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An advanced Index of Biotic Integrity for use in tropical shallow lowland streams in Costa Rica: Fish assemblages as indicators of stream ecosystem health

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ABSTRACT

This paper presents an advanced version of the Index of Biotic Integrity (IBI), a multimetric index to indicate ecosystem health. The multimetric index has been adapted in such a way that it not only indicates overall condition but also specific causes of environmental disturbance. The newly developed index (a) uses data of tolerant as well as intolerant species in a single metric to indicate environmental disturbance, (b) does not require knowledge about species from the literature, and (c) can be applied to artificial landscapes.

The metrics proposed here consist of indicator species assemblages that are selected directly for their relationship with an environmental component or specific type of environmental degradation. Thus, each metric indicates a type of environmental concern, which enables conservation practices to be targeted more effectively. Species assemblages for each single metric consist of a combination of species that can be negatively and positively related to environmental disturbances, providing a better indication of stream ecosystem health.

The area studied was assumed to be too diverse for one single index. Canonical Indirect-Gradient Principal Component Analysis indicated that the optimal division of subindices based on stream typology was for streams with drainage basin sizes <10 km^2 and >10 km^2. Pearson Product-Moment Correlations were used to identify relationships between anthropogenic disturbances and the composition and abundance of fish species at impacted as well as undisturbed sites. This index proved to be useful for indicating overall stream ecosystem health as well as local onsite environmental disturbances or the environmental components of greatest concern. This index does require extensive information about measured levels of anthropogenic disturbances with the accompanying composition and abundance of fish species.

1. Introduction

Anthropogenic impacts on streams and rivers are increasing worldwide (Nel et al., 2008; Strayer and Dudgeon, 2010). One method to monitor the effects of such impacts is the Index of Biotic Integrity (IBI), a method first introduced by Karr (1981) that is implemented internationally, predominantly in the temperate zone (Belpaire et al., 2000; Aparicio et al., 2011; Ruaro and Guniani, 2013). The IBI is a multimetric index, meaning it uses several metrics or formulas to establish stream ecosystem health. The IBI became the inspiration for several other multimetric indices that all use biological communities to provide an indication of environmental quality. Using biological communities is very effective because they reflect environmental disturbances as they are in direct contact with the environment (Karr and Chu, 1997). Unlike chemical tests, biological communities also reflect indirect effects of disturbances, of which some mechanisms are still not fully understood.

Multimetric indices consist of several equations, called metrics, that calculate the health status of an ecosystem based on groups of indicator species. Existing metrics from earlier indices are usually the base of new indices. The metrics are altered on the basis of expert judgment before they are accepted or rejected based on

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their functioning (Karr, 1981; Karr and Chu, 1997). Whether a metric functions well depends on its ability to identify a relationship between anthropogenic impact and biotic assemblages. Conventionally, these fish assemblages are defined by either taxonomic group, trophic guild, overall species diversity, or total abundance (Karr, 1981). The life history of individual species is often not considered in these conventional metrics, and actual forms of disturbance are unquantified and may remain unknown. The quality of the metrics depends largely on information from the literature about the relationship between fish species and general environmental degradation, information which is not always available, especially in the tropics (Ramirez et al., 2008).

Multimetric indices also require the use of reference sites, which should theoretically be pristine, undisturbed nature, to allow comparisons with the stream quality at test sites (Karr and Chu, 1997). In practice, however, it is often impossible to find true reference sites (Whittier et al., 2007). One reason for this is that research is often conducted at spatio-temporal scales which are too small to include enough reference sites (Fausch et al., 2002).

Earlier versions of an IBI for the streams of southeastern lowland Costa Rica (Mafla and McLarney, 2006) based on an extensive long-term data set proved to be useful to indicate stream ecosystem health. The developers were, however, unable to successfully implement conventional metrics (Karr, 1981) defined by species richness, total abundance, taxonomic group or trophic guild. Metrics were instead composed of species or species assemblages that were tolerant or intolerant to particular environmental components. The metrics were derived by expert judgment from direct field observations and improved by trial and error adjustments, substituting species until best results were accomplished.

The interest in the specific area partly arose because it is a relatively undeveloped (Data source: INEC) and therefore natural area, which has not yet been thoroughly studied. Possible development of hydroelectric dams in the area currently forms a direct threat as it may impede the hydrologic connectivity (McLarney and Mafla, 2010), indicating a need for ecological monitoring. Other major anthropogenic threats in the area are predominantly caused by deforestation, sedimentation and eutrophication related to human settlement and channelization of rivers for the sake of agriculture (Lorion and Kennedy, 2009).

According to Fausch et al. (2002), research to support the conservation of fish in streams should be based on long-term continuous data sets which include the spatially heterogeneous extent of the entire river environment. However, such data sets do not yet exist for Central American streams (Lyons et al., 1995). Drainage basins may also have become altered to such a degree that no more reference sites are left (Bennion and Battarbee, 2007), thus requiring new monitoring approaches (Moss et al., 2003). Carignan and Villard (2002) suggested the use of species assemblages, consisting of various taxonomic groups and life histories, to improve the functionality of indicator species. They also suggested that species closely associated with particular habitat features can be useful indicators.

Karr (1981) already mentioned that each fish species has characteristic tolerances to environmental disturbance, and suggested that his original IBI could be improved. We propose a method which determines fish assemblages that directly indicate and quantify specific forms of environmental disturbance. This new methodology to derive metrics is based on specific indicator groups that are directly based on their tolerance and/or intolerance to measured levels of anthropogenically induced disturbances. This enables the metrics to indicate stream ecosystem health, as well as to quantify specific types of environmental degradation. This more systematic approach to deriving metrics requires less prior knowledge about the life histories of species. Comprehensive information about different levels of anthropogenic degradation over the entire environmental gradient was used to evaluate test sites. This included information from undisturbed, pristine sites, as well as the response of species over a gradient of anthropogenic disturbances at impacted sites. The underlying biological mechanisms of the relations between the species and disturbances are not discussed in the present paper, partly to emphasize its purely methodological approach.

This paper presents a way to develop metrics that quantify specific environmental disturbances and are not based on literature data. We used Mafla and McLarney's extensive long-term Costa Rican dataset on species composition and abundance with accompanying information on environmental disturbance to create a multimetric index. The index is composed of fish assemblages and was developed particularly for the shallow streams of southeastern lowland Costa Rica. Fish are used because they are easy to identify in the field and demonstrate a variety of trophic levels and feeding guilds. Environmental disturbance was predominantly visually determined. However, depending on data availability, the methodology can also be applied if information can be obtained on other forms of disturbance, such as chemical pollution or invasive species, even if only based on literature data. The focus of this paper is the attempt to improve the functionality of multimetric indices by using functional indicator species.

In summary, the paper deals with (a) a new methodology to derive metrics which indicate specific onsite anthropogenic causes of disturbance and can be applied in artificial environments, (b) a fish-based Index of Biotic Integrity for shallow streams of southeastern lowland Costa Rica.

2. Methods

2.1. Study area

Southeastern Costa Rica is a tropical area with high average temperatures of 20–30 °C (Data source: WMO) and high rainfall of approximately 2500 mm year^{-1} (Data source: WorldClim). Most of the rain falls between November and January, while February to April and August to September tend to be drier (Lorion and Kennedy, 2009). The sites we studied are situated at elevations of up to 200 m above sea level. Water temperatures measured during site visits ranged from 31 °C at unshaded sites at lower elevation to 20 °C at elevated shaded sites. Agricultural land use within the research area is concentrated in the floodplains. The main types are industrial type monocropping of bananas and plantains. The main types of land use in sloping areas consist of timber harvesting, pasture and mixed cacao-based agroforestry on private farms (Schipper, 2010).

The study area consists of three large drainage basins, Rio Estrella, Hone Creek, and Rio Sixaola (Fig. 1). The western and eastern borders of the study area are formed by La Amistad National Park and the Caribbean Sea. The northern and southern borders are formed by the Rio Estrella watershed and the Panamanian border, respectively, although some sites in the Rio Sixaola drainage basin lie just across the border in Panama.

2.2. Sampling methods

2.2.1. Fish abundance and diversity

Only wadable parts of the three rivers were sampled as, except for Hone Creek, the main stream river channels were too deep to allow effective sampling with the available equipment. Coastal areas were excluded to minimize influences of salinity and associated marine species. Information was gathered on fish species composition and abundance during 151 visits, spread over 98 individual sites (Fig. 1). Some sites were sampled multiple