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A fish-based multimetric index for Brazilian savanna streams

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ABSTRACT

Multimetric indices (MMI) have been widely used to assess ecosystem conditions because they are low-cost, employ a rapid field method, and can incorporate various biological metrics at different levels of biological organization. Our objective was to create a fish-based multimetric index applicable to all streams of the Brazilian savanna biome (Cerrado), the second largest biome in Brazil and deemed a global biodiversity hotspot. We evaluated 156 sites in two river basins (Paraná and São Francisco) and selected metrics capable of distinguishing stream-sites across a gradient of anthropogenic disturbances. We employed two different MMI approaches to determine if an MMI based on natural variation-adjusted metrics performed better than one based on unadjusted metrics. In addition, we assessed the performance of the two final MMIs and their sensitivity to anthropogenic pressures at local (LDI), catchment (CDI) and both scales integrated (IDI). Finally, we employed the power of a probability sample survey design to infer headwater stream conditions across a hydrologic region of approximately 47,000 km^2. Our final MMI for Brazilian savanna streams included six metrics: % common species; % characiform individuals; % loricariid individuals; % trichomycterid individuals; % invertivore species, and % *Poecilia reticulata* individuals. MMI_1 (unadjusted metrics) performed better than MMI_2 (natural variation-adjusted metrics) in discriminating least- and most-disturbed sites, but MMI_2 distinguished intermediate from most-disturbed sites better than MMI_1. Both indices were negatively correlated with the CDI scores; however, only MMI_2 was negatively correlated with the IDI scores. We inferred that 709 km (9.35%) of streams in the studied hydrologic region were in good condition, 8115 km (82.73%) were intermediate, and 641 km (7.91%) were in poor condition. We conclude that the MMIs proposed in this study have great potential for widespread application because they integrate data from two of the most important Brazilian river basins included in a biome that represents more than 20% of the country. Furthermore, the metrics retained in the indexes are easy to access with a rapid low-cost field method. However, their feasibility in areas influenced by mining, as well as in different biomes, should be tested.

1. Introduction

Streams are extremely complex and susceptible to human activities occurring both in riparian zones and elsewhere in the catchment (Allan, 2004; Stanfield and Kilgour, 2013; Leal et al., 2016). Anthropogenic changes in stream physical conditions have been strongly associated with changes in stream fish assemblages (Allard et al., 2015; Teresa et al., 2015; dos Santos et al., 2015), which have been used for over 100 years to assess ecosystem conditions (Simon, 1999). For instance, Karr (1981) proposed a fish-assemblage-based multimetric index (MMI) for midwestern USA streams over 25 years ago. Since then, fish MMIs have been widely used to measure the biological condition of temperate freshwater streams (Pont et al., 2006; Pont et al., 2009; Whittier et al., 2007), rivers (Mebane et al., 2003; Pont et al., 2006; Zhu and Chang, 2008), lakes (Lyons et al., 2000; Drake and Valley, 2005; Launois et al., 2011), and estuaries (Deegan et al., 1997).

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MMIs employ quantitative measures to assess environmental conditions and they can incorporate ecological information at the individual, population, and assemblage level (Karr et al., 1986) through various biological metrics (e.g. richness, abundance, trophic guilds) (Fausch et al., 1990) at different spatial scales (McCormick et al., 2001; USEPA, 2006; Pont et al., 2007). Besides, MMIs can incorporate chemical and physical gradients from landscapes and land use (Oberdorff et al., 2002). Thus, multiple metrics are combined into a single index to reduce the variability inherent with single variable indicators (Hughes et al., 1998). A major difficulty in MMI metric selection and scoring is to discriminate differences between co-varying natural gradients and anthropogenic pressures (Moya et al., 2011). Fish assemblages are limited and structured by many natural variables such as catchment area, elevation, and channel slope (Hughes et al., 2006; Pont et al., 2009) and these natural variations must be considered to decrease risk of inference errors (Chen et al., 2014). To do so, metric scores are adjusted by regression modeling (Cao et al., 2007; Stoddard et al., 2008; Moya et al., 2011).

In Brazil, fish-based MMI's have been developed previously for streams but for relatively small regions or considering a single river basin (Bozzetti and Schulz, 2004; Ferreira and Casatti, 2006; Casatti et al., 2009; Terra et al., 2013). The development of indexes to assess the biotic integrity of Brazilian streams is important because they remain poorly studied (Reis et al., 2016), but under increasing pressure from anthropogenic activities such as agriculture expansion (DeFries and Rosenzweig, 2010; Leal et al., 2016). Despite strong evidence about the relevance of including biotic indicators of integrity for a comprehensive assessment of freshwater ecosystem condition (Casatti et al., 2006; Karr, 1981), this is rarely the case with environmental regulations in Brazil, where legal instruments have a narrow representation of freshwater courses overall. Streams and rivers are monitored in terms of water quality variables considered important for human consumption (Brasil, 1997). Other regulations focus on aquaculture and fishing activities (Brasil, 2009), or consider that the preservation of the riparian vegetation in private lands is sufficient to safeguard aquatic biodiversity and provide other ecosystem services (Brasil, 2012). The development of a suitable MMI protocol would be an important tool for monitoring and managing these aquatic ecosystems in a cost-effective manner (Hughes and Noss, 1992).

The Brazilian savanna biome (also known as Cerrado) is a global biodiversity hotspot that is, exceptionally rich in endemic species yet highly threatened and overexploited (Myers et al., 2000). In the last decades, agriculture expansion in the biome has occurred faster than ecological studies can unveil its consequences to freshwater systems. Thus, the development of a management tool that can be used to assess the condition of freshwater systems over a vast spatial scale is very relevant for conservation planning initiatives. Therefore our objectives were to (i) develop a MMI applicable to all streams of the Brazilian savanna biome, (ii) employ two different MMI approaches to determine if an index based on natural variation-adjusted metrics performed better than one based on unadjusted metrics, (iii) assess the performance of the two final MMIs in a set of validation sites, and (iv) use that MMI to infer the condition of all streams in the hydrologic units sampled. To do so we evaluated streams in two major river basins and selected fish metrics capable of distinguishing stream-sites across a gradient of anthropogenic disturbances. In addition, we employed the power of a probability sample survey design (Olsen and Peck, 2008) to infer headwater stream conditions across a hydrologic region of approximately 47,000 km^2.

2. Materials and methods

2.1. Study area

We studied 156 sites in 1st to 3rd order (map scale 1:100,000; Strahler, 1957) streams in the Paraná (117 sites) and São Francisco (39 sites) River Basins, Minas Gerais, southeastern Brazil (Fig. 1, Table A1). We selected the sites according to the methodology proposed by Olsen and Peck (2008), in which sites are located by a spatially balanced and size-stratified random selection algorithm (Macedo et al., 2014). The São Francisco River has a basin size of 665,000 km^2 and flows north and east from our sites; it is the largest river entirely in Brazil and occupies about 8% of the country area. The Paraná River has a basin area of 2,300,000 km^2 and flows west and south from our sites; it is the second largest river in South America and drains much of southern Brazil, Paraguay, northern Argentina, and a portion of Bolivia (Welcomme, 1985).

All sites were located in the Brazilian savanna (Cerrado) biome, the second largest biome in the neotropics and Brazil, covering over 20% of the country (Wantzen et al., 2006). The Brazilian savanna is second only to the Atlantic Forest biome in terms of devegetation in Brazil (Wantzen et al., 2006), and its major rivers (Paraná, São Francisco, Tocantins) are extensively dammed (ANEEL, 2012). This biome is characterized by two distinct seasons: a wet season from October to March and a dry season from April to September. Mean annual temperatures range from 21 to 27 °C and mean annual precipitation ranges from 1200 to 1800 mm.

2.2. Fish sampling

We sampled sites in September of 2010, 2011, 2012 and 2013. Each site was sampled for 40 times its mean width, with a minimum length of 150 m (Kaufmann et al., 1999; Hughes and Peck, 2008). Two people sampled fish for two hours mainly using semicircular hand nets (80 cm diameter, 1 mm mesh) and seines when possible (4 m long, 2 m high, 5 mm mesh). All catches were made during daylight hours. Specimens were killed in an anesthetic solution of eugenol and then fixed in 10% formalin. In the laboratory, all sampled fishes were washed in water, transferred to 70% alcohol, and identified to species. Voucher specimens of all species are deposited in the fish collection of the Federal University of Lavras (Coleção de Ictiologia da UFLA, CIUFLA).

2.3. Natural control variables

Catchment area, altitude, and slope were used as natural control variables and were calculated according to Macedo et al. (2016). Catchment limits upstream of each stream-site were obtained through use of the terrain model from Shuttle Radar Topographic Mission (3 arc seconds; USGS, 2005) and used to calculate catchment area via GIS software. Mean altitude was extracted directly from SRTM imagery, and mean catchment slope was calculated from the maximum rate of change in elevation in every grid cell, based on SRTM elevation rasters (Macedo et al., 2016).

2.4. Anthropogenic pressure measurements

We followed the methodology proposed by Ligeiro et al. (2013) to account for a wide range of anthropogenic pressures to streams sites. Therefore, we measured human activities at local (LDI – Local Disturbance Index) and catchment (CDI – Catchment Disturbance Index) scales, and analysed both scales together in an Integrated Disturbance Index (IDI). The LDI was represented by an index of