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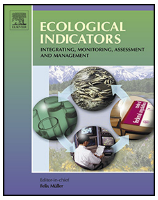

Development of a benthic macroinvertebrate multimetric index (MMI) for Neotropical Savanna headwater streams

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ABSTRACT

Assessing the ecological impacts of anthropogenic pressures is a key task in environmental management. Multimetric indices (MMIs), based on aquatic assemblage responses to anthropogenic pressures, have been used increasingly throughout the world. The MMI approach is a low-cost, rapid field method that produces an aquatic condition index that responds precisely to anthropogenic pressures, making it useful for conservation and environmental management. We developed four candidate MMIs based on benthic macroinvertebrate assemblages sampled at 40 randomly selected sites to assess the environmental condition of streams upstream of a hydroelectric power plant in the Brazilian Neotropical Savanna biome. Those MMIs were built from landscape-adjusted and unadjusted biological metrics as well as two alternative ways of choosing metrics. The alternative MMIs performances were tested by comparing their precision to distinguish least-disturbed areas, responsiveness to discriminate least- and most-disturbed areas, and sensitivity to anthropogenic pressures at catchment and local scales. The best performing MMI had landscape-adjusted metrics and was produced through use of principal component analysis for metric selection. It included 4 metrics: Ephemeroptera richness, average tolerance score per taxon, percentage of predator individuals, and percentage of Odonata individuals adjusted by elevation. This index discriminated well the anthropogenic pressures at local- and catchment-scales, and at both scales simultaneously, as indicated by an integrated disturbance index. Our methodological development included statistical criteria for identifying least- and most-disturbed sites, calibrating for natural landscape variability, and use of non-redundant metrics. Therefore, we expect it will provide a model for environmental assessment of water resources elsewhere in Brazil and in other nations.

1. Introduction

Aquatic ecosystems around the world have been highly altered by anthropogenic pressures, inducing alterations in energy and matter flows that compromise biotic viability (Hughes and Noss, 1992; Karr, 1998, 1999; Davies and Jackson, 2006). Several studies have shown that catchment-level anthropogenic pressures are reflected in local physical habitat simplification, water pollution, and degraded aquatic assemblage condition (Wang et al., 1997; Allan, 2004; Hughes et al., 2010). Multimetric indices (MMIs), built from multiple biological assemblage attributes, are very useful for evaluating anthropogenic pressures. The multimetric approach integrates responses of several assemblage components (e.g., richness, composition, trophic guilds, dominance) related to impacts caused by anthropogenic pressures in a simple, but accurate manner (Hughes et al., 1998; Karr, 1998; Hering et al., 2006; Stoddard et al., 2008; Ferreira et al., 2011; Helson and Williams, 2013). Furthermore, MMIs show an integrated response of multiple anthropogenic pressures at both catchment and site scales, and thereby avoid equivocal responses of single biological, physical or chemical measurements (Karr, 1999).

The index of biotic integrity (IBI) was the first MMI developed to evaluate biological responses to anthropogenic pressures for fish assemblages (Karr, 1998). Since then it has been applied

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successfully to benthic macroinvertebrate assemblages worldwide (e.g., Hering et al., 2006; Stoddard et al., 2008; Moya et al., 2011; Chen et al., 2014). MMIs are very useful ecological indices that are easily interpretable and rapidly developed (Karr, 1998). When correctly developed, the MMI approach is more cost effective than purely physical and chemical water monitoring (Hughes and Noss, 1992).

However, covariance of anthropogenic pressures with natural environmental gradients can confound our efforts to discern biologic responses to anthropogenic pressures (Klemm et al., 2003; Moya et al., 2011; Feld et al., 2016). To counteract the effects of this covariance, researchers model the influence of natural landscape variables on biological metrics by regressing potential controls (e.g., drainage area, slope, elevation and precipitation) against those metrics. The regression residuals are extracted to produce adjusted metric scores (e.g., Cao et al., 2007; Stoddard et al., 2008; Moya et al., 2011; Chen et al., 2014).

Another critical point in MMI development is the process for selecting among highly correlated metrics to avoid redundancy (Cao et al., 2007; Stoddard et al., 2008). Multivariate analysis has been found capable of revealing complex data structure and removing redundant metrics in a quantitative, non-subjective manner (O'Connor et al., 2000; Cao et al., 2007; Van Sickle, 2010). Principle Components Analysis (PCA) is a useful approach for selecting metrics wherein patterns of covariation and independent variation are identified to reduce the dimensions of the assemblage space and then the metric that is most strongly correlated with each significant PCA axis is selected for use in the index (O'Connor et al., 2000). For example, O'Connor et al. (2000) used PCA to select metrics for several lake assemblages (birds, fish, macroinvertebrates, zooplankton, diatoms).

Macroinvertebrate-based MMIs have been applied widely in developed countries since the 1980s (Ruaro and Gubiani, 2013). However, in neotropical biomes the number of applications has increased markedly in only the last 5 years in the Amazon Rainforest (e.g., Couceiro et al., 2012; Dedieu et al., 2015a), in the Atlantic Rainforest (Oliveira et al., 2011; Suriano et al., 2011), in the Tropical Andes (Moya et al., 2011; Villamarín et al., 2013), and in the Caribbean and Central America Rain Forest (Helson and Williams, 2013; Touron-Poncet et al., 2014). The Neotropical Savanna is the one of the largest neotropical biomes (Wantzen et al., 2006), a global biodiversity hotspot (Myers et al., 2000), and rapidly being deforested by anthropogenic activities (Ratter et al., 1997; Silva et al., 2006; Wantzen et al., 2006). However, few MMIs have been developed there (e.g., Ferreira et al., 2011), reinforcing the need for new studies. In addition, most neotropical MMIs were based on relatively few and convenient ad hoc sites, no landscape-corrected metrics, insufficient numbers of least-disturbed reference sites, metric selection to represent specific categories (e.g., richness, composition, behavior, tolerance, dominance), and inadequate quantitative assessments of chemical and physical habitat and biological conditions of the sites.

Our objective was to evaluate the biological condition of headwater streams in the Neotropical Savanna through use of randomized site selection, a standardized field protocol for sampling physical and chemical habitat and macroinvertebrates, and an MMI based on benthic macroinvertebrate assemblages. Empirical evidence suggests that gradients of anthropogenic pressure influence overall stream environmental condition, and in turn affect biotic condition. However, landscape factors that influence streams also co-vary with anthropogenic stressors. We therefore propose two methodological approaches based on two premises: (1) an MMI based on landscape-adjusted metrics will perform better than one based on unadjusted metrics; (2) metric selection based on significant PCA axes will produce a more sensitive MMI than one constructed in the more traditional manner of selecting metrics to fit specific categories.

2. Materials and methods

2.1. Study area

We conducted this study in the Upper Araguari Basin (located in the Neotropical Savanna biome and part of the Paraná River Basin) in Minas Gerais State, southern Brazil, in September 2009, during the dry season (Fig. 1). The sampled area was delimited around 7376 km^2 upstream of Nova Ponte Reservoir, the first of a sequence of hydroelectric reservoirs along the Paraná River system. There is a six-month dry season (April to September) followed by a six-month rainy season (October to March). The landscape consists of relatively flat, well-drained interfluves, with riparian forests along watercourses. Upland vegetation is typical xerophytic savanna, ranging from dense herbaceous fields, sparse shrubs and small tree cover, to occasional forests with 12–15 m high canopies (Ratter et al., 1997).

2.2. Site selection

We selected a spatially balanced sample of 40 sites using a randomized systematic procedure described by Olsen and Peck (2008) in the U.S. EPA Wadeable Stream Assessment. The spatially balanced selection algorithm was based on a Generalized Random Tessellation Stratified process (Stevens and Olsen, 2004). We targeted wadeable streams by excluding all tributaries of Strahler order >3 on a digital map (1:100,000 scale).

2.3. Data collection

2.3.1. Natural catchment-scale variables

We delineated catchments of each sampled site through use of the terrain model from Shuttle Radar Topographic Mission – SRTM (3 arc seconds; USGS, 2005). Their contributing drainage areas were calculated via GIS software. Mean catchment elevation was extracted directly from SRTM imagery, whereas mean catchment slope was calculated from the maximum rate of change in elevation in every grid cell, based on SRTM elevation rasters. Catchment total annual rainfall was calculated through use of time series data from the Brazilian National Water Agency (ANA, 2014) obtained at 14 stations within our study area. Each station had total annual rainfall records of >30 years, and those data were interpolated through use of ordinary kriging (Johnston et al., 2001). Then, the overlapping grid cell values (30 m raster resolution) of mean annual rainfall were transferred to each catchment.

2.3.2. Catchment-scale anthropogenic pressure variables

We assessed catchment land use and land cover for each site by screening digitized satellite images. We manually interpreted fine resolution (0.6–5.0 m) Google Earth images (Google, 2014) in conjunction with the September 2009 Landsat TM sensor, as described by Macedo et al. (2014). The fine resolution images provided information about the shape and texture of the elements, and the Landsat images showed specific spectral response for each land use or vegetation cover type. Our mapping identified three anthropogenic land uses (pasture, agriculture, urban) and four natural savanna cover types (woodland savanna, parkland savanna, grassy-woody savanna, wetland palm swamp). The catchment percentages of each land use and cover type were estimated for each site because preliminary analyses showed stronger correlations occurred between site conditions and catchment conditions than for riparian buffers of varying widths and distances from the sites.