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A probability-based indicator of ecological condition

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Abstract

We introduce a new method for quantifying the ecological condition (C) of sites based on documented species' responses to environmental stress. Preliminary research is needed to establish species-specific logistic functions, representing probabilities of finding individual species across an explicit reference gradient, ranging from maximally stressed ($C = 0$) to minimally stressed ($C = 10$) localities. Each function takes into account the species' tolerance to stress, the species' overall ubiquity, and the probability of detecting the species when it is present. Given a set of standardized species-specific functions, the ecological condition of any site can be derived by iteration, converging on the value of C that best "predicts" the species that are actually present. Species from multiple taxonomic groups can be included in the calculations, and results are not directly affected by species richness or sampling area. We demonstrate a successful application of this method for bird species assemblages in the U.S. portion of the Great Lakes coastal zone. Approximately, 28% of the bird species observed in the Eastern Deciduous Forest Ecological Province and 35% of the species in the Laurentian Mixed Forest Ecological Province showed strong relationships with a reference gradient of land cover variables. Functional stress–response relationships of these species can be used effectively to estimate ecological condition at new sites. The estimated condition based on bird species generally mirrors the reference condition, but deviations from the expected 1:1 relationship provide meaningful insights about ecological condition of the target areas. Sensitivity analysis using different numbers of species shows that our method is robust and can be applied consistently with 25–30 species exhibiting strong stress–response functions.

Keywords: Indicator method; Environmental stress; Great Lakes; Landscape; Bird; Probability model

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1. Introduction

The use of biological assemblages as indicators of ecological condition has followed a long tradition (Niemi and McDonald, 2004). In most applications,

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species or taxa are assigned weights reflecting their sensitivity to environmental degradation. Presence/absence or abundance of these species, alone or in some combination with other species, provides an indicator of a site's ecological condition. The saprobien system of Kolkwitz and Marsson (1908), for example, introduced the use of weighted abundances of benthic invertebrates as an index of water quality. Related measures such as the Hilsenhoff Index for stream invertebrates (Hilsenhoff, 1982) and Floristic Quality Index (Wilhelm and Ladd, 1988) are widely used today to characterize the condition of local ecosystems. Karr's Index of Biotic Integrity (IBI) addresses functional aspects of ecosystems and incorporates a range of ecological variables besides the presence/absence or abundance of indicator species (Karr, 1981). This approach has been applied effectively to many environments and taxonomic groups during the past two decades (Karr et al., 1987; Miller et al., 1988; Lyons et al., 1995; O'Connell et al., 1998; Harris and Silviera, 1999; Yoder and Rankin, 1995 and others). An implicit feature of the IBI approach is the assignment of quantitative weightings (e.g., 1,3,5) that reflect ecologically meaningful deviations from a reference condition. These weightings are at least partly subjective because the variables and scores come largely from expert opinion and the scale of comparison for a given IBI may be complicated or inflated if the biological variables are correlated. Alternatively, multivariate approaches have been developed by Armitage et al. (1987), O'Connor et al. (2000), Marchant and Hehir (2002), Clarke et al. (2003), and others. These statistical methods tend to be data intensive but require fewer subjective decisions than in the IBI approach. River Invertebrate Prediction and Classification System (RIVPACS), one of the most successful multivariate approaches to indicator development (Wright, 2000), has influenced formulation of the European Union's Water Framework Directive (European Commission, 2000).

Indicators of ecological condition are useful because they provide objective benchmarks for detecting environmental change, they create targets for management activities, and they can be used as standards for environmental regulations. Indicators based on biological communities have several important advantages over measurements of physical variables (Yoder and Rankin, 1998; Karr and Chu, 1999; Karr and Rossano, 2001). First, living organisms experience the entire range and variation of environmental conditions through time, whereas physical or chemical measures are often highly variable snapshot measurements that can easily misrepresent the true nature of conditions. Second, species integrate the effects of multiple stressors, including those whose mechanisms or even existence might be poorly known. Finally, responses of animal species are directly relevant to humans because they reflect many of the same physiological and ecological needs that affect our health.

Although community metrics such as species richness and diversity are often used as biological indicators (Niemi and McDonald, 2004), such measures can be misleading if species respond differently to stress. Some species may become more abundant with increased stress while other species may become less abundant. A more accurate and robust indicator of condition should account for these differences. Here, we introduce a new, probabilistic approach to the development of ecological indicators that incorporates clearly documented information about species' sensitivities or tolerances to environmental stress. Condition is determined by the stress–response relationships of observed species; sites inhabited mainly by sensitive species yield high values of condition, whereas sites inhabited mainly by tolerant species will yield low values. Like the method of O'Connor et al. (2000), the indicator that we describe can include multiple taxonomic groups and, like the RIVPACS approach (Wright, 2000), it relates observed species presences to expected probabilities of presence. Our approach is unique in its probabilistic method of calculation and its ability to take into account both the ecological sensitivity of species as well as the detectability of species given a prescribed sampling method.

Our quantitative concept of "ecological condition" folds anthropogenic stressors into a single gradient. We define the optimal condition for a geographic region as having a value of 10 and the maximally degraded condition a value of 0. Field data of observed species presences or frequencies (probabilities of detection) are used to estimate ecological condition according to an iterative approach described by Hilborn and Mangel (1997).

A critical assumption of this approach is that species respond (in various ways) to a common gradient of ecological condition. Specifically, a reference gradient must be defined *a priori* in order to quantify parameters