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Mayfly bioindicator thresholds for several anthropogenic disturbances in neotropical savanna streams

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ABSTRACT

Anthropogenic disturbances are widely recognized as major threats to terrestrial and aquatic biodiversity worldwide, including areas located in non-forest ecosystems. Headwater streams in the neotropical savanna are severely threatened by large-scale landscape changes that degrade local habitat characteristics and lead to biodiversity loss. The objective of our study was to evaluate Ephemeroptera assemblages as bioindicators of catchment land use and cover, local streambed and riparian vegetation conditions, and instream water quality. To do so, we sampled mayfly nymphs in 184 stream sites across a broad disturbance gradient in four hydrologic units of the Brazilian neotropical savanna. We selected seven metrics without significant co-variation with natural variability: % catchment urban, riparian vegetation condition index (RCOND), human disturbances of the stream channel and riparian zone (W1_HALL), substrate mean embeddedness (XEMBED), dissolved oxygen (mg L^{-1}), pH, and total phosphorus (mg L^{-1}). We ran threshold indicator taxa analysis (TITAN) for each disturbance metric to detect change points in mayfly genera responses (whether sensitive or tolerant) and assemblage turnover pattern. TITAN showed that 20 of the 39 genera found were robust bioindicators (based on purity and reliability values >0.95), sixteen of them being sensitive to increased disturbance. The most sensitive genera were *Tricorythopsis* (Leptohyphidae) and *Camelobaetidius* (Baetidae), showing decreased abundance to most disturbance metrics. We found a turnover pattern of mayfly genera in response to W1_HALL in a narrow variation range. For total phosphorus, the benchmark value defined in Brazilian Federal Legislation is higher than the turnover threshold of several mayfly genera. This indicates that we will lose many sensitive genera even within the limits imposed by national environmental legislation. The indicator taxa approach, based on multiple taxa rather than univariate metrics or single indicator species, demonstrates the value of quantitative ecological information for conserving and managing freshwater ecosystems globally.

1. Introduction

Freshwater ecosystems in good ecological status are indispensable for providing high-quality water supplies for humans and for biodiversity maintenance and conservation (Vörösmarty et al., 2010). Rivers and streams achieve those conditions only if their channels, upstream reaches, riparian vegetation and catchments are in good ecological status (Dudgeon et al., 2006). Increased human developments have largely modified the natural condition of freshwater ecosystems, leading to reduced ecological function and biodiversity (Steffen et al., 2015). Such human-induced ecosystem changes are observed at multiple spatial scales (global, regional, local), constituting a complex and interconnected feedback system (Rockström et al., 2009). For instance, land uses affect geomorphological processes, causing many impacts to stream channels such as channel incision (Beschta et al., 2013), bottom siltation, decreased substrate and flow diversities (Allan, 2004), diminished litter input from riparian vegetation (Boyero et al.,

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2016), and degraded water quality (Taylor et al., 2014; Woodward et al., 2012).

Headwater streams are the smaller riverine sections (Strahler, 1957), comprising around 80% of the cumulative stream length in watersheds (Benda et al., 2005). Considering their contribution to river basins and their high degree of exposure to anthropogenic disturbances, it is important to protect them (Dudgeon et al., 2006). Varying levels of anthropogenic disturbances generate disturbance gradients, yielding streams ranging from nearly pristine to severely disturbed (Davies and Jackson, 2006). The local stream biota are a result of natural environmental drivers (Feld et al., 2016), but a wide range of anthropogenic disturbances also influence their structure (Stoddard et al., 2006). To develop reliable bioindicators, it is necessary to separate the effects of natural variability from anthropogenic disturbance on assemblage structure (Chen et al., 2014; Hughes and Peck, 2008).

Assemblage turnover is observed in response to disturbance gradients, wherein the abundance and/or frequency of taxa increase or decrease abruptly at some threshold point of the gradient (King and Baker, 2014). Baker and King (2010) proposed the threshold indicator taxa analysis (TITAN), which detects points of change in environmental gradients where assemblage response becomes most evident. This allows direct inference from the data and concrete actions to minimize impacts or propose rehabilitation strategies (King et al., 2011). Different studies have demonstrated threshold responses of stream assemblages to various anthropogenic disturbances, considering them as direct cause-and-effect relationships. For instance, assemblage composition change has been related to sedimentation (Burdon et al., 2013), urbanization (King et al., 2011), and natural vegetation suppression (Rodrigues et al., 2016). However, it is necessary to demonstrate how different anthropogenic disturbances alter stream biota by selecting disturbance metrics that are weakly related to natural variability (Shimano and Juen, 2016; Stoddard et al., 2008).

Much attention has been given to conserving and restoring tropical forests, but not much attention has been given to neotropical savannas (Overbeck et al., 2015; Veldman et al., 2015). The Brazilian neotropical savanna is the source of several important large rivers in South America (Wantzen et al., 2006), and their headwaters encompass high levels of biodiversity (Agostinho et al., 2005). However, agriculture, livestock grazing and urbanization are major threats to the biological integrity of this biome (Carvalho et al., 2009; Macedo et al., 2014; Silva et al., 2006). Likewise, hydropower dams and water supply reservoirs create major barriers to dispersal of native species (Agostinho et al., 2005).

Biological assessments are recommended for developing effective stream and catchment conservation and management (Hughes et al., 1986; Stoddard et al., 2008). Benthic macroinvertebrates have been widely recognized for their ability to detect impacts on freshwater ecosystems because of their sensitivity to multiple anthropogenic disturbances (Bonada et al., 2006). When natural environments are altered, sensitive taxa are lost and those that are tolerant prevail, producing assemblage turnover (Davies and Jackson, 2006; King and Baker, 2014). Mayfly nymphs are considered good bioindicators because they are highly diverse, abundant in streams in good ecological condition (Bauernfeind and Moog, 2000; Dedieu et al., 2015), represent multiple trophic levels (Brittain, 1982), and are relatively easy to identify to genus (Domínguez et al., 2006).

Our objective in this study was to evaluate the effects of anthropogenic disturbances on neotropical savanna streams based on thresholds of mayfly assemblage responses. Specifically, we sought to find disturbance metrics that most altered mayfly assemblages. The stream sites represented multiple land use and cover types, streambed and riparian vegetation condition levels, and instream water quality covering a wide disturbance gradient. We classified the mayfly genera by their sensitivity or tolerance based on their threshold responses for each disturbance metric as well as the overall assemblage turnover. Such information can contribute to the conservation of stream integrity and watershed management by identifying critical disturbance thresholds based on reliable bioindicators, as well as for determining priorities for biodiversity conservation and ecosystem restoration.

2. Material and methods

2.1. Study area

We conducted our study in 184 wadeable stream sites (1st-3rd order sensu Strahler, 1957; defined at a 1:100,000 scale), averaging 3.4 m (±1.9) wide, and 35.5 cm (±17.1) deep in the states of Minas Gerais, Goiás, and São Paulo, southeastern Brazil. The sites were located in four hydrologic units (Seaber et al., 1987) of the upper São Francisco and Paraná River Basins (Fig. 1), comprising a total geographic area of 45,180 km^2. Nova Ponte, Três Marias, Volta Grande, and São Simão hydrologic units were defined as the contributing drainage areas within 35 km upstream of each of four major hydropower reservoirs. The Nova Ponte hydrologic unit also included a set of 25 handpicked reference sites. The sites were far enough upstream of the reservoirs to be unaffected by variable water levels in the reservoirs.

We sampled in September from 2010 to 2013, one year for each aforementioned hydrologic unit, ensuring that samples were standardized by the low flow season. Dry season sampling facilitates data collection and reduces the effect of freshets, thereby clarifying the effects of the disturbance gradient on mayfly assemblages (Hughes and Peck, 2008). We believe that rainfall differences between the sampling years did not prevent the comparability of data because the average annual precipitation in the four hydrological units were comparable (2010: 958 mm, 2011: 968 mm, 2012: 1155 mm, 2013: 1171 mm) and within the normal climatological average for the neotropical savanna (ANA, 2016). In each hydrologic unit, small and medium-size cities (up to 80,000 inhabitants) occurred and the main land uses were irrigated agriculture (soy, coffee, corn, and sugarcane) and livestock grazing (hereafter pasture) (Ligeiro et al., 2013; Macedo et al., 2014).

2.2. Survey design

Selection of sites employed a spatially balanced probabilistic survey (Stevens and Olsen, 2004), used by the U.S. Environmental Protection Agency (US-EPA) in its regional and national biomonitoring programs (Olsen and Peck, 2008). To ensure that the disturbance gradient would be well represented, in each hydrological unit we also handpicked least- and most- disturbed sites to sample. Other studies have demonstrated the effectiveness of spatially balanced methods together with targeted sampling for strengthening disturbance gradients (Bryce et al., 2010; Ligeiro et al., 2013; Smucker et al., 2013). Least-disturbed sites included 25 sites located in Serra da Canastra National Park and Serra do Salitre region in the Paraná River Basin (Nova Ponte hydrologic unit), considered *a priori* as least-disturbed sites (Hughes et al., 1986; Stoddard et al., 2006). We assumed their good ecological condition based on the effectiveness of national parks in protecting ecosystems, Google Earth® images of the area showing landscape conditions, and field reconnaissance. Most-disturbed sites included a set of 23 urban sites ranging from 0.2% to 85% of catchment urban land use.