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Chronic urbanization decreases macroinvertebrate resilience to natural disturbances in neotropical streams

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ABSTRACT

Natural disturbances play important roles in the functioning and structure of lotic ecosystems, especially in small streams. Adaptation to natural disturbances, in the form of resilience, can be affected by anthropogenic disturbances such as urbanization and industrial zones, which in turn can limit stream biodiversity. The aim of this study was to assess the effects of runoff from urban and industrial zones on the resilience of benthic macroinvertebrate assemblages in small streams. For that, we tested the hypothesis that benthic macroinvertebrate assemblages in streams affected by urbanization and industrialization have lower resilience to natural disturbances than those in reference areas. We calculated the recovery proportions of Taxa Richness, Taxa Abundance, Resistant Taxa Richness, Resistant Taxa Abundance, Sensitive Taxa Richness and Sensitive Taxa Abundance. Recovery proportions of freshwater biodiversity were calculated as the target variable values during the dry season divided by the same variable in the previous rainy season. Taxa Richness recovery proportion and Sensitive Taxa Richness recovery proportion were significantly higher ($p < 0.01$) in the reference sites. Resistant Taxa Richness and Sensitive Taxa Abundance followed the same pattern but were less significant ($p < 0.1$). These results indicate that streams draining urban and industrial areas have significantly lower resilience to natural disturbances than their counterparts in reference areas. Our results also suggest that both landscape and local environmental conditions play important roles in maintaining naturally resilient lotic ecosystems and biodiversity in the neotropics.

1. Introduction

Natural disturbances play important roles in the ecology of streams and other ecosystems (Platt and Connell, 2003; Poff, 1992; Reice et al., 1990). Major natural events, such as flash floods, wildfire and drought, tend to get considerable attention in the scientific literature (Agostinho et al., 2009; Datry et al., 2016; Dodds et al., 1996). However, smaller and more predictable natural disturbances, such as freshets and seasons, have a pivotal role in shaping lotic ecosystem processes and structure, determining crucial characteristics such as resilience (Biggs et al., 2005; Linares et al., 2013; Müller et al., 2016).

Resilience is a measure of the capacity of an ecological system to recover to a relatively steady state following a disturbance, a proxy for the system's overall dynamic stability (Müller et al., 2016; Reice et al., 1990; Steinman et al., 1991). Lotic ecosystems are characterized by their high taxa turnover rates, and therefore resilience is essential for maintaining their biodiversity (Dole-Olivier et al., 1997; Johnstone et al., 2016; Müller et al., 2016). With seasonal disturbance being an important factor in the structuring and functioning of lotic ecosystems, biological community resilience can serve as an indicator of the degree to which anthropogenic disturbances are likely to affect ecosystems (Dudgeon et al., 2006; Jaiswal and Pandey, 2021).

Urbanization is closely linked to increased watershed imperviousness, which alters the hydrology and changes the frequency and strength

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of flow events as well as streambed shape and substrate. Typically, channels are piped, covered by roads, and their riparian vegetation is removed or minimized, leading to higher water temperatures (Paul and Meyer, 2008). Residential and industrial runoff increase the concentration of nutrients, sediments, pesticides, pharmaceuticals, metals, and polycyclic aromatic hydrocarbons (Foster et al., 2014; Gál et al., 2019). Such anthropogenic modifications at both local and regional spatial extents have dramatic effects on the structure and functioning of lotic ecosystems, often drastically decreasing their biodiversity, simplifying their food webs, and shortening their energetic pathways (Kovalenko et al., 2014; Wiederkehr et al., 2020). Together, these markedly altered physical, chemical and biological conditions have come to be called the "urban stream syndrome" (Walsh et al., 2005).

Anthropogenic disturbances can also have substantial effects on the resilience of lotic ecosystems (Foster et al., 2003). In the neotropics, most resilience studies have focused on the effects of agricultural land use, riparian zone stressors, eutrophication or chemical spills (e.g., Chen and Olden, 2020; Datry et al., 2016; Firmiano et al., 2021; Callisto et al., 2021). This creates a knowledge gap regarding the effects of diffuse, chronic urban- and industrial-generated stressors on neotropical lotic ecosystem resilience, despite the high levels of urbanization and the growth of urban areas in Latin America (Rodgers et al., 2011).

Therefore, the aim of this study was to assess the effects of urbanization and industrialization on the resilience of benthic macroinvertebrate assemblages in low-order neotropical stream sites assessed over multiple years and seasons. We hypothesized that benthic macroinvertebrate assemblages in urban and industrial sites would have lower resilience to natural disturbance than those in upstream reference sites. We predicted that the urban and industrial sites would have significantly lower total taxa richness and abundance and sensitive taxa richness and abundance than those in the reference sites.

2. Methodology

2.1. Study area

We sampled two sites in each of two headwater streams located in the municipality of Ouro Branco, Minas Gerais, southeastern Brazil (Fig. 1). The streams are located at the southern end of the Espinhaço Range, in a transitional area between the Cerrado and Atlantic Forest biomes. The Köppen climate type is mesothermic (Cwb), with dry winters and wet summers (20.7 °C average annual temperature, 1200 mm average annual precipitation).

The sites were located at a mean altitude of 900 m and all sites were shaded (>90%) by riparian vegetation. These sites were chosen because our reference sites (G1 and G3) were located upstream of an urban and industrial area and had over 90% natural vegetation cover in their catchments and no direct human stressors. The two test sites (G2 and G4) were located downstream of that complex, with 43.33% and 17.30% of their catchments, respectively, occupied by urban areas and an industrial plant (Fig. 1), ideal conditions to test our hypothesis. Site G2 received treated steel mill wastewater plus occasional urban runoff, primary-treated Ouro Branco sewage, and occasional raw sewage from a broken pipe. Site G4 received only primary-treated steel mill wastewater. All sites had uniform sandy substrates, showing little variation from site to site.

To characterize the physico-chemical environment we measured water mean depth (m), velocity (m/s), water temperature (°C), pH, conductivity (μS/cm), total dissolved solids (ppm) and turbidity (NTU) during each sampling visit in both the dry and wet seasons, for a total of nine visits in the rainy season (2007–2015) and nine visits during dry season (2007–2015). We measured these metrics through use of a multimeter (YSI Multiprobe). The sampling occurred from March 2007 to September 2015, with wet season sampling in March (end of the wet season) and dry season samplings in September (end of the dry season), (Table 1; Supplementary Material S1 for the raw data).

2.2. Benthic macroinvertebrate sampling

We also collected benthic macroinvertebrates during each visit in both the dry and wet seasons, for a total of 64 samples. During each sampling visit, we took three Surber samples (30 × 30 cm, 250 μm mesh) in each site. In the laboratory, we placed the samples in a sorting tray. The tray contents (water and substrate) were then drained through a sieve (250 μm mesh), and all benthic macroinvertebrates were removed with forceps and placed into glass vials, containing 70% ethanol for later identification. The three samples taken from each site during each visit were combined into a single composite sample for subsequent data

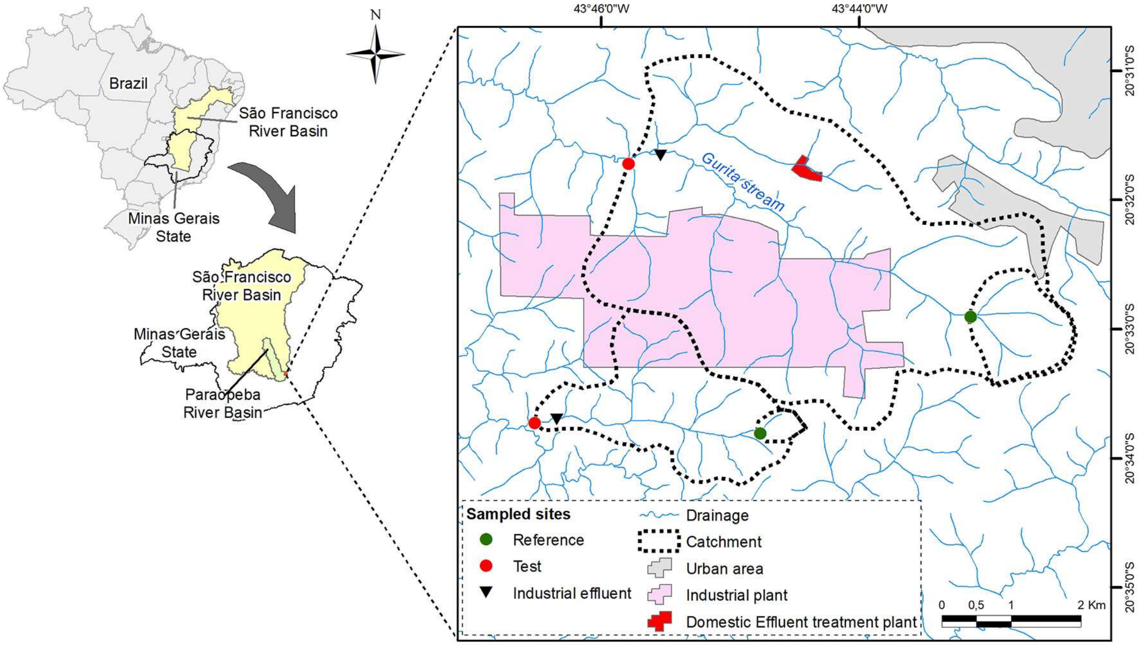

Fig. 1. Sampling site locations and catchment land uses.

Table 1
Mean values of the measured physico-chemical enviromental habitat variables in the stream sites for rainy and dry seasons during the sampling period. Values in brackets indicate minimum and maximal measured values.

	G1		G2		G3		G4	
	Rainy	Dry	Rainy	Dry	Rainy	Dry	Rainy	Dry
Mean Depth (m)	0.25 (0.02–0.4)	0.23 (0.14–0.53)	0.12 (0.01–0.23)	0.16 (0.1–0.21)	0.15 (0.08–0.50)	0.19 (0.04–0.6)	0.19 (0.01–0.5)	0.14 (0.08–0.24)
Water Flow (m/s)	0.22 (0–0.47)	0.12 (0–0.27)	0.47 (0.26–0.70)	0.62 (0.44–0.82)	0.37 (0.06–0.67)	0.31 (0.04–0.76)	0.56 (0.02–0.96)	0.50 (0.18–0.96)
Water Temperature (°C)	22.37 (19.5–27)	19.38 (16–21.6)	26.71 (20.7–31.2)	25.59 (23.9–27.7)	22.46 (20.11–26.5)	20.78 (16–24.9)	21.79 (19.5–26.5)	19.94 (14.5–24.9)
pH	7.01 (6.09–8.91)	6.90 (6.08–8.07)	9.33 (7.66–10.48)	8.31 (7.45–9.01)	7.01 (4.48–8.09)	7.56 (6.3–8.03)	7.51 (6.82–8.01)	7.48 (7.05–7.77)
Conductivity (μS/cm)	86.85 (36.7–223)	46.8 (28.6–72.1)	503.12 (95–853)	787.28 (421–1245)	107.62 (22.9–154.1)	154.48 (108.2–311)	283.69 (54.1–481)	371.48 (2.3–667)
Total Solids (ppm)	55.50 (2.47–149.6)	20.61 (6.65–51.5)	288.32 (322–434)	368.71 (190–667)	62.99 (20.8–88.5)	74.07 (28.9–132.5)	175.54 (72.7–301)	204.02 (96.7–489)
Turbidity(NTU)	23.83 (0.11–108)	18.53 (5.04–71)	33.12 (11.47–100)	63.92 (21.8–140)	21.14 (1.14–149)	2.42 (0.67–5.39)	20.92 (2.91–110)	22.83 (3.63–105)

analyses. Individuals were identified to family-level under a stereomicroscope through use of taxonomic keys (Costa et al., 2006; Mugnai et al., 2010). Macroinvertebrate family-level identification is considered an efficient, easy-to-use, reliable rapid assessment method for monitoring tropical streams that have high organism diversity (Godoy et al., 2019; Ligeiro et al., 2020; Silva et al., 2016).

2.3. Data analyses

Seasonal variation can cause significant differences in stream physical habitat structure and water quality. Therefore, we ran a one-way analysis of variance followed by a post-hoc Tukey honest test to evaluate significant difference to determine the degree that the measured environmental variables varied between reference and urban sites and between seasons (Supplementary Material S2). We found little seasonal variation, but significant differences between reference and urban and industrial sites for several key variables (Table 1).

To assess the resilience of the benthic macroinvertebrate assemblages, we calculated the recovery proportions of Taxa Richness, Taxa Abundance, Resistant Taxa Richness and Abundance, and Sensitive Taxa Richness and Abundance. Resistant and Sensitive taxa were based on Junqueira et al. (2000) (Supplementary Material S3). Recovery proportions were calculated using the following formula:

$$^{VD}/_{VR}$$

where ***VD*** is target variable (Taxa Richness, Taxa Abundance, Resistant Taxa Richness, Resistant Taxa Abundance, Sensitive Taxa Richness, Sensitive Taxa Abundance) values during the dry season, and ***VR*** is the same variable value in the previous rainy season.

To determine the degree to which benthic macroinvertebrate assemblages in urbanized sites had lower resilience to natural disturbance than those in reference sites, we tested the difference between the values of the recovery proportions of Taxa Richness, Taxa Abundance, Resistant Taxa Richness, Resistant Taxa Abundance, Sensitive Taxa Richness and Sensitive Taxa Abundance calculated for the reference sites (Sampling Sites G1 and G3) versus the urban/industrial sites (Sampling Sites G2 and G4). To do so, we used a Generalized Linear Model (GLM) with a Gaussian error structure. The model significance was tested by an Analysis of Deviance (F test). All analyses were conducted by using R software (R Core Team, 2015).

3. Results

We collected a total of 16,980 individuals belonging to 44 taxa, 12,127 of which were Chironomidae (Supplementary Material S4). Regarding the recovery proportions (Fig. 2), Taxa Richness was significantly higher ($p = 0.006$; F = 8.524) in the reference sites (Mean 1.56; SE ± 0.17) than in the urban/industrial sites (Mean 0.91; SE ± 0.14). Sensitive Taxa Richness was also significantly higher ($p = 0.005$; F = 9.0631) in the reference sites (Mean 0.72; SE ± 0.23) than in the urban/industrial sites (Mean 0.00; SE ± 0.01). The recovery proportion of Resistant Taxa Richness followed the same pattern but was less significant ($p = 0.084$; F = 3.1557), with higher values for the reference sites (Mean 1.56; SE ± 0.16) than the urban/industrial sites (Mean 1.15; SE ± 1.69). The same happened for Sensitive Taxa Abundance ($p = 0.067$; F = 3.5916) with higher values for the reference sites (Mean 1.81; SE ± 0.96) than the urban/industrial sites (Mean 0.00; SE ± 0.01). Resistant Taxa Abundance had higher values for the reference sites (Mean 6.12; SE ± 1.86) than the urban/industrial sites (Mean 5.87; SE ± 3.02), but was not significantly different ($p = 0.857$; F = 0.0331). Total Abundance, on the other hand, was higher in the urban/industrial sites (Mean 5.04; SE ± 2.25) than in the reference sites (Mean 4.70; SE ± 1.29), but also did not differ significantly ($p = 0.896$; F = 0.0172).

4. Discussion

Our hypothesis, that benthic macroinvertebrate assemblages in sites affected by urbanization and industrialization have lower resilience to natural disturbance than those in reference sites, was corroborated. Taxa Richness recovery proportion and Sensitive Taxa Richness recovery proportion were significantly higher ($p < 0.01$) in the reference sites. Resistant Taxa Richness and Sensitive Taxa Abundance followed the same pattern but were less significant ($p < 0.1$). Total Abundance and Resistant Taxa Abundance failed to show significant results because of outliers. Presumably, this is because those two measures of abundance are subject to much greater natural variability, making them poor variables for biomonitoring (Stoddard et al., 2008; Silva et al., 2017).

The significant effect on richness recovery highlights the importance of environmental quality of terrestrial ecosystems for maintaining lotic ecosystem biodiversity. Most benthic macroinvertebrate taxa depend on their adult terrestrial forms for dispersion and maintenance in a habitat, which makes them vulnerable to alterations in catchment and local land use and environmental conditions (Firmiano et al., 2020, 2021). Because of the high taxa turnover rates that characterize most benthic macroinvertebrate assemblages (Datry et al., 2016; Libório and Tanaka, 2016), disruptions or increased difficulties with dispersion can significantly decrease local diversity and act as additional environmental filters (Compin and Céréghino, 2007; Galeti et al., 2020).

Altered local environmental conditions in or near sampling sites can also explain their lower resilience, because local refuges are important factors in the resilience of lotic ecosystems (Ding et al., 2017; Platt and Connell, 2003). Our results suggest that the urban and industrial stressors in the impacted sites act as selective environmental filters,

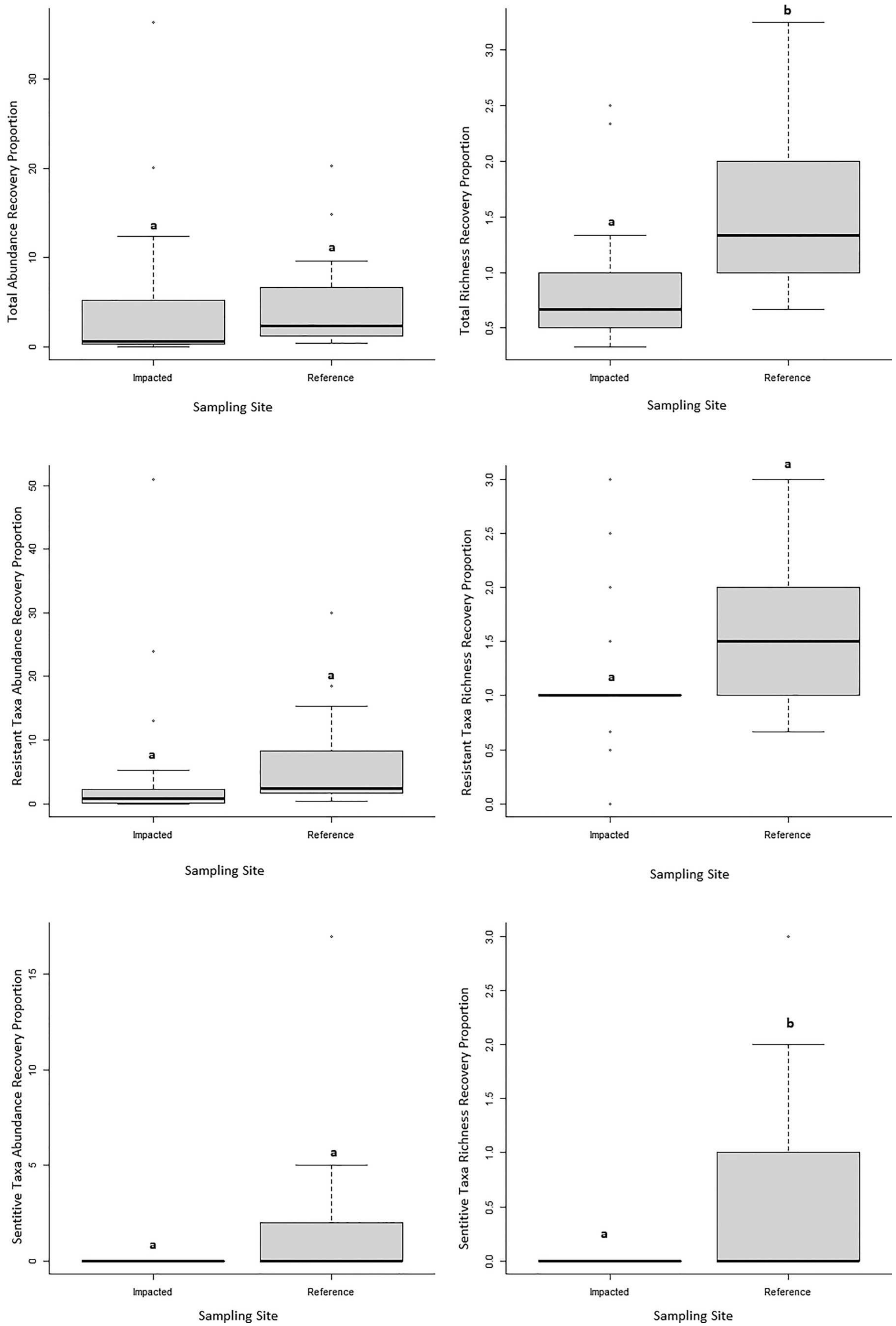

Fig. 2. Taxa Richness, Total Macroinvertebrate Abundance, Resistant Taxa Richness, Resistant Taxa Abundance, Sensitive Taxa Richness and Sensitive Taxa Abundance recovery proportions for Impacted and Reference sites. Bold horizontal lines = medians; boxes = 25th and 75th percentiles; vertical lines = ranges; circles = outliers. Different letters designate statistically significant difference.

reducing local biodiversity (Castro et al., 2018; Rahel, 2002). This process, which mainly affects rare sensitive taxa, can result in the extirpation of many species and possible biodiversity collapse in biomes such as the Atlantic Forest and the Neotropical Savanna, both biomes characterized by high endemism (Santos et al., 2019; Strassburg et al., 2017). Our results suggest that even relatively low-level stressors can cause significant losses in lotic ecosystem biodiversity, by eliminating rare sensitive species and accelerating the processes of biological homogenization (Su et al., 2021).

Our results show that diffuse industrial and urban stressors at the catchment extent had a significant impact on the resilience of benthic macroinvertebrate assemblages in our sites, decreasing their resilience to natural disturbances when compared to the reference sites. But we recognize the statistical limitations of a four-site study design, including the increased probability of both Type-1 and Type-2 statistical errors, as well as the limited spatial extent of our study. Indeed, we believe that future studies should incorporate many more test and reference sites (ideally 40 each; Olsen and Peck, 2008) and the application of these methods in other neotropical regions to test the universality of these results.

5. Conclusions

Our results show that urbanization and industrialization have significant effects in lotic ecosystem biodiversity, indicating that low order streams in urban and industrial areas have significantly lower resilience to natural seasonal disturbances than their counterparts in reference areas. In addition, this study shows the value of conducting field research over multiple years and seasons. Our results also suggest that both catchment and local environmental conditions play important roles in maintaining the natural resilience of lotic ecosystems. Finally, our study indicates the importance of understanding the negative effects of urbanization and industrialization on biodiversity resilience based on inventories of taxa presence and abundances.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crsust.2021.100095.

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