (e.g. The Nature Conservancy; Noss, 1987). The major assumption underlying this type of approach is that the status of any given species is correlated with habitat availability. Since the abundance of a species in a given site is not necessarily correlated with reproductive success and probability of persistence (Van Horne, 1983; Vickery *et al.*, 1992a), there is a risk that some sites selected for conservation will act as demographic sinks at least in some years and that, on the other hand, some demographic sources will remain unprotected. Furthermore, although coarse-filter approaches can correctly identify the habitat features and processes required for a set of species to be present in a landscape, they may be insufficient to determine the quantity and configuration of those features (Lambeck, 1997).

Fine-filter approaches focus on the protection of a certain number of elements (species, snags, coarse woody material, etc.) assuming that their status within the ecosystem reflects the status of other elements associated with them (e.g. Tracy and Brussard, 1994; Wilcove, 1994). In this type of approach, the problem is not as much the applicability of the method as it is its efficiency to protect non-target species (Franklin, 1993). Simberloff (1998) pointed out that indicator species such as large vertebrates might represent good indicators for species that require large, continuous tracts of habitat, but they may fail to protect species such as certain insects that fare better in a naturally fragmented landscape (see Tscharntke, 1992; Tscharntke *et al.*, 1998). Consequently, for such approaches to be successful, considerable attention must be given to the selection of an appropriate set of indicators if the majority of species are to be protected.

Based on the preceding arguments, the majority of conservationists now recognize that components of both fine-filter and coarse-filter approaches should be integrated in conservation planning (Hunter *et al.*, 1988; Kessler, 1994; McKenney *et al.*, 1994; Wilcove, 1994; Lambeck, 1997; Noss *et al.*, 1997). This has led to the emergence of the concept of ecosystem management, which is defined as 'management driven by explicit goals, executed by policies, protocols, and practices, and made sustainable by monitoring and research based on our best understanding of the ecological interactions and processes necessary to sustain ecosystem composition, structure, and function' (Christensen *et al.*, 1996). Wilcove and Blair (1995) mentioned that 'the vagueness of the term [ecosystem management] ensures that people can make it what they want', a situation that can be corrected, as they recognized, if clear goals are established. Grumbine's (1994) review of the concept of ecosystem management has highlighted the five most often cited goals: (1) maintain viable populations of all native species, (2) protect representative examples of all native ecosystem types across their natural range of variation, (3) maintain evolutionary and ecological processes, (4) manage landscapes and species to be responsive to both short-term and long-term environmental change, and (5) accommodate human activities within these constraints.

To be effective, ecosystem management must be based on a sound, comprehensive, scientific foundation so that a consensus on needed management actions can be reached (Brunner and Clark, 1997). Furthermore, it 'must be iterative [i.e. adaptive] in order to allow the integration of new knowledge and changing societal goals' (Stanford and Poole, 1996). To determine the success of the implementation of ecosystem management, experiments at different scales are conducted and diagnostic parameters (e.g. reproductive success; decomposition rates) are monitored. The usefulness of such investigations is that the results may indicate that harvesting methods have to be adjusted in order to lessen the negative repercussions on the ecosystem. Therefore, adaptive management is used to determine what constitutes acceptable harvesting levels and what changes are needed in order to reach the *a priori*-defined goals.

Different terminologies have been proposed to describe the state of an ecosystem under management, i.e. to determine if the goals of sustainability have been reached. Ecological integrity and ecosystem health have been the most often cited. These terms may seem interchangeable for most of us and, in many articles, in fact are since they relate to the same goal. However, the implications of each term are fundamentally different. Schaeffer *et al.* (1988) and Rapport (1989, 1992, 1995a,b) have proposed the use of the ecosystem health metaphor to promote sustainable development and facilitate the public's general understanding of the functioning of ecosystems. Rapport (1995a) argued that 'commonly observed ecosystem properties such as breakdown under stress... suggests that [the concept] has validity as a heuristic device'. On the other hand, authors such as Calow (1992), Suter (1993) and Wicklum and Davies (1995) have criticized the use of this metaphor. They argued that ecosystems cannot be compared to organisms (to which the health concept is usually applied) because (1) each ecosystem presents a unique set of structural and compositional characteristics shaped by a combination of deterministic (e.g. interspecific competition, abiotic factors) and probabilistic (e.g. stochastic events such as colonization-extinction) processes unique to its region, and (2) they do not present a unique undisturbed endpoint naturally maintained by homeostatic processes or that should be preserved during management. These authors favour the use of the terms quality or sustainability because they are less amenable to interpretation and also because they are easier to accept by various interest groups since they implicitly recognize that humans are a part of ecosystems.

The debate has not only focused on the implications of using potentially confusing terminologies but has also questioned the concepts themselves. Wicklum and Davies (1995) argued that both integrity and health are subjective concepts since (1) they are based on the representation of undisturbed ecosystems for which our knowledge is incomplete (i.e. what are the structural, compositional and functional properties of such systems?) and particularly the fact that such ecosystems are probably nonexistent today, (2) there are many possible natural endpoints that may be attained by an ecosystem, all of which could be said to have integrity or health, and (3) they often consider ethical, political and societal values. The consequence of such subjectivity is that those concepts are vulnerable to interpretation, which, potentially, could lead to further degradation of ecosystems.

Inevitably, the goals of ecosystem management (i.e. what is an acceptable compromise between naturally-disturbed ecosystems and harvesting of natural resources?) will continue to be debated. In the meantime, tools such as indicators will likely be used to determine whether harvesting is fundamentally altering ecosystem structure and function and to suggest management actions that are likely to improve ecological integrity within the ecosystem.

3. Selection of Indicators

Since managers cannot measure everything of potential interest within an ecosystem, the choice of what to measure is critical. According to Noss *et al.* (1997), this step is among the most difficult and controversial in developing a monitoring program. Valuable indicators may possess some or all of the following characteristics:

- provide early warning of natural responses to environmental impacts (Noss, 1990a; Marshall *et al.*, 1993; Munn, 1993; Woodley, 1996b);
- directly indicate the cause of change rather than simply the existence of change (e.g. measuring fecundity and survival rather than simple measurements of abundance; Herricks and Schaeffer, 1985);

– provide continuous assessment over a wide range and intensity of stresses (Woodley, 1996a; O'Connell *et al.*, 1998). This allows to detect numerous impacts on the ecosystem and also means that an indicator will not bottom out or level off at certain thresholds (Noss, 1990a; Woodley, 1993; Gibbs *et al.*, 1999);
– are cost-effective to measure and can be accurately estimated by all personnel (even non specialists) involved in the monitoring (Kriesel, 1984; Davis, 1989; di Castri *et al.*, 1992).

Indicators of ecological integrity may be found at many organizational levels including species, stand, landscape, and ecosystem. Regardless of the level at which it is selected, an indicator is an element, process, or property of the ecosystem that for some reason (logistical, budgetary, technological) cannot be measured in a more direct way.

At the species level, Lambeck (1997) and Noss (1999) proposed a wide variety of potential indicators:

– keystone species: species whose strong interactions with other species generate effects that are large relative to their abundance (Mackey *et al.*, 1994; Paine, 1995) (e.g. primary cavity-nesting birds such as woodpeckers);
– area-limited 'umbrella' species: species that require large areas of suitable habitat to maintain viable populations and whose requirements for persistence are believed to encapsulate those of an array of associated species. These species usually have very large home ranges (e.g. bears, wolves);
– dispersal-limited species: species that are limited in their ability to move from patch to patch or that face a high mortality risk in trying to do so (e.g. apterous insects; species restricted to humid microhabitats such as most amphibians);
– resource-limited species: species requiring specific resources that may be in critically short supply either temporally or spatially. These resources may include snags, nectar sources, fruits, etc. (e.g. woodpeckers restricted to large-diameter snags for nesting and foraging; oligophagous insects);
– process-limited species: species sensitive to the level, rate, spatial characteristics or timing of some ecological processes such as fire, flood, grazing, competition with exotic species, or predation (Furbish's Lousewort, *Pedicularis furbishiae*, which depends on riverbank erosion by floating ice to establish itself);
– flagship species: species that can easily attract public support for conservation (e.g. Giant Panda, *Ailuropoda melanoleuca*; whales).

Species strongly associated with particular habitat features could also be useful indicators. For example, the Ovenbird, *Seiurus aurocapillus*, is a good indicator of closed-canopy, mature forests with a sparse understory.

It should be noted that the preceding categories are not mutually exclusive. Indicator species which possess several of the above-mentioned characteristics are more desirable for monitoring purposes since the conservation of the processes, resources, and habitat features associated with them will probably coincide with the protection of the requirements of other ecologically-similar species.

At the level of forest stands, many indicators can be used to monitor trends in forest degradation. These include (1) diameter and age class distributions of trees left standing after cutting versus trees removed (Noss, 1999), (2) soil nutrient levels, and (3) stand growth efficiency (Riiters *et al*., 1992). At the landscape level, O'Neil *et al*. (1997) identified the total change in land cover (e.g. increases in the amount of clearcutting, urbanization, etc.) as an indicator of ecological integrity. The area of landscape occupied by various seral stages could also serve as a useful indicator at this scale (Noss, 1999). As for the ecosystem level, Harwell *et al*. (1999) mentioned fires (interval and intensity), nutrient cycling, insect outbreaks (frequency and amplitude), primary productivity, and hydrological regimes as potential indicators.

A comprehensive conservation plan should include measures of indicators at several scales (White and Bratton, 1980; Woodley and Theberge, 1992) and, as recommended by di Castri *et al*. (1992), incorporate indicator species from all major functional guilds (producers, herbivores, carnivores, decomposers, etc.), so as to ensure that integrity is preserved at every level.

3.1. Problems Associated with Indicator Species

Prendergast *et al*. (1993) reviewed two assumptions commonly made when using indicator species: (1) across large areas, species richness of the indicator taxon is correlated with the number of species in other less well-known taxa (Schall and Pianka, 1978) and (2) high species richness or habitat diversity is associated with the occurrence of rare or threatened species (Noss, 1990a; Pearson and Cassola, 1992). They found no support for either assumption. It seems that spatial autocorrelation in species richness among taxa is highly scale-dependent (Williams and Gaston, 1994; Weaver, 1995; Prendergast and Eversham, 1997; Pärt and Söderström, 1999a): it is clearly observable at the global scale (Buzas, 1972), but more difficult to detect at finer scales.

Other studies also failed to support the first assumption. For example, Kremen (1992) found that butterflies were good indicators of vegetation heterogeneity created by anthropogenic disturbance, but poor indicators of plant species richness. Järvinen and Väisänen (1980) reported that, although there were some broad similarities in diversity among taxa, bird species turnover rates were not always consistent with the turnover rates observed in ants and vascular plants. Pärt and Söderström (1999 a, b) found that vascular plants were unreliable as indicators of bird species richness. They suggested that species richness and occurrence of individual bird species may depend more strongly on meso-scale habitat characteristics than those of plants, which tend to be more strongly linked to local conditions (soil conditions, nutrients, etc.).

Even if co-occurrence patterns could be detected at various spatial scales, the indicator species concept would still show some weaknesses. One of the major ones comes from the fact that no two species occupy the same niche (Gause, 1934), making it unlikely that there will be a perfect correspondence between indicator species and the other species for which they are supposed to be indicative (Landres *et al.*, 1988; Niemi *et al.*, 1997; Hutto, 1998). Indeed, Martin and Li (1992) and Martin (1995) found that co-occurring species typically differ in their habitat requirements and life histories. Furthermore, Block *et al.* (1987) found that, even within the same species guild, there is no assurance that habitat suitability or population status of one species will reflect those of the other species in the guild. For these reasons, an assemblage of species thought to be associated with an indicator species based on similar ecological requirements may respond differently to disturbance (Mannan *et al.*, 1984; Lindenmayer, 1999). Hence, any single species can serve as an indicator for only a narrow range of ecological conditions within the habitat type (Koskimies, 1989), and no single biological indicator will provide all the information needed to interpret the behaviour or response of an entire ecosystem (i.e. its ecological integrity) (Cairns and Van der Shalie, 1980; Rapport, 1990).

A related problem is that the ability to detect responses to disturbance may depend on the taxon selected. According to Niemëla *et al.* (1993), some taxa with short generation times may react more quickly to disturbances, while others will show delayed responses to the same disturbances. For example, species that persist in a forest landscape during a given harvest rotation may disappear only a long time after the disturbances have ceased if sources of colonists have been eliminated (Crome, 1985), a phenomenon referred to as the extinction debt (Tilman *et al.*, 1994). Temple and Wiens (1989) pointed out that this could present a problem for species being used as ‘early warning systems’, but it does not affect their usefulness as indicators of environmental conditions over the long term.

Finally, Steele *et al.* (1984) mention that many factors unrelated to the degradation of ecological integrity of a local ecosystem may influence populations of indicator species (e.g. disease, parasites, competition, predation, conditions in other areas for migratory species, and stochastic variations). As pointed out by Morrison (1986), it is often difficult to separate the influence of individual factors affecting a population (i.e. animals seldom respond in distinctly different ways to specific environmental changes). For these reasons, it can be inappropriate to consider the population status of an indicator species as an indication of the population status of associated species or as an indication of ecosystem integrity without concurrent knowledge on the state of other elements within and outside the ecosystem.

Although a large body of literature identifies the constraints associated with the use of indicator species, they may still be useful if precautions are taken in their selection and in the interpretation of their responses to environmental changes (Morrison, 1986; Landres, 1992). Hence, we believe that a conservation plan that focuses on the protection of a certain number of indicator species, the resources they utilize, and the habitat features and processes they require, will lead to the protection of other species that are associated with similar conditions (assuming that the indicator species are not too ecologically specialized) (Hutto *et al.*, 1987; Henjum, 1996). The challenge is to choose, from a large array of potential indicator species, those that should faithfully reflect stand, landscape, or ecosystem conditions and that represent the largest number of other taxa.

4. Which Species Should We Choose?

Previously used or suggested indicator organisms include plants (De Boer, 1983; Zonneveld, 1983; Keddy *et al.*, 1993), beetles (Pearson, 1992; Pearson and Cassola, 1992; Dufrêne and Legendre, 1997; Rodrìguez *et al.*, 1998), benthic invertebrates (Paine, 1969), butterflies (Kremen, 1992, 1994; Launer and Murphy, 1994), amphibians (Fisher and Shaffer, 1996; Welsh *et al.*, 1997; Adams, 1999), fishes (Karr, 1981), birds (Beintema, 1983; Powell and Powell, 1986; Bost and Mayo, 1993; Daily *et al.*, 1993; Bradford *et al.*, 1998; Hutto, 1998), and mammals (Starfield and Bleloch, 1983; Hanley, 1993; Soulé and Terborgh, 1999; Reunanen *et al.*, 2000). Each study presents arguments on the suitability of each taxon as a potential indicator. For example, Dufrêne and Legendre (1997) mention that many studies show that invertebrates in general are appropriate indicators of ecosystem integrity. Their presence is generally more strongly associated with environmental factors than with biological factors such as competition, predation and parasitism (Schoener, 1986).

The use of invertebrates and plants as indicators must nonetheless be considered with caution because they mainly react to disturbances at fine spatial scales and hence, would potentially be inadequate indicators for organisms that mainly react to larger-scale disturbances. Similarly, larger organisms may represent poor indicators of species that mainly react to fine-scale disturbances. Murphy *et al.* (1990) stated that this lack of overlap may reflect differences in the rates of population increase, generation time, and habitat specificity between the two groups, which could also explain the observed variability in the time required for each group to react to disturbance (Pearson, 1994).

Birds may offer a bridge between these two groups because they have been shown to respond to environmental changes over many spatial scales (Temple and Wiens, 1989). They are also well suited for monitoring because (1) they advertise their presence through vocalizations, making them relatively easy to detect and identify, (2) they can be censused efficiently over large spatial scales, and (3) their occurrence (Villard *et al.*, 1995), abundance (Robbins *et al.*, 1989; Mazerolle and Villard, 1999) and reproductive success (Villard *et al.*, 1993; Robinson *et al.*, 1995) have been shown to be influenced by the nature and configuration of surrounding habitats.

We mentioned that indicator species should be selected from a wide array of potential taxa. Since the reliance on one or a few species chosen within a single taxon could result in the protection of these species at the expense of others, many authors (Terborgh, 1974; Koskimies, 1989; Karr, 1991; Kremen, 1994; McKenney *et al*., 1994; Griffith, 1997) now advocate the use of a greater variety of indicator species in management strategies. Assemblages which include species that collectively (1) occupy a broad range of habitats, (2) have a wide range of requirements in terms of habitat patch size, habitat structure and configuration, and (3) depend on certain ecological processes are expected to display a wider range of sensitivities to habitat modification and disturbance of natural processes. Hence, the protection of such assemblages would be likely to maintain functional ecosystems. Furthermore, consistent causes of change should be easier to identify and local deviation in behaviour of one of the species should be less influential (Zonneveld, 1983).

5. Procedures for the Selection of Indicator Species

Many procedures have been proposed to select potential indicator species. The U.S. Fish and Wildlife Service used to select indicator species based on their perceived importance (economic value, public interest, ecological role) or because they were believed to act as indicators for a habitat type or other species in the community that have similar requirements (see Roberts and O'Neil, 1985). A major problem associated with this method is that the indicator species chosen (e.g. White-tailed Deer, *Odocoileus virginianus*; Black-capped Chickadee, *Poecile atricapillus*) may not necessarily be sensitive to the deterioration of ecological integrity within a given ecosystem.

Hutto (1998) proposed a quantitative method that is based on species occurrences in a series of *a priori*-defined habitat types. Species restricted to one or a few habitat types potentially represent better indicators than habitat generalists owing to their greater susceptibility to local or regional extinction following environmental changes. Kremen (1992) used an ordination method (correspondence analysis) to associate butterfly species to habitat types with different characteristics (topography, moisture, and disturbance histories) in order to identify indicator groups associated with particular conditions. Dufrêne and Legendre (1997) have also proposed statistical procedures, including ordination and clustering methods, to associate beetle assemblages to particular habitat types. Their approach allows identifying species that have the highest potential as indicators within each assemblage and for each habitat type, thereby ensuring that each assemblage is monitored while limiting the amount of effort that has to be invested in the monitoring.

Since the use of indicator species in conservation programs continues to be debated, relying on quantitative criteria during the selection process seems highly desirable compared to more subjective, qualitative criteria. We propose a simple procedure to select potential indicator species based on two quantitative criteria. First, the use of differences in frequency of occurrence among areas with contrasting degrees of human disturbance. If a species is found to be significantly more frequent in a relatively undisturbed area, it could be considered a 'positive' indicator of ecological integrity (i.e. a species negatively associated with human disturbance), whereas if it is found to be significantly more frequent in a moderately-disturbed area, it could be considered a 'negative' indicator of ecological integrity (i.e. a species positively associated with disturbance). Population trends for these 'positive' and 'negative' indicator species could then be used to determine whether management actions are required, or whether such actions increase or deteriorate the ecological integrity of the regional ecosystem. Because the selection of indicator species based on the frequency of occurrence criterion could potentially be unduly influenced by various natural phenomena occurring at the time of the surveys (e.g. insect outbreaks, drought), a second criterion should be added. Following Hutto (1998), we suggest using habitat specialization since it is less likely to be influenced by such natural variations in environmental conditions. Furthermore, species restricted to fewer habitat types are more susceptible to regional extirpation due to human activities. Again, population trends could help indicate whether the integrity of the habitats to which these species are restricted is improving or deteriorating following management actions. We applied these two criteria to the selection of avian indicators of ecological integrity in the Greater Kouchibouguac Ecosystem, New Brunswick (Canada) (Carignan and Villard, in review).

6. Discussion

There seems to be a consensus among natural resources managers and conservation biologists on the appropriateness of ecosystem management as a conceptual framework. Because it is impossible to measure everything of potential relevance within an ecosystem, indicators can be used to reduce the number of components that have to be investigated and monitored to determine whether harvesting of resources is carried out in a sustainable manner. There is less debate on the validity of indicators at higher levels (stand, landscape, ecosystem) than there is about indicators at the species level. Our review focused on the latter in an attempt to clarify the issues at stake.

We found two main arguments against the use of indicator species. First, since no two species occupy the same niche, no single species should be expected to act as an indicator for an entire ecosystem (Cairns and Van der Shalie, 1980; Rapport, 1990). As noted earlier, this does not invalidate the indicator species concept altogether. It rather implies that several species, representing different taxa and sensitivity to a variety of disturbances should be monitored in order to identify the causes of change more precisely and limit errors of interpretation. The second argument is that many factors unrelated to the degradation of ecological integrity may affect the population status of an indicator species and, thus, complicate the detection and interpretation of population trends. This argument does not discredit the use of indicator species but it calls for caution in the interpretation of changes in their demographic parameters and distribution. Consequently, if management recommendations are to be issued based on changes in the status of indicator species, it is crucial to have an adequate knowledge of potential causal factors unrelated to the degradation of ecological integrity. Finally, we mentioned that quantitative criteria are preferable to qualitative criteria when selecting potential indicator species for a focal region. Using a database from the focal region ensures that the selection of potential indicator species reflects on-site ecological conditions rather than the perceived importance of particular species. If used, qualitative criteria should be combined with a set of quantitative ones.

In this paper, we have only referred to approaches pertaining to the selection of indicator species. Other approaches focus on communities or guilds as indicators of ecological integrity. Karr (1981) was among the first to introduce this concept. His method integrates components of species composition and richness (e.g. number and identity of species intolerant to disturbance) as well as physiological indicators (e.g. disease) in fish communities to assess the biotic integrity of entire streams and rivers. The index developed can be used to rank river sections or entire watersheds from very poor to excellent based on total scores derived from the sum of scores obtained for each of 12 evaluation criteria. A similar index, based on guilds, has been developed by O'Connell *et al.* (1998) for bird communities. These community-level indices can provide an initial, coarser, assessment of the ecological integrity of a particular ecosystem. However, they may not be appropriate to detect changes at finer scales or to provide early warning signs, which are essential for monitoring ecological integrity. This is where methods using indicator species become useful by providing information to managers on specific phenomena affecting the population status of a particular species (e.g. increase in nest predation rate). However, to provide this finer assessment of ecological integrity, the population parameters must go beyond measurements of abundance and consider reproductive success or other population parameters sensitive to environmental conditions in the short term.

Others have proposed procedures to estimate the integrity of an ecosystem by measuring the rates of certain processes. For example, Kay and Schneider (1992) developed a method based on thermodynamics in which an ecosystem is considered to have integrity when it is in a state of equilibrium. This state of equilibrium or optimum operating point is not necessarily a unique endpoint in the development of an ecosystem. Any given ecosystem can have multiple optimal operating points, which are characterized by a state in which the system is more organized and effective at dissipating solar energy and retaining nutrients (Kay and Schneider, 1992). If the system is functioning outside optimal operating points (at desequilibrium), it is considered to have lost its integrity. A host of parameters such as nutrient imports and exports, primary productivity, and respiration are examined at different trophic levels to diagnose the ecological integrity of the ecosystem.

The goal of this paper was not to develop the perfect method to measure ecological integrity. When taken individually, each of the methods presented in this paper will in fact fail to provide a complete assessment of the ecological integrity of any particular ecosystem. Owing to the subjectivity involved in determining what represents an ecosystem with a high degree of integrity, it seems unlikely that any method will allow to make such a claim any time soon. However, we believe that we have developed a solid framework for the use of indicator species which should, at the very least, provide insight on whether ecological integrity is increasing or decreasing within the ecosystem. Furthermore, by monitoring indicators at other levels of organization at the same time, managers could improve their ability to interpret the responses of indicator species to changes in their environment by correlating the responses of indicators across levels. A conservation program that considers the issues discussed in this paper should yield useful information to manage natural resources and identify desired levels of ecological integrity.

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References

Adams, M. J.: 1999, 'Correlated factors in amphibian declines: exotic species and habitat change in western Washington', *J. Wild. Manag.* **63**, 1162–1171.

Beintema, A. J.: 1983, 'Meadow birds as indicators', *Environ. Monit. Assess.* **3**, 391–398.

Block, W. M., Brennan, L. A. and Gutiérrez, R. J.: 1987, 'Evaluation of guild-indicator species for use in resource management', *Env. Manage.* **11**, 265–269.

Bost, C. and Mayo, Y.: 1993, 'Seabirds as bioindicators of changing marine ecosystems: new perspectives', *Acta Oecol.* **14**, 463–470.

Bradford, D. F., Franson, S. E., Neale, A. C., Heggem, D. T., Miller, G. R. and Canterbury, G. E.: 1998, 'Bird species assemblages as indicators of biological integrity in Great Basin rangeland', *Environ. Monit. Assess.* **49**, 1–22.

Brooks, R. P., O'Connell, T. J., Wardrop, D. H. and Jackson, L. E.: 1998, 'Towards a regional index of biological integrity: the example of forested riparian ecosystems', *Environ. Monit. Assess.* **51**, 131–143.

Brunner, R. D. and Clark, T. W.: 1997, 'A practice-based approach to ecosystem management', *Conserv. Biol.* **11**, 48–58.

Buzas, M. A.: 1972, 'Patterns of species diversity and their explanation', *Taxon* **21**, 275–286.

Cairns, J. Jr. and Van der Shalie, W. H.: 1980, Biological monitoring: Part I- early warning systems', *Water Res.* **14**, 1179–1190.

Calow, P.: 1992, 'Can ecosystems be healthy? Critical consideration of concepts', *J. Aq. Ecosyst. Health* **1**, 1–5.

Canterbury, G. E., Martin, T. E., Petit, D. R., Petit, L. J. and Bradford, D. F.: 2000, 'Bird communities and habitat as ecological indicators of forest condition in regional monitoring', *Conserv. Biol.* **14**, 544–558.

Christensen, N. L., Bartuska, A. M., Brown, J. H., Carpenter, S., D'Antonio, C., Francis, R., Franklin, J. F., MacMahon, J. A., Noss, R. F., Parsons, D. J., Peterson, C. H., Turner, M. G. and Woodmansee, R. G.: 1996, 'The report of the Ecological Society of America committee on the scientific basis for ecosystem management' *Ecol. Appl.* **6**, 665–691.

Crome, F. H.: 1985, 'Problems of Wildlife Management in Relation to Forestry Practices in the Southern Hemisphere', in: J. Kikkawa, (ed.), *Wildlife Management in the Forests and the Forestry-controlled Lands in the Tropics and the Southern Hemisphere*. Proceedings of the IUFRO workshop, July 1984, p. 15–21

Daily, G. C., Ehrlich, P. R. and Haddad, N. M.: 1993, 'Double keystone bird in a keystone species complex', *Proc. Nat. Acad. Sci.* **90**, 592–594.

Davis, G. E.: 1989, 'Design of a long-term ecological monitoring program for Channel Islands National Park, California', *Nat. Areas J.* **9**, 80–89.

de Boer, T. A.: 1983, 'Vegetation as an indicator of environmental changes' *Environ. Monit. Assess.* **3**, 375–380.

di Castri, F., Vernhes, J. R. and Younés, T.: 1992, 'Inventoring and monitoring biodiversity: a proposal for an international network' *Biol. Internat.* **27**, 1–27.

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

Fisher, R. N. and Shaffer, H. B.: 1996, 'The decline of amphibians in California's Great Central Valley', *Conserv. Biol.* **10**, 1387–1397.

Franklin, J. F.: 1993, 'Preserving biodiversity: species, ecosystems, or landscapes?', *Ecol. Appl.* **3**, 202–205.

Gause, G. F.: 1934, *The Struggle for Existence*. Williams and Wilkins, Baltimore (Maryland).

Gibbs, J. P., Snell, H. L. and Gaston, C. E.: 1999, 'Effective monitoring for adaptive wildlife management: lessons from the Galàpagos islands', *J. Wildl. Manage.* **63**, 1055–1065.

Griffith, J. A.: 1997, 'Connecting ecological monitoring and ecological indicators: a review of the literature', *J. Env. Systems* **26**, 325–363.

Grumbine, R. E.: 1994, 'What is ecosystem management?' *Conserv. Biol.* **8**, 27–38.

Hall, H. M. and Grinnell, J.: 1919, 'Life-zone indicators in California', *Proc. Calif. Acad. Sci.* **9**, 37–67.

Hanley, T. A.: 1993, 'Balancing economic development, biological conservation, and human culture: the Sitka Black-tailed Deer *Odocoileus Hemionus sitkensis* as an ecological indicator', *Biol. Conserv.* **66**, 61–67.

Harig, A. L. and Bain, M. B.: 1998, 'Defining and restoring biological integrity in wilderness lakes', *Ecol. Appl.* **8**, 71–87.

Harwell, M. A., Myers, V., Young, T., Bartuska, A., Gassman, N., Gentile, G. H., Harwell, C. C., Appelbaum, S., Barko, J., Causey, B., Johnson, C., McLean, A., Smola, R., Templet, P. and Tosini, S.: 1999, 'A framework for an ecosystem integrity report card', *BioScience* **49**, 543–556.

Henjum, M. G.: 1996, 'Maintaining ecological integrity of inland forest ecosystems in Oregon and Washington', *Wildl. Soc. Bull.* **24**, 227–232.

Herricks, E. and Schaeffer, D. J.: 1985, 'Can we optimize biomonitoring?', *Env. Manage.* **9**, 487–492.

Hunter, M. L., Jacobson Jr., G. J. and Webb III, T.: 1988, 'Paleoecology and the coarse-filter approach to maintaining biological diversity', *Conserv. Biol.* **2**, 375–385.

Hutto, R. L.: 1998, 'Using Landbirds as an Indicator Species Group', in: J. M. Marzluff, and R. Sallabanks (eds), *Avian Conservation: Research and Management*. Island Press, Washington (D.C.). p. 75–91.

Hutto, R. L., Reel, S. and Landres, P. B.: 1987, 'A critical evaluation of the species approach to biological conservation', *Endangered Species Update* **4**, 1–4.

Järvinen, O., and Vaïsänen, R. A.: 1980, 'Quantitative biogeography of Finnish land birds as compared with regionality in other taxa', *Ann. Zool. Fenn.* **17**, 67–85.

Karr, J. R.: 1981, 'Assessment of biotic integrity using fish communities', *Fisheries* **6**, 21–27.

Karr, J. R.: 1991, 'Biotic integrity: A long-neglected aspect of water resource management', *Ecol. Appl.* **1**, 66–84.

Karr, J. R. and Dudley, D. R.: 1981, 'Ecological perspective on water quality goals', *Env. Manage.* **5**, 55–68.

Kay, J. J. and Schneider, E. D.: 1992, 'Thermodynamics and Measures of Ecological Integrity', in: D. H. McKenzie, D. E. Hyatt and V. J. McDonald (eds), *Ecological Indicators*. Elsevier Applied Science, New York. p. 159–181

Keddy, P. A., Lee, H. T. and Wisheu, I. C.: 1993, 'Choosing Indicators of Ecological Integrity: Wetlands as a Model System', in: S. Woodley, J. Kay and G. Francis (eds), *Ecological Integrity and the Management of Ecosystems*. St-Lucie Press, Florida. p. 61–82.

Kessler, W. B.: 1994, 'The Need for Ecosystem Vital Signs', in: D. W. McKenney, R. A. Sims, M. E. Soulé, B. G. Mackey and K. L. Campbell (eds.), *Towards a Set of Biodiversity Indicators for Canadian Forests: Proceedings of a Forest Biodiversity Indicators Workshop*. Natural Resources Canada, Sault Ste-Marie (Ontario). p. 92–97.

Koskimies, P.: 1989, Birds as a tool in environmental monitoring', *Ann. Zool. Fenn.* **26**, 153–166.

Kremen, C.: 1992, 'Assessing the indicator properties of species assemblages for natural areas monitoring', *Ecol. Appl.* **2**, 203–217.

Kremen, C.: 1994, 'Biological inventory using target taxa: a case study of the butterflies of Madagascar', *Ecol. Appl.* **4**, 407–422.

Kriesel, W.: 1984, 'Representation of the environmental quality profile of a metropolitan area', *Environ. Monit. Assess.* **4**, 15–33.

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

Landres, P. B.: 1992, 'Ecological Indicators: Panacea or Liability?', in: D. H. McKenzie, D. E. Hyatt and V. J. McDonald (eds), *Ecological Indicators*. Elsevier Applied Science, New York. p. 1295–1318.

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

Launer, A. E. and Murphy, D. D.: 1994, 'Umbrella species and the conservation of habitat fragments: A case of a threatened butterfly and a vanishing grassland ecosystem', *Biol. Conserv.* **69**, 145–153.

Lindenmayer, D. B.: 1999, 'Future directions for biodiversity conservation in managed forests: indicator species, impact studies and monitoring programs', *For. Ecol. Manage.* **115**, 277–287.

MacDonald, L. H. and Smart, A.: 1993, 'Beyond the guidelines: Practical lessons for monitoring', *Environ. Monit. Assess.* **26**, 203–218.

Mackey, B. G., McKenney, D. W. and Sims, R. A.: 1994, 'Towards a Set of Biodiversity Indicators for Canadian Forests', in: D. W. McKenney, R. A. Sims, M. E. Soulé, B. G. Mackey and K. L. Campbell (eds), *Towards a Set of Biodiversity Indicators for Canadian Forests: Proceedings of a Forest Biodiversity Indicators Workshop*, Natural Resources Canada, Sault Ste-Marie (Ontario). p. 23–51.

Mannan, R. W., Morrison, M. L. and Meslow, E. C.: 1984, 'The use of guilds in forest bird management', *Wildl. Soc. Bull.* **12**, 426–430.

Marshall, I. B., Hirvonen, H. and Wiken, E.: 1993, 'National and Regional Scale Measures of Canada's Ecosystem Health', in: S. Woodley, J. Kay and G. Francis (eds), *Ecological Integrity and the Management of Ecosystems*. St-Lucie Press (Florida). p. 117-130.

Martin, T. E.: 1995, 'Avian life history evolution in relation to nest sites, nest predation and food', *Ecol. Monogr.* **65**, 101–127.

Martin, T. E. and Li, P.: 1992, 'Life history traits of open versus cavity-nesting birds' *Ecology* **73**, 579–592.

Mazerolle, M. J. and Villard, M.-A.: 1999, 'Patch characteristics and landscape context as predictors of species presence and abundance: a review', *Ecoscience* **6**, 117–124.

McKenney, D. W., Sims, R. A., Soulé, M. E. and Mackey, B. G.: 1994, 'Workshop Results', in: D. W. McKenney, R. A. Sims, M. E. Soulé, B. G. Mackey and K. L. Campbell (eds), *Towards a Set of Biodiversity Indicators for Canadian Forests: Proceedings of a Forest Biodiversity Indicators Workshop*. Natural Resources Canada, Sault Ste-Marie (Ontario). p. 1–22.

Morrison, M. L.: 1986, 'Bird populations as indicators of environmental change', *Current Ornithol.* **3**, 429–451.

Moyle, P. B. and Randall, P. J.: 1998, 'Evaluating the biotic integrity of watersheds in the Sierra Nevada, California', *Conserv. Biol.* **12**, 1318–1326.

Munn, R. E.: 1993, 'Monitoring for Ecosystem Integrity', in: S. Woodley, J. Kay, and G. Francis (eds), *Ecological Integrity and the Management of Ecosystems*. St-Lucie Press, Florida. p. 105–116.

Murphy, D. D., Freas, K. E. and Weiss, S. B.: 1990, 'An environmental-metapopulation approach to population viability analysis for a threatened invertebrate', *Conserv. Biol.* **4**, 41–51.

Niemëla, J., Langor, D. and Spence, J. R.: 1993, 'Effects of clear-cut harvesting on boreal ground beetles assemblages (Coleoptera: Carabidae) in Western Canada', *Conserv. Biol.* **7**, 551–561.

Niemi, G. J., Hanowski, J. M., Lima, A. R., Nicholls, T. and Weiland, N.: 1997, 'A critical analysis on the use of indicator species in management', *J. Wildl. Manage.* **61**, 1240–1252.

Noss, R. F.: 1987, 'From plant communities to landscapes in conservation inventories: A look at the Nature Conservancy (U.S.A.)', *Biol. Conserv.* **41**, 11–37.

Noss, R. F.: 1990, 'Indicators for monitoring biodiversity: A hierarchical approach', *Conserv. Biol.* **4**, 355–264.

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

Noss, R. F., O'Connell, M. A. and Murphy, D. D.: 1997, '*The Science of Conservation Planning: Habitat Conservation under the Endangered Species Act*'. World Wildlife Fund et Island Press, Washington.

O'Connell, T. J., Jackson, L. E. and Brooks, R. P.: 1998, 'A bird community index of biotic integrity for the Mid-Atlantic highlands', *Environ. Monit. Assess.* **51**, 145–156.

Paine, R. T.: 1969, 'A note on trophic complexity and community stability', *Am. Nat.* **103**, 91–93.

Paine, R. T.: 1995, 'A conversation on refining the concept of keystone species', *Conserv. Biol.* **9**, 962–964.

Pärt, T., and Söderström, B.: 1999a, 'Conservation value of semi-natural pastures in Sweden: contrasting botanical and avian measures', *Conserv. Biol.* **13**, 755–765.

Pärt, T., and Söderström, B.: 1999b, 'The effects of management regimes and location in landscape on the conservation of farmland birds in semi-natural pastures', *Biol. Conserv.* **90**, 113–123.

Pearson, D. L.: 1992, 'Tiger beetles as indicators of biodiversity patterns in Amazonia', *Nat. Geogr. Res. Explor.* **8**, 116–117.

Pearson, D. L.: 1994, 'Selecting indicator taxa for the quantitative assessment of biodiversity', *Phil. Trans. Roy. Soc. London* **345**, 75–79.

Pearson, D. L. and Cassola, F.: 1992, 'World-wide species richness patterns of tiger beetles (Coleoptera: Cicindelidae): indicator taxon for biodiversity and conservation studies', *Conserv. Biol.* **6**, 376–391.

Powell, G. V. N. and Powell, A. H.: 1986, 'Reproduction by Great white herons *Ardea herodias* in Florida bay as an indicator of habitat quality', *Biol. Conserv.* **36**, 101–113.

Prendergast, J. R. and Eversham, B. C.: 1997, 'Species covariance in higher taxa: Empirical tests of the biodiversity indicator concept', *Ecography* **20**, 210–216.

Prendergast, J. R., Quinn, R. M., Lawton, J. H., Eversham, B. and Gibbons, D. H.: 1993, 'Are species, the coincidence of diversity hotspots and conservation strategies', *Nature* **365**, 335–337.
Rapport, D. J.: 1989, 'What constitute ecosystem health?', *Persp. Biol. Med.* **33**, 120–132.
Rapport, D. J.: 1990, 'Challenges in the detection and diagnosis of pathological change in aquatic ecosystems', *J. Great Lakes Res.* **16**, 609–618.
Rapport, D. J.: 1992, 'Evolution of Indicators of Ecosystem Health', in: D. H. McKenzie, D. E. Hyatt and V. J. McDonald (eds), *Ecological Indicators*. Elsevier Applied Science, New York. p. 117–133.
Rapport, D. J.: 1995a, 'Ecosystem health: Exploring the territory', *Ecosyst. Health* **1**, 5–13.
Rapport, D. J.: 1995b, 'Ecosystem health: More than a metaphor?', *Env. Values* **4**, 287–309.
Reunanen, P., Mönkkönen, M. and Nikula, A.: 2000, 'Managing the boreal forest landscapes for flying squirrels', *Conserv. Biol.* **14**, 218–226.
Riiters, K. H., Law, B. E., Kucera, R. C., Gallant, A. L., DeVelice, R. I. and Palmer, C. J.: 1992, 'A selection of forest condition indicators for monitoring', *Environ. Monit. Assess.* **20**, 21–33.
Robbins, C. S., Dawson, D. K. and Dowell, B. A.: 1989, 'Habitat area requirements of breeding forest birds of the middle Atlantic states', *Wildl. Monogr.* **103**, 1–34.
Roberts, T. H. and O'Neil, L. J.: 1985, 'Species selection for habitat assessments', *Trans. N.A. Wildl. Nat. Res. Conf.* **50**, 352–362.
Rodrìguez, J. P., Pearson, D. L. and Barrera, R. R.: 1998, 'A test for the adequacy of bioindicator taxa: are tiger beetles (Coleoptera: Cicindelidae) appropriate indicators for monitoring the degradation of tropical forests in Venezuela?', *Biol. Conserv.* **83**, 69–76.
Schaeffer, D. J., Herricks, E. E. and Kerster, H. W.: 1988, 'Ecosystem health. I. Measuring ecosystem health', *Env. Manage.* **12**, 445–455.
Schall, J. J. and Pianka, E. K.: 1978, 'Geographical trends in number of species', *Science* **201**, 679–686.
Schoener, T. W.: 1986, 'Patterns in Terrestrial Vertebrates Versus Arthropod Communities: Do Systematic Differences in Regularity Exist?' in J. Diamond and T. J. Case (eds), *Ecology*. Harper and Row, New York (New York). p. 556–586.
Simberloff, D.: 1998, 'Flagships, umbrellas, and keystones: is single-species management passé in the landscape era?', *Biol. Conserv.* **83**, 247–257.
Soulé, M. E. and Terborgh, J.: 1999, 'Conserving nature at regional and continental scales: a scientific program for North America', *BioScience* **49**, 809–817.
Stanford, J. A. and Poole, G. C.: 1996, 'A protocol for ecosystem management', *Ecol. Appl.* **6**, 741–744.
Starfield, A. M. and Bleloch, A. L.: 1983, 'An initial assessment of possible lion population indicators', *S. Afr. J. Wildl. Res.* **13**, 9–11.
Steele, B. B., Bayn, R. L. Jr. and Grant, C. V.: 1984, 'Environmental monitoring using population of birds and small mammals: analyses of sampling effort', *Biol. Conserv.* **30**, 157–172.
Suter II, G. W.: 1993, 'A critique of ecosystem health concepts and indexes', *Env. Toxicol. Chem.* **12**, 1533–1539.
Temple, S. A. and Wiens, J. A.: 1989, 'Bird populations and environmental changes: can birds be bio-indicators?', *Am. Birds* **43**, 260–270.
Tergorgh, J.: 1974, 'Preservation of natural diversity: the problem of extinction prone species', *BioScience* **24**, 715–722.
Tilman, D., May, R. M., Lehman, C. L. and Nowak, M. A.: 1994, 'Habitat destruction and the extinction debt', *Nature* **371**, 65–66.
Tracy, C. R. and Brussard, P. F.: 1994, 'Preserving biodiversity: species in landscapes', *Ecol. Appl.* **4**, 205–207.
Tscharntke, T.: 1992, 'Fragmentation of *Phragmites* habitats, minimum viable population size, habitat suitability, and local extinction of moths, flies, aphids, and birds', *Conserv. Biol.* **6**, 530–53.

Tscharntke, T., Gathmann, A. and Steffan-Dewenter, I.: 1998, 'Bioindication using trap-nesting bees and wasps and their natural enemies: community structure and interactions', *J. Appl. Ecol.* **35**, 708–719.

Van Horne, B.: 1983, 'Density as a misleading indicator of habitat quality', *J. Wildl. Manage.* **47**, 893–901.

Vickery, P. D., Hunter Jr., M.L. and Wells, J. V.: 1992, 'Is density an indicator of breeding success?', *Auk* **109**, 706–710.

Villard, M.-A., Martin, P. and Drummond, G. C.: 1993, 'Habitat fragmentation and pairing success in the Ovenbird (*Seiurus aurocapillus)', Auk* **110**, 759–768.

Villard, M.-A., Merriam, G. and Maurer, B. A.: 1995, 'Dynamics in subdivided populations of neotropical migratory birds in a temperate fragmented forest', *Ecology* **76**, 27–40.

Weaver, J. C.: 1995, 'Indicator species and scale of observation', *Conserv. Biol.* **9**, 939–942.

Welsh, H. H. Jr., Ollivier, L. M. and Hankin, D. G.: 1997, 'A habitat-based design for sampling and monitoring stream amphibians with an illustration from Redwood National Park', *Northwestern Nat.* **78**, 1–16.

White, P. S. and Bratton, S. P.: 1980, 'After preservation: philosophical and practical problems of change', *Biol. Conserv.* **18**, 241–255.

Wicklum, D. and Davies, R. W.: 1995, 'Ecosystem health and integrity?', *Can. J. Bot.* **73**, 997–1000.

Wilcove, D.: 1994, 'Response to Franklin (1993)', *Ecol. Appl.* **4**, 207–208.

Wilcove, D. S. and Blair, R. B.: 1995, 'The ecosystem management bandwagon', *Trends Ecol. Evol.* **10**, 345.

Williams, P. H. and Gaston, K. J., 1994, 'Measuring more of biodiversity: Can higher-taxon richness predict wholesale species richness?', *Biol. Conserv.* **67**, 211–217.

Woodley, S.: 1993, 'Monitoring and Measuring Ecosystem Integrity in Canadian National Parks', in: S. Woodley, J. Kay and G. Francis (eds), *Ecological Integrity and the Management of Ecosystems*. St-Lucie Press, Florida. p. 155–176

Woodley, S.: 1996a, 'A scheme for ecological monitoring in national parks and protected areas', *Environments* **23**, 50–59.

Woodley, S.: 1996b, 'Monitoring, assessing and reporting upon ecological change: implications for planning and management', *Environments* **24**, 60–68.

Woodley, S. and Theberge, J.: 1992, 'Monitoring for Ecosystem Integrity in Canadian National Parks', in: J. H. M. Willison, S. Bondrup-Nielsen, C. Drysdale, T. B. Herman, N. W. P. Munro and T. L. Pollock (eds), *Science and the Management of Protected Areas*. Elsevier Applied Science, New York (New York). p. 369-377.

Zonneveld, I. S.: 1983, 'Principles of bioindication', *Environ. Monit. Assess.* **3**, 207–217.