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Faunal indicator taxa selection for monitoring ecosystem health

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Abstract

Maintaining healthy ecosystems is a prerequisite for conserving biodiversity. The complex nature of ecosystems often necessitates the use of indicator taxa to monitor ecosystem health. However, ambiguous selection criteria and the use of inappropriate taxa have brought the utility of indicator taxa under question. This review compiles existing selection criteria from the literature, evaluates inconsistencies among these criteria, and proposes a step-wise selection process. In addition, 100 vertebrate and 32 invertebrate taxa documented in the conservation science literature as indicators of ecosystem health are examined to assess how well they adhere to the referenced criteria. Few vertebrate taxa fulfill multiple criteria, as most are highly mobile generalists that lack established tolerance levels and correlations with ecosystem changes. Most suggested invertebrate taxa also lack correlations to ecosystem changes, but satisfy other selection criteria. However, invertebrate taxa are often suggested at high taxonomic levels, encompassing many species, making it difficult to measure specific attributes, and potentially including many unnecessary and even inappropriate species.

Keywords: Conservation; Guidelines; Monitoring; Vertebrates; Invertebrates

1. Introduction

The complexity of ecosystems has forced conservation biologists to develop alternative methods to monitor change that would be too costly or difficult to measure directly (Landres et al., 1988; Meffe and Carroll, 1997). One such method is the use of indicator taxa, which are species or higher taxonomic groups whose parameters, such as density, presence or absence, or infant survivorship, are used as proxy measures of ecosystem conditions. For example, indicator taxa have been used to evaluate toxicity levels, abundance of specific resources, levels of biodiversity, target taxa status, endemism levels, and ecosystem health (Temple and Wines, 1989; Wilcove, 1989; Croonquist and Brooks, 1991; van Franeker, 1992; Kremen et al., 1993; Kushlan, 1993; Maho et al., 1993; Bortone and Davis, 1994; Anderson-Carnahan et al. 1995; Louette et al., 1995; Cherel and Weimerskirch, 1995; Harris, 1995; Nyholm, 1995; Faith and Walker, 1996).

This paper focuses on utilization of taxa as appropriate indicators for assessing general ecosystem health. This use of indicator taxa is important to biological conservation yet lacks well-established methodologies. The goal of monitoring ecosystem health is to identify chemical, physical and/or biological changes due to human impacts (Hughes et al., 1992). The term ecosystem health has been hotly debated in the literature (Jamieson, 1995; Lackey, 1995; Rapport, 1995a; Wicklum and Davies, 1995; Callicott and Mumford, 1997; Simberloff, 1998). While some condone complete abdication of the term, ecosystem health remains a widely used concept and many papers reviewed here used the term. We prefer Rapport's (1995a,b) definition which states ecosystem health as the absence of signs of ecosystem distress, an ecosystem's ability to recover with speed and completeness (resilience), and/or a lack of risks or threats pressuring the ecosystem composition, structure, and/or function. Kolasa and Pickett (1992) also suggest that measures of ecosystem health should be based on a pre-defined scale using a baseline condition.

Multiple monitoring methods are usually required to address complex ecosystems (Soule, 1985). The index of biotic integrity (Karr, 1981), developed to assess degradation in streams, uses an array of ecological measures,

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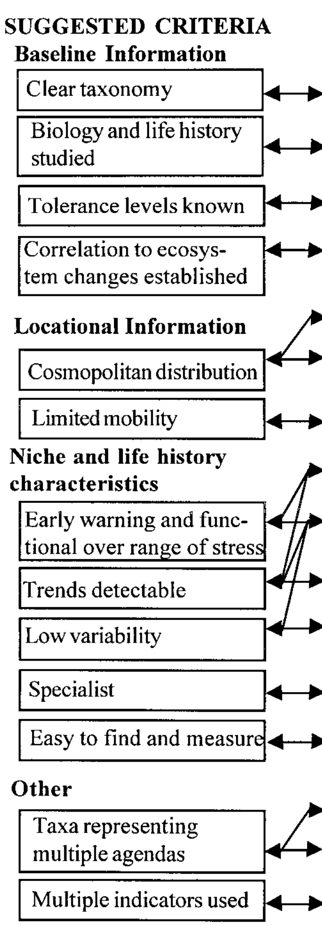
one of which is indicator taxa (Fausch et al., 1990). If selected correctly a set of complementary indicator taxa may provide early warning of problems and help monitor change over large temporal and spatial scales (Rapport, 1992; Harris 1995).

While use of indicator taxa has become integrated into many ecosystem health monitoring programs, the appropriateness of using indicator taxa has been questioned. Simberloff (1998), for example, proposes focusing on keystone species rather than indicator taxa because of concern about the true utility of indicator taxa. Unclear guidelines, dubious assumptions about the ability of indicator taxa to represent other ecosystem trends, and difficulties in differentiating human impact and non-human related changes have led indicator taxa to be the subject of much debate (Rosenberg et al., 1986; Landres et al., 1988; Fausch et al., 1990; Pearman et al, 1995; Taper et al., 1995; Simberloff, 1998).

The objectives of this review are: (1) to evaluate various criteria that have been proposed by others in the conservation science literature for selecting indicator taxa, (2) to offer a step-wise process for indicator taxa selection, and (3) to test the criteria against the indicator taxa that biologists and natural resource managers are currently using to monitor ecosystem health.

1.1. Review of the suggested criteria for selecting indicator taxa

We found nine articles published in the last 13 years that outline criteria for selecting indicator taxa (Soule, 1985; Hellawell, 1986; Landres et al., 1988; Kelly and Harwell, 1990; Noss, 1990; Regier, 1990; Pearson and Cassola, 1992; Johnson et al., 1993; Kremen, 1994). The indicator selection criteria reviewed applied to conservation-oriented efforts but not necessarily to indicators of ecosystem health. However, significant overlap in criteria of reviewed papers suggests that indicator taxa for ecological monitoring share the same basic requirements. We focus on 13 selection criteria mentioned in more than one reference. These criteria fall into four general categories (Fig. 1): (1) baseline information, (2)



ATTRIBUTES	VERTEBRATES % yes	VERTEBRATES % no	INVERTEBRATES % yes	INVERTEBRATES % no
Taxonomic status clear	100	0	97	3
>30 primary literature articles	56	44	75	25
Tolerance levels studied	8	92	84	16
Correlation to ecosystem	1	99	3	97
Global distribution	54	46	69	31
Not migratory	38	62	100	0
Home range size small	36	64	100	0
Reproductive rate high	28	72	0	100
Small body size	23	77	—	—
Low or medium trophic level	64	36	82	16
Low population fluctuations*	—	—	38*	16*
Food/habitat specialist	15	85	100	0
Easy to find*	—	—	56	13
Species at risk	30	70	19	81
Economically valuable	18	82	3	93
Multiple indicators suggested	9	91	0	100

* Only some authors categorized suggested taxa by Population Fluctuation or Easy to Find.

Fig. 1. Suggested criteria for selecting indicator taxa of ecosystem health and attributes used to assess if taxa fulfill the criteria are in columns 1 and 2, respectively. Columns 3 and 4 include summary results of measured attributes for 100 suggested vertebrate and 32 suggested invertebrate taxa. Where percents do not add up to 100, not all taxa were categorized.

location information, (3) niche and life history attributes, and (4) other. Except where discussed, the reviewed criteria apply to both single species and higher level taxon. Not all useful indicator taxa will necessarily fit all criteria, but each taxon, selected as part of a complementary set, should satisfy multiple criteria.

Adequate baseline information means the biology, taxonomy, and tolerance of a taxon's measurable characteristics should be understood (Hellawell, 1986; Landres et al., 1988; Kelly and Harwell, 1990; Regier, 1990; Pearson and Cassola, 1992; Johnson et al., 1993; Kremen, 1994). Studies asserting cause and effect assure that observed changes in the characteristics measured for the indicator taxa are induced by human actions (Landres et al., 1988). In addition, clear correlation between the taxon's response to impacts and ecosystem changes should be established (Landres et al., 1988; Kelly and Harwell, 1990; Pearson and Cassola, 1992; Kremen 1994).

Location information is also important in selecting indicator taxa. Reviewed literature indicate that selected taxa should have a cosmopolitan distribution to assist in cross-comparisons of sites (Hellawell, 1986; Noss, 1990; Regier, 1990; Pearson and Cassola, 1992; Johnson et al., 1993). An indicator taxon should also have limited mobility, so that the taxon is less likely to be able to avoid disturbances (Landres et al., 1988; Johnson et al., 1993). For example, changes in a population of migratory birds could be due to impacts in any part of their migratory route, not just at the study site.

Specified niche and life history characteristics should also be considered for each indicator taxon. A taxon should have low variability both genetically and ecologically, so neither random fluctuations in populations nor species adaptations hinder detection of impacts (Hellawell, 1986; Landres et al., 1988; Noss, 1990; Johnson et al., 1993). In addition, the life history of the selected indicator taxa should be such that it will both be able to provide early warning and be effective over a wide range of stress (Soule, 1985; Kelly and Harwell, 1990; Noss, 1990). Finally, the life history characteristic specialized/endemic is a debated criterion in the literature review (Landres et al., 1988; Pearson and Cassola, 1992; Johnson et al., 1993; Kremen, 1994).

Other considerations proposed for selecting indicator taxa include cost effectiveness, ease of detection and mensuration, and ability to detect and quantify changes (Hellawell, 1986; Kelly and Harwell, 1990; Noss, 1990; Regier, 1990; Pearson and Cassola, 1992; Johnson et al., 1993; Kremen, 1994). Inadequate sample size, lack of statistical power, or inability to detect the difference between environmental variation and changes induced by human impacts can prevent effective hypothesis testing. Another proposed criterion is the selection of taxa that serve other agendas, such as social, political or economic priorities. Using species at risk, flagship species, or otherwise prioritized species also as an indicator taxon is controversial and debated in the literature (Soule, 1985; Hellawell, 1986; Landres et al., 1988; Kelly and Harwell, 1990; Pearson and Cassola, 1992). Finally, use of a set of complementary indicator taxa where each selected taxon can satisfy multiply criteria is critical (Soule, 1985; Landres et al., 1988; Kelly and Harwell, 1990; Noss, 1990).

1.2. Critique of suggested criteria

The criteria outlined above suffer from several problems. Some of the criteria are unclear, conflict with one another, or are disputed among authors. Also, these criteria have never been prioritized in order of importance, and most of the criteria are difficult to determine for most taxa because there are few measurable attributes associated with the suggested criteria.

The criterion, cosmopolitan, conflicts with the recommendation for endemic and specialized taxa because no one taxon can be both endemic and cosmopolitan at the same taxonomic level. While one possible solution is to select higher ranking taxa; thereby assessing their distribution at the taxonomic level suggested and evaluating their level of endemism at the species level, use of higher taxonomic levels is not necessarily appropriate. Instead, use of low ranking taxa is important to minimize the possibility of including inappropriate species. Selection of high taxonomic level taxa is also problematic because species within a taxon can vary dramatically across sites making comparisons difficult, and a taxon may only be an appropriate indicator in part of its range (Landres et al., 1988). Given that cosmopolitan can conflict with the criterion of specialization and endemic, and that cross-site comparisons are potentially limited even with cosmopolitan distribution of a taxon, we recommend that cosmopolitan be considered a secondary criterion to be considered after the other criteria have been satisfied (Table 1).

Two other criteria, early warning and low variability, are both important but can also be conflicting. For example, large bodied, high trophic level, generalist vertebrates with low reproductive rates are indicative of taxa that have low population variability, but these same characteristics imply limited ability to provide early warning of impacts. We suggest that indicators should be selected in such a way that early warning detection is maximized while minimizing unpredictable fluctuations in populations (Table 1). Some invertebrates, such as Collembola and Odonata, satisfy both the early warning and low variability criteria (Brown, 1991).

The criterion, specialization, is disputed in the literature. While specialists are argued to be more information rich (Pearson and Cassola, 1992), there is concern that they may not adequately represent ecosystem complexity (Landres et al., 1988). We believe that specialization

Table 1
Step-wise decision-making framework for selecting indicator taxa[a]

Step 0	Decide what ecosystem attribute(s) indicator taxa should reflect.
Step 1	Make a list of all species in the area that best satisfy the baseline information criteria.
Step 2	From this initial list, retain species that best meet the suggested niche and life history criteria.
Step 3	Remove species that may respond to changes occurring outside the system of interest.
Step 4	Use only those species that can be easily detected and monitored with available funds.
Optional step	Reduce the list further by selecting taxa in the list with cosmopolitan distributions and/or that represent other agendas of interest.
Step 5	Select a set of complementary indicator taxa from different taxonomic groups so that all selection criteria are met by more than one taxon.

[a] See Fig. 1, column 1 for a detailed list of criteria.

should be considered an important criterion because generalists, like more mobile species, can potentially avoid impacts by switching food sources or altering their habitat use, thereby failing to respond to the impact. For example, coyotes (*Canis latrans*) rely on different prey items depending on land use patterns, allowing them to persist in areas of human development where eradication programs no longer exist (Quinn, 1997). A set of complementary specialist indicator taxa representing a spectrum of ecosystem niches would potentially allow for detection of fine scale impacts and earlier detection, while use of multiple generalists is unlikely to lead to enhanced fine scale or early detection.

The importance of selecting indicator taxa that also fulfill political, economic or social agendas is also a criterion of contention. Simultaneously servicing other agendas may increase support for the project (Pearson and Cassola, 1992), but attempts to address more than one agenda with the same taxon too often pre-empts the selection of more appropriate indicators that would satisfy the recommended criteria (Landres et al., 1988). In addition, use of taxa servicing other agendas opens the door to a host of other problems. Economically important taxa, such as harvested or hunted species, are affected by off-take that can confound data collected for detecting changes in ecosystem health (Merenlender et al., 1998).

Similarly, use of taxa identified at risk of extinction as indicators of ecosystem health can be problematic. First, species at risk are often difficult to study because the precarious status of the taxon prohibits further disruption, impeding necessary studies to establish baseline information. Second, endangered populations are often at low densities or have restricted distributions, which result in reduced sampling size and statistical power for trend analyses. Third, taxa at risk may not function as an indicator of ecosystem change over a range of human impacts. Given the potential pitfalls, selection of indicator taxa that represent other agendas should be secondary to the other criteria. To improve the indicator taxon selection process and prioritization of criteria, we provide a step-wise process to select the best available indicator taxa in Table 1.

Another potential problem with the compiled criteria is that the concepts are not easily translatable to land managers. In other words, many of the criteria are conceptual and often lack easily measurable attributes, so it is difficult for practitioners to make unbiased evaluations of potential indicator taxa. We identified attributes for which information is relatively easy to gather to determine if a particular taxon meets each suggested selection criteria. A list of these identified attributes are described in the methods section and are cross referenced to the published suggested selection criteria in Fig. 1. The cost of using a particular taxon is not included because cost is dependent on the location, circumstances, and resources available. Many of the attributes collected are not independent variables, but instead serve together to provide evidence as to whether the taxa satisfy suggested selection criteria. We used these attributes to examine how indicator taxa found in the literature satisfied the suggested selection criteria.

2. Methods

2.1. Literature search and restrictions

A literature search was conducted focusing on the primary biological literature published in English in the past 10 years that explicitly identified taxa as indicators of ecosystem health. The phrases bio-indicators and management indicator species were accepted only when authors explicitly stated that a taxon was used for assessment, management, or monitoring of ecosystem health. Terms considered equivalent to ecosystem health when discussed in the context of monitoring human impacts include: water quality, disturbance, impacts, landuse change impacts, health of ecosystem, health condition, ecosystem deterioration, forest health, ecosystem, state of ecosystem, ecosystem degradation, intact ecosystem, and the effects of land management. Only indicator taxa suggested for or used in the field were analyzed, and studies referring solely to a specific impact of ecosystem health such as of the effect of building a road, were not included because we focused on indicator taxa that potentially address multiple impacts.

Papers that referred to high level taxonomic groups such as birds, fish, or macroinvertebrates as indicators (e.g. Hocutt, 1981; Morrison, 1986; Adamus, 1995) had to be excluded because analysis of all of the species falling into such a high taxonomic level would prove unwieldy. We also did not analyze biotic indices or similar procedures because our analysis required a concrete list of species, and we wanted to focus on indicator taxon selection and not the host of other techniques included in these methods. Finally, we did not include flora in the review because life history characteristics of plants can not be directly compared with those of animals.

Information for attributes associated to the list of criteria (Fig. 1) was collected from a number of sources. When available, data were collected from the reference in which the indicator taxon was suggested. Other sources were consulted to obtain information on conservation status and life history attributes (Appendixes A and B). When a suggested taxon included multiple species, the characteristics of the majority of the group were considered to hold true for the entire taxon. Details on the attributes collected for each identified indicator taxon are listed below.

2.2. Baseline information and research

2.2.1. Taxonomic status

When neither the author nor other sources reviewed claimed the suggested indicator to be taxonomically unclear at the taxonomic level used, the taxonomy was recorded as established.

2.2.2. Estimation of information from primary literature

We conducted a keyword search in Biosis (1997) for the common and scientific names of each taxon. We tabulated the relative number of citations as an estimate of the amount of primary literature available on each indicator taxon used. Any search result of greater than 30 references was considered to reflect adequate baseline information, regardless of the applicability of the references to ecosystem health.

2.2.3. Tolerance

This category reflects an indicator taxon's ability to withstand a broad range of human impacts. A more tolerant taxon would not show any measurable change as a result of small or medium impacts. If the author(s) suggesting the indicator taxa tested or cited studies testing the tolerance, the tolerance was considered addressed. Adequacy of the studies was not examined. If tolerance had been established in previous studies but was not cited by the author, it would not have been recorded.

2.2.4. Correlation to other biota

Similar to tolerance, this category addresses whether changes in each indicator taxon have been correlated with ecosystem changes. The suggested taxon satisfied this criterion if the author performed or cited studies that established this correlation. Adequacy of studies was not examined, and studies not cited by the author went undetected.

2.3. Locational information

2.3.1. Distribution

Three categories were used to define the taxon's distribution: local, regional, and global. Local was defined as a biogeographic unit (e.g. mountain range) or specific local habitat type (e.g. California redwood forest) and regions as entire continents or sub-continent (e.g. Mongolia, North India, or North America). Global classification required presence of the taxon on multiple continents.

2.3.2. Migratory

Any taxon that had a defined seasonal shift in non-contiguous habitats in any part of the taxon's range was classified as migratory.

2.3.3. Home range

Range was considered only for terrestrial mammals because the migratory criteria covered invertebrates, herps, birds, and aquatic mammal mobility. All invertebrates reviewed in this paper are classified as having small home range because their home ranges are small compared to the extent of most ecosystem health study sites. The median of nineteen randomly selected terrestrial mammals, 700 ha, served as a rough division point between large and small home ranges (van Gelder, 1982).

2.4. Niche and life history characteristics

2.4.1. Trophic level

Low trophic level taxa included only herbivorous species of which the adults were potentially prey for other species. Medium trophic level included omnivorous and carnivorous taxa of which the adults were also potential prey to other species. High trophic level was defined as carnivorous taxa of which adults were not actively hunted by any non-human species. For example, lake trout are terminal predators in the Great Lakes system and therefore classified as high trophic level (Marshall et al., 1987).

2.4.2. Specialist vs generalist

Vertebrate habitat specialists include all species defined as such by authors or other references, or any taxon found in only one habitat type as defined by Miller (1951). Invertebrate taxa were classified as specialists if authors or others defined them as such, or if they utilized only one substrate type (Merrit and Cummins, 1996). Food specialists were defined as monophagous or oligophagous.

2.4.3. Reproductive rates

As all invertebrates, fishes, and amphibians reviewed in this paper fall into the life history strategy of producing many young, these animals were all classified as having high reproductive rates. To separate different reproductive strategies among birds and mammals, the median of 19 randomly selected mammals and birds, 5.5 per year, served as a division point between high and low reproductive rates (Burt and Grossenheider, 1980; van Gelder, 1992).

2.4.4. Damped fluctuations

This category was only applied to invertebrate taxa where authors categorized taxa as having low or high population fluctuations. Such fluctuations in populations might be the consequence of environmental factors such as resource availability or weather or a result of population densities.

2.4.5. Body size

The median length of 19 randomly selected mammals and birds, 29 cm, served as a rough division point between large and small body sizes for mammals and birds. Whereas bird and mammal body size is indicative of life history strategies, this is less well-established for amphibians, fishes, and invertebrates, so these groups were not classified by body size.

2.4.6. Easy to find

Some authors suggesting invertebrate indicator taxa classified the taxa as easy or difficult to find, so we included their classifications in the compilation of data.

2.5. Other agendas served by suggested indicators and implementation

2.5.1. Taxon at risk

The vertebrate taxon was considered at risk if it was listed in IUCN red data list, in state, federal, or other countries' listings.

2.5.2. Economic value

If stated by author or other references, or there is a known market for the taxon, it was included in this category. Hunting was considered an economic value.

2.5.3. Other indicators used or suggested

The author(s) suggested or used multiple indicator species.

3. Results and discussion

Appendixes A and B list the 100 vertebrate and 32 invertebrate indicator taxa reviewed. The results for whether or not each taxon met the attributes and corresponding selection criteria are summarized in Fig. 1. Baseline information for suggested indicator taxa is generally inadequate. The taxonomy is the only baseline information criterion that appears to be well-established for almost all of the taxa at the taxonomic level suggested, although taxonomy may not be clear at the species level. Forty-four percent of reviewed vertebrates and 25% of reviewed invertebrates failed the biology and life history criteria, based on apparent lack of primary references. Studies of physical tolerance levels of the vertebrate taxa were only executed or referred to 8% of the vertebrate articles. In contrast, authors cited or completed physical tolerance studies on invertebrate indicators 84% of the time. In both vertebrates and invertebrates only 1 and 3% of the taxa, respectively, referred to studies correlating changes in the indicator status with changes to the ecosystem. While such research may be difficult, establishing tolerance levels and correlating changes of the indicator with the ecosystem is critical for indicators to be informative about ecosystem health. Otherwise, determining the magnitude of an impact and how the ecosystem health is affected when a taxon indicates an impact remains unclear.

Not all of the proposed indicator taxa satisfied the locational criteria either. Only 54% of the vertebrates and 69% of the invertebrates reviewed have a global distribution, although this criterion, as discussed earlier, should be of secondary importance. More importantly, many suggested vertebrate taxa are highly mobile. Fifty-nine of the 67 avian taxa and three of the 16 mammalian taxa migrate, and seven of the 11 suggested terrestrial mammals fall into the large home range category. If mobile taxa are used, characteristics monitored should reflect conditions of the study site. For example, nestling success in the study area of some migratory birds is the type of data that may be attributed more easily to local conditions, despite their migratory status. Invertebrates reviewed in this paper are, for the most part, unable to move long distances, and their inability to escape adverse local conditions contributes to their potential value as indicators.

Vertebrate taxa also fared poorly in fulfilling suggested niche and life history criteria. Eighty-five percent of the vertebrates are generalists, failing the specialist criterion. In contrast, all of the invertebrate taxa are specialists and have high reproductive rates, and only 16% are categorized as high trophic level, attributes associated with biota that are likely to satisfy the early warning criterion. These same attributes, however, are also often indicative of populations that tend to fluctuate, failing the low variability criterion. This can make it difficult to differentiate between natural population fluctuations (noise) and population decline due to human impacts (signal). Only five of 17 invertebrates classified have populations that fluctuate in number.

In contrast to invertebrates, 72% of the vertebrates have low reproductive rates, 24% are large-bodied, and

36% are high trophic level taxa. These attributes suggest that these taxa, while their populations do not fluctuate much, may not be useful early warning detectors because longevity and low reproductive rates of these taxa make for slow changes in population structure and number. Large bodies and high trophic level status also indicate that such taxa are probably found at low densities (Blueweiss et al. 1978) and more susceptible to local extinction (Shaffer, 1981). Susceptibility to local extinction means that these taxa may also fail to fulfill the criterion of monitoring a wide range of stresses. In addition, low-density taxa can prove to be more difficult to find and quantitatively assess. Although no authors recommending vertebrate taxa classified taxa by ease of finding, 18 of 22 invertebrates are categorized as easy to find.

A number of suggested indicator taxa are also priorities on political, social, or economic agendas. Thirty percent of vertebrate taxa and 19% of invertebrate taxa include at least one species considered at risk. Additionally, 18% of the vertebrates have some economic value compared to only one invertebrate taxon. Reviewed taxa may also serve other agendas such as flagship (Dietz et al., 1994; Hunter and Sulzer, 1996) or umbrella species (Clark et al., 1996), but we only quantify at risk and economically valuable taxa making this estimate very conservative. As many of these taxa fail to satisfy the other criteria, selection of taxa servicing other agendas may be inhibiting selection of taxa that would be more appropriate as indicators of ecosystem health.

Finally, use of multiple indicator taxa is suggested for 91% of the vertebrate indicator taxa; all of the proposed invertebrate taxa are suggested as part of a set of complementary indicator taxa. That no single taxa can accurately reflect ecosystem health is well understood. Poor selection of multiple indicator taxa, however, will still lead to poor monitoring of ecosystem health. Each indicator should embody as many of the criteria as possible to create the most effective set of complementary indicator taxa.

While it may appear that invertebrates satisfy more criteria, this result is confounded by the higher level taxonomy of most suggested invertebrates as compared to vertebrates. All but four vertebrates reviewed were suggested at the species level, while the suggested invertebrates represented seven orders, 12 families, four subfamilies, and nine species. This difference in the level of taxonomy makes direct comparisons between invertebrates and vertebrates difficult. High taxonomic level suggestions such as beetles or birds may lead to inclusion of inappropriate taxa as indicators and unclear outcomes. In addition, the analysis of high level taxon may not reveal inclusion of poor indicator taxa because of generalizations made for each taxon at the level suggested.

Despite the limitations of most indicators reviewed, several proposed indicator taxa fulfill important multiple criteria that might make them more appropriate for future use. For example, Coleoptera: Cicindelidae (Pearson and Cassola, 1992), Lepidoptera: Morphinae and Satyrinae (Brown, 1991), Hymenoptera: Apoidae, Vespidae, and Sphecidae (Brown, 1991) are easy to find specialists. They are also relatively immobile, have detectable trends, and baseline studies examining tolerance levels and correlation of the taxa changes in the ecosystem are available. Few suggested vertebrate taxa satisfy multiple criteria. However, the spring peeper (*Pseudacris crucifer*) (Hecnar and M'Closkey, 1996), a vertebrate specialist, has limited mobility and adequate baseline information, and has shown detectable changes in local abundance. Few negative indicators, taxa that may increase in abundance with increased levels of human disturbance, were suggested. Yet negative indicators, such as Diptera, brown-headed cowbirds, and Norway rats, are potentially easier to find, quantitatively measure, and manipulate. Negative indicators might also provide data over a larger range of stress although, as with all indicator taxa, changes in the taxa need to be correlated to changes in the ecosystem (Landres et al., 1988).

4. Conclusion

This review demonstrates that there is room for improvement in selecting both vertebrate and invertebrate taxa that better satisfy the criteria put forth in the conservation science literature for identifying useful indicator taxa. The major shortcomings of the invertebrates reviewed include failure to establish correlation between changes in the indicator taxa and the ecosystem and selecting taxa at high taxonomic level, which potentially increases the number of inappropriate species and noise in the data. In general, the vertebrates reviewed lack established tolerance levels and correlation with changes in the ecosystem. Most suggested vertebrates are also low density, highly mobile generalists, and service other agendas while lacking other characteristics desirable for indicator taxa.

Our efforts revealed that published criteria for selection of indicator taxa are often unclear and conflicting in many cases. Failure of proposed indicator taxa to adhere to suggested criteria may be, in part, due to unclear criteria. Our step-wise framework clarifies and prioritizes selection criteria and assures that each taxon in a complementary set fulfill a majority of the criteria. This framework could eliminate the shortcomings associated with past selection of indicator taxa, so that a set of complementary indicator taxa may better serve as a tool for conservation of biological resources. Moving toward clear and objective selection of indicator taxa is one way to enhance the utility of indicator taxa. However, successful use of indicator taxa also depends on clear and established understanding of what indicator taxa will indicate, and on establishment of objective metrics of ecosystem health that can be associated to indicator taxa.

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Appendix A

Table A1
List of vertebrate indicator taxa reviewed

Suggested vertebrate taxa[a]		Reference
Chaetodontidae	Butterflyfishes	Hourigan et al., 1988
Micropterus dolomieu	Small-mouth bass	Ecosystem Objectives Committee, 1990
Salvelinus namaycush	Lake trout	Marshal et al., 1987; Ecosystem Objectives Committee, 1990
Stizostedian vitreum	Walleye	Ecosystem Objectives Comittee, 1990
Ambystoma maculatum	Spotted salamander	Hecnar and M'Closkey, 1996
Notophthalmus viridescens	Fire salamander	Hecnar and M'Closkey, 1996
Bufo americanus	American toad	Hecnar and M'Closkey, 1996
Bufo boreas	Western toad	Kiester and Eckhardt, 1994
Hyla versicolor	Grey tree frog	Hecnar and M'Closkey, 1996
Rana sylvatica	Wood frog	Hecnar and M'Closkey, 1996
Rana pipiens	Northern leopard frog	Hecnar and M'Closkey, 1996
Rana pretiosa	Spotted frog	Kiester and Eckhardt, 1994
Rana catesbeiana	Bull frog	Hecnar and M'Closkey, 1996
Rana clamitans	Green frog	Hecnar and M'Closkey, 1996
Rana palustris	Pickerel frog	Hecnar and M'Closkey, 1996
Pseudacris crucifer	Spring peeper	Hecnar and M'Closkey, 1996
Pseudacris triseriata	Western chorus frog	Hecnar and M'Closkey, 1996
Histrionicus histrionicus	Harlequin duck	Kiester and Eckhardt, 1994
Pelecanus occidentalis californicus	California brown pelican	Davis, 1989
Phalacrocorax auritus	Double-crested cormorant	Davis, 1989
Ardeidae	Herons	Spalding and Frederick, 1995
Ardea herodias	Great blue heron	Kiester and Eckhardt, 1994
Ardea cinerea	Grey heron	Bharucha and Gofte, 1990
Ardea purpurea	Purple heron	Bharucha and Gofte, 1990
Egretta	Egrets	Spalding and Frederick, 1995
Egretta garzetta	Smaller egret	Bharucha and Gofte, 1990
Ciconia ciconia	White necked stork	Bharucha and Gofte, 1990
Mycteria leucocephela	Painted stork	Bharucha and Gofte, 1990
Anastomus oscitans	Asian open-billed stork	Bharucha and Gofte, 1990
Phoenicopterus ruber	Lesser flamingo	Bharucha and Gofte, 1990
Threskiornithinae	Ibises	Spalding and Frederick, 1995
Plegadis falcinellus	Glossy ibis	Bharucha and Gofte, 1990
Plataleinae	Spoonbills	Spalding and Frederick, 1995
Platalea leucorodia	Eurasian spoonbill	Bharucha and Gofte, 1990
Anthropoides virgo	Demoiselle crane	Bharucha and Gofte, 1990
Grus grus	Eurasian common crane	Bharucha and Gofte, 1990
Anas penelope	Eurasian wigeon	Bharucha and Gofte, 1990
Anas crecca	Common teal	Bharucha and Gofte, 1990
Anas clypeara	Northern shoveller	Bharucha and Gofte, 1990
Anas acuta	Northern pintail	Bharucha and Gofte, 1990
Gallinago stenura	Painted pintail	Bharucha and Gofte, 1990
Aythya ferina	Common pochard	Bharucha and Gofte, 1990
Aythya australis	White-eyed pochard	Bharucha and Gofte, 1990

continued on next page

Table A1 (*continued*)

Suggested vertebrate taxa[a]		Reference
Aythya fuligula	Tufted pochard	Bharucha and Gofte, 1990
Tadorna ferruginea	Ruddy shelduck	Bharucha and Gofte, 1990
Porphyrio porphyrio	Purple moorhen	Bharucha and Gofte, 1990
Fulica atra	Common coot	Bharucha and Gofte, 1990
Himantopus himantopus	Black-winged stilt	Bharucha and Gofte, 1990
Charadrius alexandrinus	Snowy plover	Davis, 1989
Charadrius dubius	Little-ringed plover	Bharucha and Gofte, 1990
Charadrius alexandrinus	Kentish plover	Bharucha and Gofte, 1990
Limosa limosa	Black-tailed godwit	Bharucha and Gofte, 1990
Numenius arquata	Eurasian curlew	Bharucha and Gofte, 1990
Tringa nebularia	Common greenshank	Bharucha and Gofte, 1990
Tringa achropus	Green sandpiper	Bharucha and Gofte, 1990
Actitis macularia	Spotted sandpiper	Bharucha and Gofte, 1990
Actitis hypoleucos	Common sandpiper	Bharucha and Gofte, 1990
Calidris temminckii	Temminck stint	Bharucha and Gofte, 1990
Larus argentatus	Herring gull	Bharucha and Gofte, 1990
Larus brunnicephalus	Brown headed gull	Bharucha and Gofte, 1990
Larus occidentalis	Western gull	Davis, 1989
Synthliboramphus hypoleuca	Xantu murrelet	Davis, 1989
Ptychoramphus aleuticus	Cassin auklet	Davis, 1989
Haliaeetus leucocephalus	Bald eagle	Kiester and Eckhardt, 1994; USDA, 1996; Suring and Sidle, 1987
Harpia harpyja	Harpy eagle	Albuquerque, 1994
Aquila pomarna	Spotted eagle	Bharucha and Gofte, 1990
Circus cyaneus	Northern marsh harrier	Bharucha and Gofte, 1990
Accipiter gentilis	Northern goshawk	Suring and Sidle, 1987; Rissler, 1995; AFSEE, 1996
Pandio haliaetus	Osprey	Bharucha and Gofte, 1990; Suring and Sidle, 1987
Falco sparverius	American kestrel	Davis, 1989; Johnson-Duncan et al., 1986
Dendragapus obscurus	Blue grouse	Suring and Sidle, 1987;Kiester and Eckhardt, 1994
Strix occidentalis caurina	Northern spotted owl	Doak, 1989; Rissler, 1995 Foster, Thomas, Korth, Bowmer, 1995
Otus kennicotti	Western screech owl	Johnson-Duncan et al., 1986
Micrathene whitneyi	Elf owl	Johnson-Duncan et al., 1986
Glaucidium brasilianum	Ferruginous pygmy-owl	Johnson-Duncan et al., 1986
Aegolius funeleus	Boreal owl	Kiester and Eckhardt, 1994
Athene cunicularia	Burrowing owl	Johnson-Duncan et al., 1986
Chaetura vauxi	Vaux swift	Kiester and Eckhardt, 1994
Sphyrapicus ruber	Red-breasted sapsucker	Kiester and Eckhardt, 1994; USDA, 1996
Picoide villosus	Hairy woodpecker	Kiester and Eckhardt, 1994; USDA, 1996
Certhia americana	Brown creeper	Suring and Sidle, 1987; Kiester and Eckhardt, 1994; USDA, 1996
Ixoreus naevius	Varied thrush	Kiester and Eckhardt, 1994
Melospiza melodia	Song sparrow	Davis, 1989
Loxia sp.	Crossbill	Kiester and Eckhardt, 1994; USDA, 1996
Ursus americanus	Black bear	Suring and Sidle, 1987; Kiester and Eckhardt, 1994; USDA, 1996
Ursus arctos	Brown bear	Suring and Sidle, 1987; Kiester and Eckhardt, 1994; USDA, 1996
Canis lupus ligoni	Alexander archipelago wolf	Suring and Sidle, 1987; Kiester and Eckhardt, 1994; USDA, 1996
Martes americana	Marten	Suring and Sidle, 1987; Kiester and Eckhardt, 1994; USDA, 1996
Lutra canadensis	River otter	Suring and Sidle, 1987; Kiester and Eckhardt, 1994; USDA, 1996
Urocyon littoralis	Island fox	Davis, 1989
Zalophus californianus	California sea lion	Davis, 1989
Callorhinus ursinus	Northern fur seal	Davis, 1989
Phoca vitulina richardsi	Harbor seal	Davis, 1989
Pagophilus groenlandicus	Harp seal	Timoshenko, 1995
Mirounga angustirostris	Northern elephant seal	Davis, 1989
Tamiasciurus hudsonicus	Red squirrel	Suring and Sidle, 1987; Kiester and Eckhardt, 1994; USDA, 1996
Glaucomys sabrinus	Northern flying squirrel	Kiester and Eckhardt, 1994
Peromyscus maniculatus	Deer mouse	Davis, 1989
Odocoileus hemionus sitkansis	Sitka black-tailed deer	Suring and Sidle, 1987; Kiester and Eckhardt, 1994; USDA, 1996
Oreamnos americanus	Mountain goat	Suring and Sidle, 1987; Kiester and Eckhardt, 1994; USDA, 1996

[a] Additional sources were used to gather information on life history and conservation status, including Stebbins, 1962; Stebbins, 1985; Herald, 1972; Breen, 1974; Carlander, 1977; Burt and Grossenheider, 1980; Lee et al., 1980; Terres, 1980; Frost, 1985; Perrins and Middletin, 1985; Wheeler, 1985; National Geographic Society, 1987; Ehrlich et al., 1988; Capulo, 1989; Dubois, 1990; Parker, 1990; Sibley and Monroe, 1990; Nowak, 1991; del Hoyo et al., 1992; van Gelder, 1982; Witt, 1992; Frtjord, 1993; Weigant and Steinhaus, 1993; Brauning et al., 1994; Kostyushin, 1994; Maedlow and Mayer, 1996; Ogilvie, 1996; Ranner et al., 1995; Garrison et al., 1996; Rasmussen, 1996; Rodger, 1996; USFWS, 1996; WCMC, 1997.

Appendix B

Table B1
List of invertebrate indicator taxa reviewed

Suggested invertebrate taxa[a]		Reference
Oligochaeta: Lumbricus terrestris	Earth worm	Xiaoming and Grizelle, 1995
Bivalvia: Macoma balthica	Clam	Wilson, 1994
Amphipoda: Pontoporeia hoyi	Benthic anthropod	Ecosystem Objectives Committee, 1990
Araneae: Erigone dentipalpis	Spider	Pristavko and Zhukovets, 1988
Araneae: Oedothorax apicatus	Spider	Pristavko and Zhukovets, 1988
Araneae: Pachygnata degeeri	Spider	Pristavko and Zhukovets, 1988
Araneae: Xerolycosa miniata	Spider	Pristavko and Zhukovets, 1988
Araneae: Pardosa pullata	Spider	Pristavko and Zhukovets, 1988
Homoptera: Membracidae, Cercopidae	Tree hoppers, froghoppers, spittlebugs	Brown, 1991
Coleoptera: Carabidae, Cicindelidae, Elateridae, Cerambycidae	Of beetles	Brown, 1991
Coleoptera: Carabidae	Carabid beetles	Pizzolotto, 1994
Coleoptera: Cicindelidae	Tiger beetles	Pearson and Cassola, 1992
Diptera	Flies	Brown, 1991; Resh, 1995
Diptera: Chironomidae	Midges	Saether, 1979; Hannaford and Resh, 1995; Brown, 1991
Lepidoptera: Arctiidae	Tiger moths, footman moths	Brown, 1991
Lepidoptera: Bait-attracted Nymphalinae	Brush-footed butterflies	Brown, 1991
Lepidoptera: Heliconiini, Ithomiinae	Heliconine and ithomiine butterflies	Brown, 1991
Lepidoptera: Morphinae, Satyrinae	Morpho butterflies, wood nymphs, satyrs	Brown, 1991
Lepidoptera: Papilionidae, Pieridae	Swallow tails, whites, sulphurs orange-tips	Brown, 1991
Lepidoptera: Satyrinae: Henotesia	Satyrs, wood nymphs	Kremen, 1994
Lepidoptera: Sphingidae, Saturnoidae	Hawk and silk moths	Brown, 1991
Hymenoptera: Formicidae	Ants	Brown, 1991
Hymenoptera: Apoidea, Vespidae, Sphecidae	Bees, vespid and sphecid wasps	Brown, 1991
Hemip.: Coreidae, Pentatomidae, Cygaeidae, Tingidae, Myridae	True bugs	Brown, 1991
Collembola	Spring tails	Brown, 1991
Ephemeroptera	Mayflies	Eaton and Lenat, 1991; Resh, 1995
Ephemeroptera: Cinygmula	Mayfly	Jackson and Resh, 1988
Ephemeroptera: Hexagenia limbata	Burrowing mayfly	Brown, 1991
Isoptera	Termites	Brown, 1991
Odonata	Dragonflies, damsel fllies	Brown, 1991
Plecoptera	Stoneflies	Eaton and Lenat, 1991; Resh, 1995
Trichoptera	Caddisflies	Eaton and Lenat, 1991; Resh, 1995

[a] Additonal source were used to provide information life history and conservation status, including Borror et al., 1976; Merrit and Cummins, 1996; WCMC, 1997.

References

Adamus, P.R., 1995. Validating a habitat evaluation method for predicting avian richness. Wildlife Society Bulletin 23, 743–749.

AFSEEE (Association of Forest Service Employees for Environmental Ethics), 1996. Tongass in Transition: Blueprint for a Sustainable Future. The AFSEEE-Sponsored Alternative Plan for the Tongass National Forest in Southeast Alaska, AFSEEE, Eugene, OR.

Albuquerque, J.L.B., 1995. Observations of rare raptors in southern atlantic rainforest of Brazil. Journal Field Ecology 66, 363–369.

Anderson-Carnahan, L.S., Foster, M., Thomas-Korth, W., Bowmer, K.H., 1995. Selection of a suitable cladoceran species for toxicity testing in turbid waters. Australian Journal of Ecology 20, 28–33.

Bharucha, E.K., Gogte, P.P., 1990. Avian profile of a man-modified aquatic ecosystem in the backwaters of the Ujjani Dam. Bombay Natural Hist. Society 87, 73–87.

Biosis, 1997. Biosis Inc., Philadelphia, PA.

Blueweiss, L., Fox, H., Kudzma, V., Nakashima, D., Peters, R., Sams, S., 1978. Relationships between body size and some life history parameters. Oecologia 37, 257–272.

Borror, D.J., DeLong, D.M., Triplehorn, C.A., 1976. An Introduction to the Study of Insects, Holt, Rinehart and Winston, New York.

Bortone, S.A., Davis, W.P., 1994. Fish intersexuality as indicator of environmental stress. Bioscience 44, 165–172.

Brauning, D.W., Brittingham, M.C., Gorss, D.A., Leberman, R.C., Master, T.C., Muvihill, R.S., 1994. Pennsylvania's breeding birds of special concern: a listing rational and status update. Journal of the Pennsylvania Academy of Science 68, 3–28.

Breen, J.F., 1974. Encyclopedia of Reptiles and Amphibians. T.F.H. Publications, Neptune City, NJ.

Brown, K.S., 1991. Conservation of neotropical environments: insects as indicators. In: Collins, N.M., Thomas, J.A. (Eds.), The Conservation of Insects and their Habitats. Academic Press, London, pp. 349–404.

Burt, W.H., Grossenheider, R.P., 1980. A Field Guide to Mammals. (Peterson Field Guides). Houghton Mifflin Company, Boston, MA.

Callicott, J.B., Mumford, K., 1997. Ecological sustainability as a conservation concept. Conservation Biology 11, 32–40.

Capulo, M., 1989. Guide to Reptiles and Amphibians of the World, Simon and Schuster, New York.

Carlander, K.D., 1977. Handbook of Freshwater Fishery Biology, vols. 1–2. Iowa State University Press. Ames, IA

Cherel, Y., Weimerskirch, H., 1995. Seabirds as indicators of marine resources: black-browed albatrosses feeding on ommastrephid squids in Kerguelen waters. Marine Ecology Progress Series 129, 295–300.

Clark, T.W., Paquet, P.C., Curlee, A.P., 1996. Special section: large carnivore conservation in the Rocky Mountains of the United States and Canada. Conservation Biology 10, 936–939.

Croonquist, M.J., Brooks, R.P., 1991. Use of avian and mammalian guilds as indicators of cumulative impacts in riparian-wetland areas. Environmental Management 15, 701–714.

Davis, G.E., 1989. Design of a long-term ecological monitoring program for Channel Islands National Park, California. Natural Areas Journal 9, 80–89.

del Hoyo, J., Elliot, A., Sargatal, J. (Eds.), 1991. Handbook of the Birds of the World, vols. 1–3. Lynx Ediciones, Barcelona.

Dietz, J.M., Dietz, L.A., Nagagata, E.Y., 1994. The effective use of flagship species for conservation of biodiversity: the example of lion tamarins in Brazil. In: Olney, P.J.S., Mace, G.M., Feistner, A.T.C (Eds.), Creative Conservation: Interactive Managment of Wild and Captive Animals. Chapman and Hall, London, pp. 32–49.

Doak, D., 1989. Spotted owls and old growth logging in the Pacific Northwest. Conservation Biology 3, 389–396.

Dubois, P.J., 1990. Com homologation national list of rare birds in France 1989. Alauda 58, 245–266.

Eaton, L.E., Lenat, D.R., 1991. Comparison of a rapid bioassessment method with North Carolina's qualitative macroinvertebrate collection method. J. N. Am. Bentol. Soc 10, 335–338.

Ecosystem Objectives Committee, 1990. Final report of the Ecosystem Objectives Committee, March 1990. Report to the Great Lakes Science Advisory Board, Windsor, ON.

Ehrlich, P.R, Dobkin, D.S., Wheye, D., 1988. The Birder's Handbook: A Field Guide to the Natural History of North American Birds, Simon and Schuster, New York.

Faith, D.P., Walker, P.A., 1996. Environmental diversity: on the best-possible use of surrogate data for assessing the relative biodiversity of sets of areas. Biodiversity and Conservation 5, 399–415.

Fausch, K.D., Lyons, J., Karr, J.R., Angermeier, P.L., 1990. Fish communities as indicators of environmental degradation. In: Adama, S.M. (Ed.), Biological Indicators of Stress in Fish. American Fisheries Symposium 8, Bethesda, MD, pp 123-145.

Frost, D.R., 1985. Amphibian Species of the World: A Taxonomic and Geographical Reference. Allen Press/Association of Systematics Collections, Lawrence, KS.

Frtjord, K., 1993. Food Habits of Arctic foxes *Alopex lagopus* on the western coast of Suabard. Arctic 46, 49–54.

Garrison, B.A., Hunting, K.W., Sernka, K.J., 1996. Training Manual for the California Wildlife Habitat Relationships System, CWHR Database, ver. 5.2. California Interagency Wildlife Task Group/California Department of Fish and Game, Sacramento, CA

Hannaford, M.J., Resh, V.H., 1995. Variability in macroinvertebrate rapid-bioasessment surveys and habitat assessment in a northern California stream. J. N. Am Benthol. Soc. 14, 430–439.

Harris, J.H., 1995. The use of fish in ecological assessments. Australian Journal of Ecology 20, 65–80.

Hecnar, S.J., M'Closkey, R.T., 1996. Regional dynamics and the status of amphibians. Ecology 77, 2091–2097.

Hellawell, J.M., 1986. Biological Indicator of Freshwater Pollution and Environmental Management, Elsevier Applied Science Publishers, London.

Herald, E.S., 1972. Fishes of North America, Doubley and Company, New York.

Hocutt, C.H., 1981. Fish as indicators of biological integrity. Fisheries 6, 28–31.

Hourigan, T.F., Tricas, T.C., Reese, E.S., 1988. Coral reef fishes as indicators of environmental stress in coral reefs. In: Soule, D.F., Kleppel, G.S. (Eds.), Marine Organisms as Indicators. Springer-Verlag, New York, pp. 107–135.

Hughes, R.M., Whittier, T.R., Thiele, S.A., Pollard, J.E., Peck, D.V., Paulsen, S.G., Mcmullen, D., Lazorchak, J., Larsen, D.P., Kinney, W.L., Kaufmann, P.R., Hedtke, S, Dixit, S.S., Collins, G.B., Baker, J.R., 1992. Lake and stream indicators for the United States Environmental Protection Agency's environmental monitoring and assessment program. In: McKenzie, D.H., Hyatt, D.E., McDonald, V.J. (Eds.), Ecological Indicator, I. Elsevier Applied Science, London, pp. 305–335.

Hunter, M.L., Sulzer, A., 1996. Fundamentals of Conservation Biology, Blackwell Science, Cambridge.

Jackson, J.K., Resh, V.H., 1988. Sequential decision plans in monitoring benthic macroinvertebrates: cost savings, classification accuracy, and development of plans. Can. J. Fish. Aquat. Sci 45, 280–286.

Jamieson, D., 1995. Ecosystem health: some preventative medicine. Environmental Values 4, 333–344.

Johnson-Duncan, E.E., Duncan, D.K., Johnson, R.R., 1986. Small nesting raptors as indicators of change in the southwest desert. Proceeding of the Southwest Raptor Management Symposium and Workshop, 21–24 May 1986. National Wildlife Federation Scientific and Technical Series No. 11, University of Arizona, Tucson, AZ.

Johnson, R.K., Widerholm, T., Rosenberg, D.M., 1993. Freshwater biomonitoring using individual organisms, populations, and species assemblages of benthic macroinvertebrates. In: Rosenberg, D.M., Resh, V.H. (Eds.), Freshwater Biomonitoring and Benthic Macroinvertebrates. Chapman and Hall, New York, pp. 40–158.

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

Kelly, J.R., Harwell, M.A., 1990. Indicators of ecosystem recovery. Environmental Management 14, 527–545.

Kiester, A.R., Eckhardt, C., 1994. Review of Wildlife Management and Conservation Biology on the Tongass National Forest: A Synthesis with Recommendations. USDA, Forest Service, Pacific Northwest Research Station, Corvallis, OR.

Kolasa, J., Pickett, S.T.A., 1992. Ecosystem stress and health: an expansion of the conceptual basis. Journal of Aquatic Ecosystem Health 1, 7–13.

Kostyushin, V.A., 1994. New record of rare and protected bird species in Nikolaev Oblast. Vestink Zoologii 5, 47.

Kremen, C., 1994. Biological inventory using target taxa: a case study of the butterflies of Madagascar. Ecological Applications 4, 407–422.

Kremen, C., Colwell, R.K., Erwin, T.L., Murphy, D.D., Noss, R.F., Sanjayan, M.A., 1993. Terrestrial arthropod assemblages: their use in conservation planning. Conservation Biology 7, 796–808.

Kushlan, J.A., 1993. Colonial waterbirds as bioindicators of environmental change. Colonial Waterbirds 16, 223–251.

Lackey, R.T., 1995. Ecosystem health, biological diversity, and sustainable development: research that makes a difference. Renewable Resources Journal 13, 8–13.

Landres, P.B., Verner, J., Thomas, J.W., 1988. Critique of vertebrate indicator species. Conservation Biology 2, 316–328.

Lee, D.S., Gilbert, C.R., Hocult, C.H., Jenkins, P.E., McAllister, D.E., Stauffer, J.R., 1980. Atlas of North American Freshwater Fishes, Publication #1980-12 of the North Carolina Biological Survey, North Carolina State Museum of Natural History, NC.

Louette, M., Bijnenes, L., Agenenong'a, D.U., Fotso, R.C., 1995. The utility of birds as bioindicators: case studies in equatorial Africa. Beig. J. Zool 125, 157–165.

Maedlow, W., Mayr, C., 1996. Population trends of some scarce breeding birds in Germany 1990-1994. Vogelwelt 117, 249–260.

Maho, Y.L., Gendner, J.P., Challet, E., Bost, C.A., Gilles, J., Verdon, C., Plumere, C., Robin, J.P., Handrich, Y., 1993. Undisturbed breeding penguins as indicators of changes in marine resources. Marine Ecology Progress Series 95, 1–6.

Marshall, T.R., Ryder, R.A., Edwards, C.J., Spangler, G.R., 1987. Using the lake trout as an indicator of ecosystem health- application of the dichotomous key. Great Lakes Fishery Commission, Technical Report No. 49, Ann Arbor, MI.

Meffe, G.K., Carroll, C.R., 1997. Principles of Conservation Biology, 2nd Ed. Sinauer Associates Sunderland, MA.

Merenlender, A., Kremen, C., Rakotondratsima, M., Weiss, A., 1998. Monitoring impacts of natural resource extraction on lemurs of the Masoala Peninsula, Madagascar. Conservation Ecology [online] 12,www.consecol.org/vol2/iss2/art5

Merrit, R.W., Cummins, K.W., 1996. An Introduction to the Aquatic Insects of North America, 3rd ed. Kendall/Hunt, Dubuque, IA.

Miller, A.H., 1951. An analysis of the distribution of birds of California. University of California Publ. Zool 50, 531–644.

Morrison, M.L., 1986. Bird populations as indicators of environmental change. Current Ornithology 3, 429–451.

National Geographic Society, 1987. Field Guide to the Birds of North America, 2nd ed. The National Geographic Society, Washington, DC.

Noss, R.F., 1990. Indicators for monitoring biodiversity: a hierarchical approach. Conservation Biology 4, 355–364.

Nowak, R.M., 1991. Walker's Mammals of the World, 5th ed., vols. I–II. Johns Hopkins University Press, Baltimore, MD.

Nyholm, N.E., 1995. Monitoring of terrestrial environmental metal pollution by means of free- living insectivorous birds. Annali di Chimica 85, 343–351.

Ogilvie, M., 1996. Rare breeding birds in the United Kingdom in 1994. British Birds 89, 387–417.

Parker, S.P. (Ed.), 1990. Grizmek's Encyclopedia of Mammals. vols. 1 and 4. McGraw-Hill, New York.

Pearman, P.B., Guerrero, M., Sisk, T.D., Murphy, D.D., 1995. Correlation patterns among groups proposed as biological indicators: what do they indicate. Supplement to the Bulletin of the Ecological Society of America 76, 375.

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

Perrins, C.M., Middletin, A.L.A., 1985. The Encyclopedia of Birds, Equinox Ltd, New York.

Pizzolotto, R., 1994. Soil arthropods for faunal indices in assessing changes in natural value resulting from human disturbance.. In: Boyle, T.J.B., Boyle, C.E.B. (Eds.), Biodiversity, Temperate Ecosystems, and Global Change, NATO ASI Series, vol.20. Springer-Verlag, Berlin, pp. 291–313.

Pristavko, V.P., Zhukovets, E.M., 1988. Spiders (Araneida) as objects of ecological monitoring in the Berezinskiy Nature Reserve. Entomological Review 67, 26–32.

Quinn, T., 1997. Coyote (*Canis latrans*) food habits in three urban habitat types of western Washington. Northwest Science 71, 1–5.

Ranner, A., Laber, J., Berg, H.M., 1995. Record of rare and remarkable species in Australia 1980–1990. First report of the Avifaunistic Commission of Birdlife Australia. Egretta 38, 59–98.

Rapport, D.J., 1992. Evaluating ecosystem health. Journal of Aquatic Ecosystem Health 1, 15–24.

Rapport, D.J., 1995a. Ecosystem health: more than a metaphor. Environmental Values 4, 287–387.

Rapport, D.J., 1995b. Ecosystem health: an emerging integrative science. In: Rapport, D.J., Gaudet, C.L., Calow, P. (Eds.), Evaluating and Monitoring the Health of Large-Scale Ecosystems. Springer, New York, pp. 5–33.

Rasmussen, P.A.F., 1996. Rare birds in Denmark and Greenland in 1994. Dannsk Ornitologisk Forenigs Tids-Krift 90, 141–152.

Regier, H., 1990. Workgroup issue paper: indicators and assessment of the state of fisheries. Environmental Monitoring and Assessment 15, 289–294.

Resh, V.H., 1995. Freshwater benthic macroinvertebrates and rapid assessment procedures for water quality monitoring in developing and newly industrialized countries. In: Davis, W.S., Simon, T.P. (Eds.), Assessment and Criteria Tools for Water Resource Planning and Decision Making. Lewis, London, pp. 167–177.

Rissler, L.J., 1995. Resource partitioning of two indicator species (northern spotted owl and northern goshawk): analysis of forest structure. Bulletin of the Ecological Society of America 72, 227.

Rodger, J.A., 1996. Birds. In: Pritchard, P.C.H. (Ed.), Rare and Endangered Biota of Florida, vol. V. University Press of Florida, Gainesville, FL.

Rosenberg, D.M., Hanks, H.V., Lehmkuhl, D.M., 1986. Importance of insects in environmental impact assessment. Environmental Management 10, 773–783.

Saether, O.A., 1979. Chironomid communities as water quality indicators. Holarctic Ecology 2, 65–74.

Shaffer, M.L., 1981. Minimum population sizes for species conservation. Bioscience 31, 131–134.

Sibley, C.G., Monroe, B.L. Jr., 1990. Distribution and Taxonomy of Birds of the World, Yale University Press, New Haven, CT.

Simberloff, D., 1998. Flagships, umbrellas, and keystones: is single-species management passe in the landscape era. Biological Conservation 83, 247–257.

Soule, M.E., 1985. Biodiversity indicators in California: taking nature's temperature. California Agriculture 49, 40–44.

Spalding, M.G., Frederick, P.C., (1995). The everglades: what can indicator species tell us about ecosystem health? Proceedings: American Association of Zoo Veterinarians, 12–17 August, 1995. Wildlife Disease Association, American Association of Wildlife Veterinarians, Joint Conference.

Stebbins, R.C., 1962. Amphibians of Western North America. University of California Press, Berkeley, CA.

Stebbins, R.C., 1985. Western Reptiles and Amphibians, 2nd ed. Peterson Field Guides. Houghton Mifflin Company, Boston.

Suring, L.H., Sidle, W.B., 1987. Selection and use of management indicator species on national forests in Alaska. Proceedings of the Western Raptor Management Symposium and Workshop 26–28 October 1987. National Wildlife Federation Scientific and Technical Series No. 12, Boise, IN.

Taper, M.L., Bohning-Gaese, K., Brown, J.H., 1995. Individualistic responses of bird species to environmental change. Oecologia 101, 478–486.

Temple, S.A., Wiens, J.A., 1989. Bird populations and environmental changes: can birds be bio-indicators. American Birds 43, 260–270.

Terres, J.K., 1980. Encyclopedia of North American Birds, Alfred A Knopf, New York.

Timoshenko, Y.K., 1995. Harp seals as indicators of the Barents Sea ecosystem. In: Blix, A.S., Walloe, L., Ultang, O. (Eds.), Whales, Seals, Fish and Man; International Symposium on the Biology of Marine Mammals in North East Atlantic, Tromso, Norway, November 29–December 1, 1994. Elsevier Science, Amsterdam, pp. 509–523.

USDA 1996. Tongass Land Management Plan Revision. Final Environmental Impact Statement. Part 1: Summary, Chapters 1 and 2, and Chapter 3 (Physical and Biological Environment). United States Department of Agriculture, Forest Service R10-MB-338b, Juneau, AK.

USFWS 1996. Endangered and Threatened Wildlife and Plants 50 CFR 17.11 and 17.12. USFWS, Department of Interior, United States Government.

van Franeker, J.A., 1992. Top predators as indicator for ecosystem events in the confluence zone and marginal ice zone of the Weddell and Scotia seas, Antarctica, November 1988 to January 1989 (EPOS Leg 2). Polar Biology 12, 93–102.

van Gelder, R.G., 1982. Mammals of the National Parks, John Hopkins University Press, Baltimore, MD.

WCMC (World Conservation Monitoring Centre), 1997. Electronic Animals Database 1997. IUCN Red List of Threatened Animals. IUCN Species Survival Commission.
Weigant, W.M., Steinhaus, G.H., 1993. Commissie Dwaalgasten Nederlandse Avifauna. Rare and scarce birds in Netherlands in 1993. Limosa 69, 13–22.
Wheeler, A., 1985. The World Encyclopedia of Fishes, Macdonald Books, Great Britain.
Wicklum, D., Davies, R.W., 1995. Ecosystem health and integrity. Can. J. Bot. 73, 997–1000.
Wilcove, D.S., 1989. Protecting biodiversity in multiple-use lands: lessons from the US Forest Service. TREE 4, 385–388.
Wilson, J.G., 1994. The role of bioindicators in estuarine management. Estuaries 17, 94–101.
Witt, K., 1992. Population changes of some selected endangered breeding bird species of Western Germany 1977 to 1989. Vogelwelt 113, 289–310.
Xiaoming, Z., Grizelle, G., 1995. Earthworm as an indicator of changes in ecosystem processes in reforested tropical lands. Bulletin of the Ecological Society of America 76, 290.