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Review

How do ecologists select and use indicator species to monitor ecological change? Insights from 14 years of publication in *Ecological Indicators*

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ABSTRACT

Indicator species (IS) are used to monitor environmental changes, assess the efficacy of management, and provide warning signals for impending ecological shifts. Though widely adopted in recent years by ecologists, conservation biologists, and environmental practitioners, the use of IS has been criticized for several reasons, notably the lack of justification behind the choice of any given indicator. In this review, we assess how ecologists have selected, used, and evaluated the performance of the indicator species. We reviewed all articles published in *Ecological Indicators* (EI) between January 2001 and December 2014, focusing on the number of indicators used (one or more); common taxa employed; terminology, application, and rationale behind selection criteria; and performance assessment methods. Over the last 14 years, 1914 scientific papers were published in EI, describing studies conducted in 53 countries on six continents; of these, 817 (43%) used biological organisms as indicators. Terms used to describe organisms in IS research included "ecological index", "environmental index", "indicator species", "bioindicator", and "biomonitor," but these and other terms often were not clearly defined. Twenty percent of IS publications used only a single species as an indicator; the remainder used groups of species as indicators. Nearly 50% of the taxa used as indicators were animals, 70% of which were invertebrates. The most common applications behind the use of IS were to: monitor ecosystem or environmental health and integrity (42%); assess habitat restoration (18%); and assess effects of pollution and contamination (18%). Indicators were chosen most frequently based on previously cited research (40%), local abundance (5%), ecological significance and/or conservation status (13%), or a combination of two or more of these reasons (25%). Surprisingly, 17% of the reviewed papers cited no clear justification for their choice of indicator. The vast majority (99%) of publications used statistical methods to assess the performance of the selected indicators. This review not only improves our understanding of the current uses and applications of IS, but will also inform practitioners about how to better select and evaluate ecological indicators when conducting future IS research.

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1. Introduction

Many ecologists and environmental scientists are striving to find management solutions to urgent global environmental issues, including climatic change, habitat loss and fragmentation, pollution and contamination, disease outbreaks, and the spread of invasive species. Among many suggested strategies, one of the most popular has been to adopt monitoring techniques that can detect ecological changes both at an early stage and over the long term. Such *biological monitoring* allows for better-informed and more cost-effective management decisions (Landres et al., 1988; Spellerberg, 2005).

Indicator Species (IS) are living organisms that are easily monitored and whose status reflects or predicts the condition(s) of the environment where they are found (Landres et al., 1988; Cairns and Pratt, 1993; Bartell, 2006; Burger, 2006). The strategy of using IS is derived from the hypothesis that cumulative effects of environmental changes are integrated over, or reflected by, the current status or trends (short- or long-term patterns of change) in the diversity, abundance, reproductive success, or growth rate of one or more species living in that environment (Cairns and Pratt, 1993; Bartell, 2006; Burger, 2006).

Typically, the dynamics of a single population or a group of populations of one or more taxa are monitored as IS. Because the demographic parameters of a single population (e.g. abundance, density, age/size structure, reproduction rate and growth rate) are easy to measure and thought to be sensitive to environmental changes (e.g. drought), monitoring single population dynamics is considered to be a relatively cost-effective and reliable way to detect ecosystem change (Spellerberg, 2005). Identifying changes in IS also may reflect effects either of short-term severe stress events or of long-term changes, thus allowing scientists to react to unforeseen variation and to predict future conditions (Cairns and Pratt, 1993). These perceived advantages of IS not only have motivated the environmental research community to use them, but also have led to a large number of publications about IS in a range of technical journals (Burger, 2006). Further, as the use of IS has increased rapidly in recent decades, specialized journals focusing on IS have been established, including *Ecological Indicators* (est. 2001) and *Environmental Indicators* (formerly *Environmental Bioindicators*; est. 2005). This heightened focus is reflected in a recent survey by Borrett et al. (2014) of the most important ecological concepts and methods described in the literature, which listed the term "indicator organism" (or "indicator species") as among the top 15 concepts, a rapid increase relative to its 29th ranking in 1986 (Cherrett, 1989).

Despite the increasing popularity of using IS, several limitations of IS have been described (e.g. Lindenmayer et al., 2000; Lindenmayer and Fischer, 2003; U.S. EPA, 2008; Morrison, 2009; Lindenmayer and Likens, 2011). Primary limitations include: a single population rarely reflects the complexity of the environment; selection criteria for indicators are subjective; terminology is ambiguous (e.g. ecological indicator, indicator species, bioindicator, biomonitor); association between the indicator and the environmental contexts (i.e. monitoring goals) are vague; the influences of other biological interactions at the community level (e.g. predation/parasitism) often are ignored; methodological difficulties (e.g. indicator detectability, sampling protocols) may bias results; and finally the effects of future climatic changes on effectiveness of indicator species are unclear. Although these limitations have not slowed the increasing use of IS, research is needed to evaluate how ecologists and environmental scientists have employed them.

To help make progress toward the goal of developing a comprehensive understanding of the use of IS in their role as a tool for monitoring ecosystems, we reviewed all of the nearly 2000 papers published in *Ecological Indicators* between its founding in 2001 and the end of 2014. This focused review of the literature of this journal allowed us to narrow our scope to a single body of literature that focuses on the application of IS to monitoring and management that we could examine in detail. Our goal was to address the following questions:

- How many publications explicitly describe the use of IS, and how has this number changed through time?
- What determines terminology choice, and is terminology used in a manner consistent with accepted definitions (Box 1)?
- What are the motivations and criteria used to select indicators, and from which taxa are indicators most commonly selected?
- What are the varying methodologies by which IS are used?

Given the pressing need to monitor community and ecosystem dynamics, answering these questions will aid the development of effective tools for monitoring environmental change; therefore we end with a discussion of an updated protocol for selecting and using IS in ecological monitoring.

2. Methods

We reviewed and analyzed all 1914 articles published in *Ecological Indicators* between January 2001 and December 2014. This particular journal was chosen for three reasons. First, it is specialized in scope, with an exclusive concentration on the ecological and environmental indicators that are the focus of the current study. Second, the journal is representative of IS research; it has published ~30% of all articles published in the ecological literature that address indicator species (Borrett et al., 2014), and that cover ecological applications including biodiversity and population dynamics, ecological integrity, environmental disturbances, risk assessment, and ecosystem restoration. Third, the journal has existed for 14 years, a timescale we believe is both short enough to reflect current trends in the use of IS, while also long enough to allow for assessment of trends in the usage of the IS concept.

We conducted the literature analysis in two phases. First, we conducted a *preliminary survey* of 40 randomly selected articles to establish analytical questions and a corresponding coding system to classify IS use, and to test the validity of the coding system and troubleshoot analysis techniques (Box 2). Then, we performed the