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Environmental gradients as filters on the composition of aquatic insect of the Cerrado-Caatinga, Brazil

Carolina Gomes Viana, Ingrid Reis Campos, Guilherme Santana Lustosa, Daniel Silas Veras

[a] *Instituto Federal de Educação, Ciência e Tecnologia do Maranhão, Caxias, 65609-899, Maranhão, Brasil.*
**carolina.viana@acad.ifma.edu.br*

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Abstract

The patterns of aquatic insect diversity are influenced by landscape structure and environmental gradients that can be altered significantly through changes in land use. The aim of the present study was to verify if the patterns of diversity of the orders Odonata and Trichoptera vary significantly between preserved and altered sites, along a gradient of environmental impact. Data were collected on the structural and environmental characteristics of the stream, and the assemblages of aquatic insects at seven sampling points in a Cerrado-Caatinga ecotone of northeastern Brazil, in the dry seasons of 2018 and 2019. The results indicated that altered streams had higher electrical conductivity and lowest HII (habitat integrity index) values in comparison with the preserved ones, being determinant in the distribution of genera, and low pH values increased genera richness, informations that can guide management strategies for biodiversity conservation. Which supports the conclusion that the diversity of aquatic insects is determined by the influence of environmental filters in the streams.

Keywords: Heterogeneity, Odonata, stream ecology, Trichoptera.

Gradientes ambientais como filtros na composição de insetos aquáticos do Cerrado-Caatinga, Brasil

Resumo

Os padrões de diversidade de insetos aquáticos são influenciados pela estrutura da paisagem e gradientes ambientais que podem ser alterados significativamente através de mudanças no uso da terra. O objetivo do presente estudo foi verificar se os padrões de diversidade das ordens Odonata e Trichoptera variam significativamente entre locais preservados e alterados, ao longo de um gradiente de impacto ambiental. Foram coletados dados sobre as características estruturais e ambientais do córrego e das assembleias de insetos aquáticos em sete pontos de amostragem em um ecótono Cerrado-Caatinga do Nordeste, Brasil, nas estações secas de 2018 e 2019. Os resultados indicaram que córregos alterados apresentaram maiores valores de condutividade elétrica e menores valores de IIH (índice de integridade de habitat) em comparação aos preservados, sendo determinantes na distribuição de gêneros, e baixos valores de pH aumentaram a riqueza de gêneros, informações que podem orientar estratégias de manejo para a conservação da biodiversidade. Reforçando a conclusão de que a diversidade de insetos aquáticos é determinada pela influência de filtros ambientais nos riachos.

Palavras-chave: Heterogeneidade, Odonata. ecologia de riachos, Trichoptera.

Introduction

The occupation and use of land for a range of human activities have exerted increasing pressure on natural landscapes around the world, and in the specific case of lotic systems, one of the principal impacts is derived from the suppression of the riparian vegetation (Nessimian *et al*. 2008; Dala-Corte *et al*. 2020). The removal of the riparian vegetation results in a higher incidence of sunlight, an increase of sediment entry in streams, an increase in water flow and a loss of organic matter (Miguel *et al.* 2017), having as a consequence alterations of habitat structure and, on a micro-scale, their physicochemical characteristics (Nessimian *et al*. 2008; Veras *et al*. 2019).

Changes in environmental factors, caused by different land uses, may result in the homogenization of streams, due to the reduction in microhabitats that does not allow species to coexist, persist and diversify (Stein *et al*. 2014). This homogenization leads to a replacement of specialist individuals by more widespread generalists (Seidu *et al.* 2017). Given this, changes in environmental gradients will determine differences in the diversity patterns of the assemblages of aquatic organisms (Colzani *et al*. 2013; Dala-Corte *et al*. 2020).

Environmental conditions can affect the distribution of species and their functionality in the aquatic system (Colzani *et al*. 2013; Paiva *et al.* 2017). The composition and distribution of these insects may vary in both local (e.g., water chemistry, substrate, habitats) and regional (biome, latitude, continent) frameworks (Oliveira-Junior & Juen, 2019; Brasil *et al*. 2020), as well as over a temporal scale (Chi *et al*. 2017), through the influence of both biotic and abiotic variables, and their interactions, which together determine community structure.

The diversity pattern of aquatic insects has been predicted primarily through the analysis of niches (Mendes *et al*. 2015; Brasil *et al*. 2020), with niche partitioning being determined by the tolerance, resistance, and sensitivity of individuals to the variation in environment conditions (Martins *et al*. 2017). This pattern is typical of communities of insects, such as those of the Odonata (Brasil *et al*. 2016; Oliveira-Junior & Juen, 2019) and Trichoptera (Pereira *et al*. 2012; Paiva *et al.* 2017).

The insects of the orders Odonata and Trichoptera are considered water quality indicators in aquatic ecosystems, cosmopolitans and are very sensitive to changes in physical and chemical structure of aquatic environments (Pereira *et al.* 2012; Miguel *et al*. 2017). Both groups have relatively high species richness, with their larval stages as the focus of biomonitoring studies, in addition, similar methodologies can be used to sample each group (Curry *et al.* 2012).

Aquatic insects are fundamental elements in the dynamics of lotic ecosystems, and play an important role in the cycling of organic matter and energy transfer within the aquatic system (Vannote *et al.* 1980). However, the disturbance of the physical-chemical factors and the alteration of the natural dynamics of the communities, as a result of anthropic activities, cause a significant drop in water quality and loss of aquatic biodiversity (Goulart & Callisto, 2003).

Given this, it is fundamentally important to identify the predictors that determine the structure of aquatic insect assemblages, in addition to understanding whether, and how, shifts in environmental integrity may affect this structure. Thus, the aim of the present study was to verify if the patterns of diversity of the orders Odonata and Trichoptera vary significantly between preserved and altered sites, along a gradient of environmental impact.

Materials and Methods

Study area

The study was carried on the municipality of Caxias, in the eastern extreme of the Brazilian state of Maranhão (Figure 1). The region's climate is equatorial hot and humid, with a maximum temperature of 38.3ºC and minimum of 21.2ºC. The local vegetation is of the savanna type, with a complex mosaic of phytophysiognomies and topographies being found with the transition zone between the Cerrado savanna of central Brazil and the Caatinga dry forest biome of the Brazilian Northeast (Silva, 2007).

The hydrographic system of the municipality includes parts of the basins of the Parnaíba, Itapecuru, and Munin rivers. In this study, tributaries of the Itapecuru river were sampled, which has an average slope of approximately 14 cm/km, and has several meanders, resulting from factors such as width and depth of the river. Due to the low speed it is characterized as a plain river (Silva & Conceição, 2011), where the relief of the region is flat to undulating, with a low density, standard drainage system, that is normally dendritic. The local economy is based on agriculture, the retail sector, and the extraction of natural plant resources (IBGE, 2017).

The data were collected in the dry season, that is, between August and October, in 2018 and 2019, at seven sampling points (Figure 1). So that we could better measure the existing biodiversity, each stream was sampled twice. Given the long interval between fieldwork sessions, the 14 samples were considered to be true replicates for analysis.

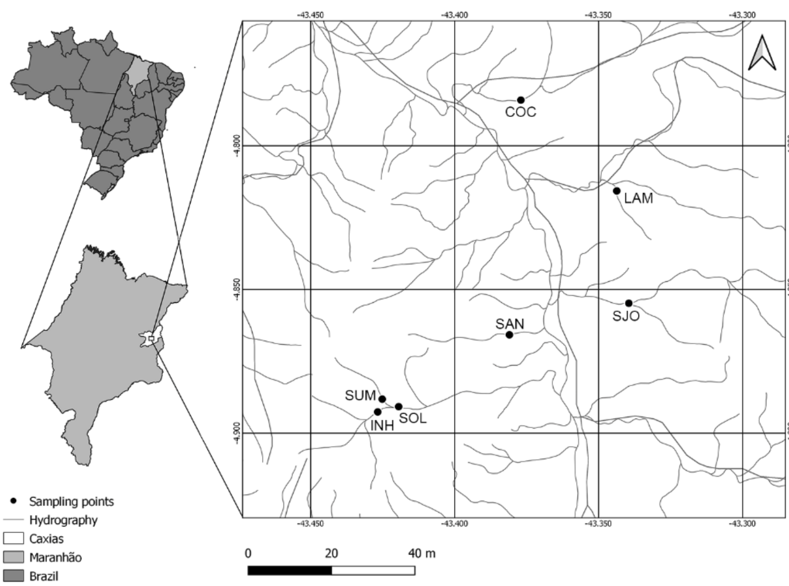

Figure 1. Streams in the basin of the Itapecuru River in Caxias, Maranhão, Brazil: COC = Cocos; LAM = Lamêgo; INH = Inhamum; SAN = Sanharó; SJO = São José; SOL = Soledade; SUM = Sumidouro do Padre.

The study streams with greater habitat integrity, such as those of the Inhamum Environmental Protection Area (EPA Inhamum), were characterized primarily by continuous native forest cover with few clearings in the riparian zone, with presence of organic matter, that simulates a retention mechanism providing the occurrence of deposit areas and greater variability in water flow (Fidelis *et al*. 2008). By contrast, the impacted sites were inserted within an agricultural matrix, and were characterized by extensive deforestation and the conversion of land to farming and residential development, with presence of gullies and scars along the channel, riparian forest with frequent breaks, solid residues and even effluent discharge.

Environmental Variables

Four environmental variables were measured at each study site using an Akso AK88 multiparameter probe: (i) pH, (ii) water temperature (°C), (iii) the dissolved oxygen concentration (DO: mg/L^{-1}), and (iv) electrical conductivity (µm/s). Stream width and depth were measured using a surveyor's tape, with measurements being taken at three points along a 100-m transect, and the mean of these three values being used in the subsequent analyses. The values obtained for the physicochemical and structural parameters at each sampling point are shown in Table 1.

Table 1. Depth, width, Habitat Integrity Index (HII) and physicochemical parameters (pH, Temp: temperature, EC: electrical conductivity; DOC: dissolved oxygen concentration), recorded in the study streams in Caxias, Maranhão, northeastern Brazil.

Stream	Depth	Width	HII	pH	Temp	EC	DOC
LAM	13.4	107.3	0.437	6.31	28.6	37.7	5.9
SJO	31.6	369.6	0.436	6.42	27.7	128.06	10.9
SAN	31.4	256	0.494	7.23	26.5	79.7	16.9
COC	30.6	440.3	0.397	6.23	26.5	43.3	16.9
SOL	34.5	236	0.681	5.83	27.4	11	13.2
SUM	20	180	0.563	5.47	27.7	9.76	14
INH	31.6	261.6	0.702	5.97	26.1	15.3	6.7
LAM	17	337	0.498	6.02	26.2	42.3	1.93
SJO	23.7	239.3	0.581	6.34	26.5	103.5	6.43
SAN	27.1	211.6	0.543	6.71	25.9	65.7	14.3
COC	42.8	388.3	0.568	5.89	27.4	67.3	3.35
SOL	58.5	351	0.706	5.44	25.7	12.7	2.36
SUM	33.5	281.6	0.813	4.68	26.4	10.6	1.7
INH	20.8	1021.3	0.701	5.06	23.4	12.6	3.3

Legend of sampling points: COC = Cocos; LAM = Lamêgo; INH = Inhamum; SAN = Sanharó; SJO = São José; SOL = Soledade; SUM = Sumidouro do Padre.

The Habitat Integrity Index (HII) of Nessimian *et al.* (2008) was used to determine the conservation status of each study stream. This index combines the values recorded for a set of environmental variables related to land use, the characteristics of the riparian vegetation (presence/absence, quality, extension), sediments and barriers, structure of the margins, stream bed, riffles and meanders, and the presence of debris. The value of the HII varies from 0 to 1, with higher values representing sites with a higher degree of integrity (Nessimian *et al*. 2008).

Biological data (taxon richness, abundance, and composition)

The sampling of Trichoptera and Odonata specimens followed the method of scanning fixed areas, establishing a transect of 100 meters in the stream, divided into 20 segments (pseudoreplicates) of 5 meters. The immature insects were collected using granulometric sieves with a 0.05 mm mesh and tweezers, with each substrate being sieved three times (Chun *et al.* 2017). The samples were separated, identified, stored in plastic bags containing water from the stream and sent to the laboratory for processing and storage in 70% ethyl alcohol (Hamada *et al*. 2014). The material was identified to the lowest possible taxonomic level based on the diagnosis of morphological traits in the taxonomic keys available for the Trichoptera (Hamada *et al*. 2014; Pes *et al*, 2018) and Odonata (Costa *et al*. 2004; Hamada *et al*. 2014).

Data Analysis

The cumulative genera curves were plotted based on the 20 segments (pseudoreplicates) demarcated within the transect established in each study stream, while for all other analyses, the stream (sampling point) was considered as the sample. The efficiency of the sampling effort was evaluated based on a species accumulation curve using a first-order nonparametric Jackknife species richness estimator, which considers the rarity (abundance) of species represented by a single specimen (Magurran, 2013). A matrix of Pearson correlations was used to verify the correlation between variables, when the correlation between the variables was equal to or greater than 70%, only one of them was selected and used in the analysis. A multiple linear regression was used to verify the effects of the environmental variables on taxon richness, in which the variables not considered to be significant (P>0,05) were omitted from the final model by backward stepwise selection.

A Redundancy Analysis, or RDA (Borcard *et al*. 2018) was used to determine the degree to which the composition of the insect assemblage was explained by the environmental gradient. The species abundance matrices were Hellinger-transformed prior to statistical analyses to reduce the importance of more abundant species and give low weights to rare species (Legendre & Gallagher, 2001). In this analysis, the variables not considered to be significant were omitted from the final model by forward stepwise selection (P<0,05). Statistical analyses were performed using *lmtest* and *vegan* packages of the R environment (R Development Core Team, 2015).

Results and Discussion

According to the cumulative species curve, which approached the asymptote, the sampling effort was 90% efficient for the determination of the taxon richness of the immature insects. While a mean of 29 (± 1.19) genera were recorded, a total of 31.99 (± 1.72) were predicted by the analysis.

A total of 641 specimens were collected, including 588 odonates and 53 trichopterans (Table 2). The most abundant odonate genera were *Acanthagrion* (104 specimens) and *Dythemis* (74), while the least abundant were *Phyllogomphoides* (2), *Dasythemis* (2) and *Agriogomphus*, with only one specimen. In the case of the Trichoptera, the most abundant genera were *Smicridea* (16) and *Macrostemum* (14), while *Cyrnellus* and *Cernotina* were each represented by only a single specimen.

Considering the correlation matrix of Pearson, the correlated variables were pH with HII, and temperature with width. For the multiple regression, pH and temperature were the selected variables to proceed with the analysis. On the other hand, with the purpose of adjusting the model for better results, for Redundancy Analysis, the variables HII and temperature were selected, with HII variable being chosen because of its greater predictive power.

Table 2. Odonata and Trichoptera collected in the study streams in Caxias, Maranhão, northeastern Brazil.

Order Odonata					
Suborders, families and genera	N	Streams*	Suborders, families and genera	N	Streams*
Anisoptera, Gomphidae			Anisoptera, Libellulidae		
Agriogomphus (Selys, 1869)	1	[4]	*Dasythemis* (Karsch, 1889)	2	[4]
Aphyla (Selys 1854)	15	[1; 2; 4; 5]	*Diastatops* (Rambur, 1842)	16	[1; 5; 6]
Epigomphus (Selys, 1854)	10	[3; 5]	*Dythemis* (Hagen, 1861)	74	[1-4; 6; 7]
Phyllocycla (Selys, 1854)	48	[2; 4; 5]	*Erythemis* (Hagen, 1861)	4	[2; 3; 7]
Phylogomphoides (Selys, 1854)	2	[1; 7]	*Erythrodiplax* (Brauer, 1868)	13	[2-4]
Progomphus (Selys, 1854)	19	[1-7]	*Orthemis* (Hagen,1861)	37	[1; 2; 4-6]
Zonophora (Selys, 1854)	24	[3; 4; 6; 7]	*Perithemis* (Hagen, 1861)	68	[1-7]
Zygoptera, Coenagrionidae			*Tauriphila* (Kirby, 1889)	9	[1; 6; 7]
*Acanthagrion (*Selys 1876)	104	[1; 2; 4-7]	*Tramea* (Hagen, 1861)	35	[2; 3; 5-7]
Argia (Hagen in Selys, 1865)	38	[1; 2; 4; 5; 7]	*Zenithoptera* (Selys, 1869)	13	[6]
Zygoptera, Protoneuridae			Zygoptera, Calopterygidae		
Epipleoneura (Williamson, 1915)	47	[1-7]	*Hetaerina* (Hagen, 1853)	9	[1; 2; 5; 7]
Order Trichoptera					
Philopotamidae			Hydropsychidae		
Wormaldia (McLachlan, 1865)	4	[7]	*Leptonema* (Guérin-Méneville, 1843)	6	[3; 7]
Chimarra (Stephens, 1829)	4	[7]	*Macronema* (Pictet, 1836)	7	[3; 5; 7]
Polycentropodidae			*Macrostemum* (Kolenati, 1859)	14	[1; 3; 4; 7]
Cyrnellus (Banks, 1913)	1	[7]	*Smicridea* (McLachlan, 1871)	16	[1; 3; 7]
Cernotina (Ross, 1938)	1	[3]			

* Stream where the specimen was found. Legend (Spatial distribution in Figure 1): [1]: COC = Cocos; [2]: LAM = Lamêgo; [3]: INH = Inhamum; [4]: SAN = Sanharó; [5]: SJO = São José; [6]: SOL = Soledade; [7]: SUM = Sumidouro do Padre.

The multiple linear regression (Figure 2) indicated that the variables analyzed explained 42% of the total variation in the taxon richness of immature insects (R^2 = 0. 425; p= 0.048). As they did not have a significant effect, three variables – temperature, conductivity and dissolved oxygen – were excluded from the final model by backward stepwise selection. Of the two parameters selected, i.e., pH and depth, only pH presented a significant partial coefficient, negatively influencing on richness (t= -2, 584; p = 0.025), therefore when the pH increases, the richness tends to decrease. The variable stream depth did not show a significant partial coefficient (t= -1.607; p = 0.136). None of the variables had a significant effect on insect abundance (R^2 = 0. 253; p = 0. 935).

The Redundancy Analysis (Figure 3A) indicated that the environmental variables had a significant effect on the composition of insect genera ($F_{(2,11)}$ = 1.898; p = 0.012), explaining 30% of the total variation (RDA1: 25%; RDA2: 5%). The variables stream depth and width, and the temperature, pH, and dissolved oxygen concentrations of the water did not present any significant effect, and were thus excluded from the final model by forward stepwise selection. Electrical conductivity was correlated negatively with axes 1 and 2, while the HII was correlated positively with axis 1 and negatively with axis 2.

The analysis identified two distinct groups, reflecting the difference in the taxonomic composition of the altered and preserved streams. Of the total of 29 genera, 12 were shared between sites, seven occurred only in preserved sites and four only in altered sites (Figure 3B). The preserved streams (highest HII values) showed a greater number of specialist genera, such as *Epigomphus, Cernotina, Chimarra, Cyrnellus, Leptonema* and *Wormaldi*a (n=6) (Carvalho &

Nessimian, 1998; Fidelis *et al*. 2008; Pereira *et al*. 2012), at the expense of altered streams where the genera *Agriogomphus* and *Phyllocycla* (n = 2) were observed (Carvalho & Nessimian, 1998; Hamada *et al.* 2014; Costa *et al.* 2004). Thus, based on this observation, more heterogeneous environments (preserved) support a higher richness through partitioned niche space, implying a positive relationship between heterogeneity and diversity (Yang *et al*. 2015).

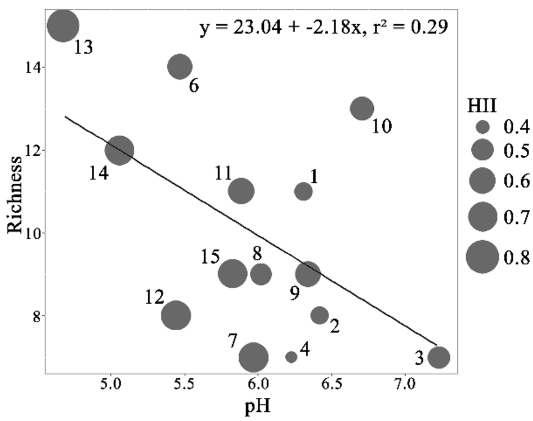

Figure 2. Multiple linear regression of the relationship between taxon richness, power of Hydrogen (pH), and environmental integrity. The size of the bubble representing each sample is proportional to the integrity of the habitat at the respective sampling point.

Legend of streams: Lamêgo (1 and 8); São José (2 and 9); Sanharó (3 and 10); Cocos (4 and 11); Soledade (5 and 12); Sumidouro do Padre (6 and 13); Inhamum (7 and 14).

The results of the present study indicate that the environmental gradients determined by the variation in the level of conservation of the different streams act as predictors of the diversity of aquatic insects. Thus, the taxonomic composition was influenced by environmental parameters that showed effects on community structure (Mendes *et al*. 2015; Bream *et al.* 2017). The principal predictors of the composition of the insect genera were the electrical conductivity and the HII, variables that are closely related to the species composition of aquatic insects and are also affected by the conservation status of the stream (Brasil *et al.* 2020).

One other pertinent finding was that the sampling points located within the urban zone of the municipality of Caxias (Lamêgo, São José and Sanharó) had much higher electrical conductivity (43.3–128.6 ± 59.93) in comparison with those located within the EPA Inhamum. These streams also presented the lowest HII values, linked to the loss of riparian vegetation, which led to an increase in the concentrations of dissolved solids (Loock-Hattingh *et al*. 2015).

The pH of the streams affected their taxon richness, with the preserved sites having 0.31 genera more than the altered sites, on average. This is consistent with the findings of previous studies that have shown that these variables act as environmental filters of taxon diversity (Paiva *et al.* 2017; Brasil *et al*. 2020). Here, the sites with the highest taxon richness had the lowest pH, a characteristic of better preserved streams (Paiva *et al*. 2017). The pH had a positive effect on both the taxonomic richness of odonates, which are moderately tolerant of variation in the pH, and also on the taxonomic richness of the trichopterans, which are considered to be more tolerant (Rychla el al. 2011).

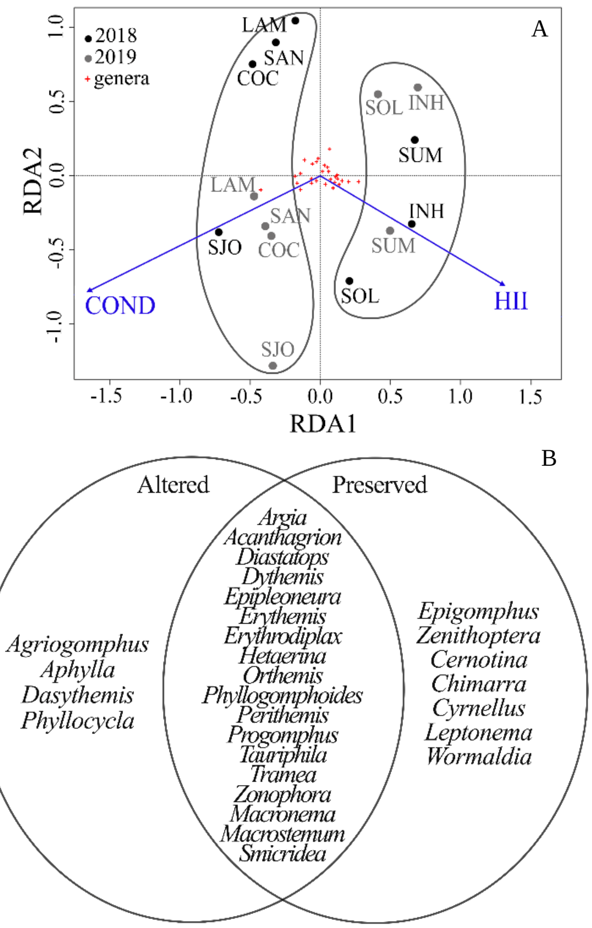

Figure 3. Ordination plot of the Redundancy Analysis - RDA (A), between the environmental factors and the composition of the aquatic insect assemblages and Venn diagram (B) showing the composition of genera in the altered and preserved study streams.

Legend: COND = electrical conductivity; HII = Habitat Integrity Index; COC = Cocos; LAM = Lamêgo; INH = Inhamum; SAN = Sanharó; SJO = São José; SOL = Soledade; SUM = Sumidouro do Padre.

In order to more accurately assess the influence of environmental variables on composition patterns, in future studies it would be important to include variables that were not analyzed in this research (e.g. substrate type, microhabitat, turbidity, average velocity, slope, precipitation, biological oxygen demand) for the purpose of obtaining greater explanatory power.

The results corroborate the previous observation that different forms of land use and occupation affect the landscape structure (e.g. riparian canopy) and environmental variables of streams (e.g. productivity, depth, water flow, pH, conductivity) (Brasil *et al*. 2020; Veras *et al*. 2019). These habitat modifications can generate thresholds in environmental gradients, in which points of change in the occurrence and frequency of community abundance may occur, affecting the patterns of diversity, a fact observed in aquatic insect assemblages (Dala-Corte *et al*. 2020; Giehl *et al*. 2019).

Conclusion

Overall, this research has provided important contributions to understand how environmental gradients act as filters that determine the diversity of aquatic insects in the streams of the Cerrado-Caatinga ecotone in northeastern Brazil. These informations can also guide management strategies in the land use and occupation, mitigating its effects on lotic systems that lead to the loss of species, and preserving the biodiversity of aquatic communities. As can be seen by the results of the present study, conductivity and habitat integrity (HII) were determinant in genera distribution, with individuals restricted to preserved and altered sites, and low pH values increased genera richness.

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