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MYLLENA SUZI LIMA SILVA

MUDANÇAS NO USO DA TERRA ALTERAM OS RIACHOS E AFETAM OS GRUPOS FUNCIONAIS ALIMENTARES DE INSETOS AQUÁTICOS NA AMAZÔNIA

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Dissertação apresentada ao programa de Pós-Graduação em Ecologia Aquática e Pesca da Universidade Federal do Pará, como requisito para obtenção do título de *Master of Sciences* em Ecologia Aquática e Pesca.

Orientador: Dr. Leandro Schlemmer Brasil

Coorientador: Leandro Juen

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APRESENTAÇÃO

Esta dissertação é composta por um capítulo único (artigo), um resumo geral, uma introdução geral e conclusão geral. As secções supracitadas estão redigidas na língua portuguesa, em exceção do artigo referente ao trabalho da dissertação, que está na língua inglesa cumprindo normas de submissão da revista cientifica *Journal of Insect Conservation*.

RESUMO GERAL

A substituição das paisagens naturais por diferentes usos da terra na Amazônia exerce influência negativa sobre as condições ambientais dos ecossistemas aquáticos e biodiversidade. A remoção da vegetação ripária reduz a entrada de material alóctone que é o principal recurso alimentar explorado por diferentes grupos funcionais alimentares de insetos aquáticos, alterando a dinâmica e processos ecossistêmicos essenciais para a manutenção da biodiversidade. O objetivo deste trabalho é avaliar os efeitos das mudanças na paisagem, em uma região com um mosaico de múltiplos usos da terra, com predominância de pastagens sobre a distribuição de grupos funcionais alimentares das comunidades de Ephemeroptera, Plecoptera e Trichoptera de riachos na Amazônia Oriental. Para este estudo, foram amostrados 30 igarapés amazônicos (1ª a 3ª ordens) distribuídos na Bacia Hidrográfica do Médio Rio Capim no município de Paragominas, Pará, Brasil. Os riachos amostrados foram selecionados por compreenderem um gradiente de distúrbios antrópicos, especialmente pela fragmentação ou substituição das paisagens naturais por matrizes de diferentes usos da terra. Todos os grupos funcionais alimentares das comunidades de EPT apresentaram relação com as mudanças ambientais decorrentes do desmatamento na zona ripária. Nossos resultados demonstram que as alterações do desmatamento afetam as condições ambientais dos riachos e a abundância de insetos aquáticos fragmentação. Essa alteração traz prejuízos funcionais, uma vez que com a diminuição dos fragmentadores pode ocorrer a diminuição da fragmentação de folhas, afetando toda a rede trófica. Ressaltamos a sensibilidade e a eficiência da utilização desses grupos tróficos como ferramenta de biomonitoramento da qualidade ambiental. Portanto, é importante o incentivo para ações de reflorestamento das áreas alteradas bem como a intensificação da fiscalização para combater o desmatamento ilegal das faixas de zona ripária determinadas pelo Código Florestal Brasileiro para a preservação dos recursos naturais e biodiversidade.

Palavras-chaves: Mudanças na paisagem, desmatamento, zona ripária, EPT, grupos tróficos.

ABSTRACT

The substitution of natural landscapes for different land uses in the Amazon has a negative influence on the environmental conditions of aquatic ecosystems and biodiversity. The removal of riparian vegetation reduces the input of allochthonou material, which is the principal food resource exploited by different functional groups of aquatic insects, changing the dynamics and ecosystem processes essential for maintaining biodiversity. The objective of this work is to evaluate the effects of changes in the landscape, in a region with a mosaic of multiple land uses, with a predominance of pastures on the distribution of functional food groups of the communities of Ephemeroptera, Plecoptera and Trichoptera of streams in the Eastern Amazon. For this study, were sampled 30 Amazon streams (1st to 3rd orders) distributed in the Hydrographic Basin of the Middle Capim River in the municipality of Paragominas, Pará, Brazil. The streams sampled were selected because they comprise a gradient of anthropic disturbances, especially due to the fragmentation or replacement of natural landscapes by matrices of different land uses. All functional food groups in the EFA communities were related to the environmental changes resulting from deforestation in the riparian zone. Our results demonstrate that changes in deforestation affect the environmental conditions of streams and the abundance of aquatic shredder insects. This alteration brings functional impairments since with the decrease of the shredder insects the decrease of the fragmentation of leaves can occur, affecting the whole trophic network. We emphasize the sensitivity and efficiency of using these trophic groups as a tool for the biomonitoring of environmental quality. Therefore, it is important to encourage reforestation actions in the altered areas, as well as the intensification of inspection to combat illegal deforestation of the riparian zones determined by the Brazilian Forest Code for the preservation of natural resources and biodiversity.

Keywords: Changes in landscape, deforestation, riparian zone, EPT, trophic groups.

INTRODUÇÃO GERAL

A Amazônia por ser a maior floresta tropical do planeta se concentra o hotspot da biodiversidade mundial. No entanto, a região vem passando por inúmeras transformações em suas paisagens naturais, abrindo espaços para diferentes usos da terra (Gardner et al. 2009; Leal et al., 2016). A pressão das ações humanas no bioma amazônico se deve predominantemente ao crescimento substancial da produção agrícola, pecuária, exploração mineral e madeireira, responsáveis pelos maiores índices de desmatamento na região nas últimas décadas (Fearnside et. al.,2005; Hirai, et al.,2008, Ferreira et al., 2012). A substituição da vegetação nativa para tais atividades, culmina na degradação dos ecossistemas naturais e perda da biodiversidade, interferindo diretamente na dinâmica ecossistêmica e serviços ambientais (Leal et al., 2016).

O aumento exponencial das áreas desmatadas para as atividades antrópicas são uma crescente preocupação e grave ameaça para a conservação da biodiversidade e qualidade dos recursos hídricos na região Amazônica (Laurance et al., 2013). Quando essas modificações nas paisagens naturais são conduzidas nas bacias de drenagem dos riachos, ganham proporções mais severas exercendo pressão negativa sobre a estrutura do habitat físico dos sistemas aquáticos e os organismos que compõem esses sistemas (Goulart & Callisto, 2003; Dias et al., 2010; Yoshimura, 2012). Os riachos, em especial os de pequeno porte (1ª a 3ª ordens) são os mais sensíveis e ameaçados pelas mudanças ambientais, uma vez que dependem das interações ecológicas e recursos alóctones fornecidos pela vegetação ripária para o equilíbrio da biodiversidade e bom funcionamento do ecossistema (Castello et al.,2013).

A remoção da vegetação ripária nas margens dos riachos pelos diferentes usos da terra provoca a desestabilização do leito oportunizando carreamento de nutrientes, o aumento da concentração de sedimentos finos em suspensão nas redes fluviais e a redução da entrada de energia alóctone, alterando consideravelmente as condições ambientais do habitat (Allan, 2004; Allan & Castillo, 2007; Nessimian et al., 2008; Juen et al., 2016). Essas modificações na composição da paisagem natural alteram a disponibilidade de substratos orgânicos e fontes alimentares (energia alóctone) indispensáveis para muitas espécies aquáticas (De Long & Brusven, 1994). Além disso, com a perda da heterogeneidade ambiental pela fragmentação e perda/destruição dos habitats naturais pode haver uma diminuição na biodiversidade aquática ou até mesmo a extinção local de espécies mais especialistas (Carvalho et al., 2018).

Considerando a intrínseca relação e importância da vegetação ripária para as comunidades aquáticas dos riachos, o uso das respostas biológicas dos organismos às mudanças ambientais tem sido comumente empregado em estudos ecológicos (Bonada et al., 2006). Dentre esses organismos, os insetos aquáticos, em destaque os das ordens Ephemeroptera, Plecoptera e Trichoptera (EPT) exibem requerimentos ecológicos específicos, tendo um grande potencial bioindicador (táxons sensíveis e tolerantes) às alterações que ocorrem na zona ripária (Seger et al., 2012), qualidade hídrica e composição dos micro-habitats (substratos orgânicos) (Rosenberg & Resh 1993; Kikuchi & Uieda, 1998; Farias et al., 2017; Zequi et al., 2019). Além disso, atuam na fragmentação da matéria orgânica contribuindo para o transporte de energia em níveis tróficos superiores, e componentes importantes na base da cadeia alimentar sendo fonte de alimento para diferentes espécies aquáticas (Goulart & Callisto, 2003; Abílio et al.,2007; Callisto & Esteves, 1995).

Além da riqueza, composição e abundância desses organismos como métrica da avaliação ambiental, o uso dos grupos funcionais alimentares vem trazendo informações importantes sobre a integridade, dinâmica e funcionalidade dos sistemas aquáticos (Shimano et al., 2012; Brasil et al., 2014; Luiza-Andrade et al., 2020). Essa abordagem proposta por Cummins et al. (1973) considera os aspectos morfológicos e comportamentais dos organismos para aquisição de alimento e o tipo de recurso alimentar explorado. Assim, troficamente, os insetos são classificados em cinco grupos funcionais de alimentação: os insetos fragmentadores, coletores (filtradores e apanhadores), raspadores e os predadores. Os insetos fragmentadores consomem matéria orgânica particulada grossa (MOPG >1mm, folhas, madeira e gravetos), transformando-a em matéria orgânica particulada fina (MOPF<1mm) que, por sua vez, servem como fonte de alimento para os coletores. Os organismos raspadores, raspam os perifítons aderidos aos substratos alimentando-se de pequenas algas, fungos e bactérias. Já os predadores, alimentam-se de pequenos invertebrados e/ou pequenos vertebrados (Cummins et al., 1973; Callisto & Esteves 1995; Cummins et al., 2005).

De acordo a Teoria do Rio Contínuo (TRC) proposta por Vannote et al. (1980) a distribuição dos grupos funcionais alimentares estaria condicionada a disponibilidade de recursos alimentares e fluxo de energia alóctone e autóctone ao longo dos rios, onde as variações ecológicas da nascente à foz influenciariam na composição trófica no contínuo fluvial. Outra teoria muito importante na ecologia é a Teoria Hierárquica de Manchas (THM) que prediz que os grupos tróficos podem se distribuir em manchas com condições ambientais favoráveis e diferentes recursos alimentares (Brasil et al., 2014; Thorp et al., 2006).

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LAND USE CHANGES DISRUPT STREAMS AND AFFECT THE FUNCTIONAL FEEDING GROUPS OF AQUATIC INSECTS IN THE AMAZON

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Abstract - Modifications made to the vegetation surrounding watercourses directly affect the input of allochthonous material to the system, the main food source for different functional feeding groups (FFG) of aquatic macroinvertebrates, interfering with the ecosystem processes that sustain biodiversity. The objective of this study is to evaluate the effects of changes made to the landscape on the distribution of functional feeding groups of Ephemeroptera, Plecoptera and Trichoptera communities of streams in Eastern Amazon, a region with a mosaic of multiple land uses and prevalence of pastures. The hypothesis tested is that shredders and collector-gatherer, naturally prevalent in preserved first-order streams, will be more affected by in-stream environmental changes caused by deforestation of the riparian vegetation, since the changes would restrict the availability of food resources for these groups. For this study, 30 Amazonian streams (1st to 3rd orders) located in the Capim River Basin, municipality of Paragominas, Pará, Brazil, were sampled. The most representative model of modifications was for the abundance of shredders. The reduced abundance of shredders can reduce leaf fragmentation, affecting the entire trophic network, highlighting the sensitivity and efficiency of using these groups as a tool for biomonitoring environmental quality. Therefore, it is important to encourage the reforestation of the altered areas and the intensification of inspections to combat illegal deforestation of riparian zones determined by the Brazilian Forest Code and for the preservation of natural resources and biodiversity.

Keywords: riparian zone, deforestation, landscape changes, EPT, trophic groups.

INTRODUCTION

The Amazon region has a great diversity of natural resources and biodiversity, which are under constant pressure caused by human actions (Gardner et al. 2013), mainly because areas of great socioeconomic interest overlap with areas of high biodiversity (Frederico et al. 2018). In addition, many commodities are produced within the amazon region. As a result, many changes have been made to the natural landscape, mostly for livestock breeding, agriculture, mineral exploitation and timber extraction (Fearnside et al. 2005).

Most changes occur directly in terrestrial environments. However, aquatic environments suffer indirectly from deforestation and other landscape changes that take place in the basin. These changes modify the physical and chemical structure within the streams and the aquatic communities (Dias et al. 2010; Juen et al. 2016; Chen et al. 2017). The impacts of landscape changes on aquatic ecosystems are most pronounced in small streams (up to five meters wide), because the energy that sustains biodiversity in these environments is almost exclusively of allochthonous origin, i.e., from the riparian vegetation through leaves, branches, fruits and trunks (Shimano et al. 2012).

The land use near of water bodies can drastically alter biological communities in streams (Fierro et al. 2017), due to the importance of the surrounding vegetation for this system. Thus, the reduction or removal of riparian vegetation, destabilizes the margins and the transport of particles, increasing the concentration of fine suspended sediments in river networks and reducing organic matter input (Allan & Castillo, 2007; Nessimian et al. 2008; Juen et al. 2016). These changes in the composition of the natural landscape directly alter the availability of substrates and food sources (allochthonous energy), which are essential for many aquatic species, causing small anthropized streams to have a fauna that is partially functionally similar to what is expected for large rivers (De Long & Brusven, 1994; Dala-Corte et al. 2019; Luiza-Andrade et al. 2020). This scenario reduces the prevalence of the functional groups most associated with the fragmentation of allochthonous material and increases scrapers and filterers (Shimano et al. 2012).

Insects of the orders Ephemeroptera, Plecoptera and Trichoptera (EPT) are widely used in ecological studies and as tools for biomonitoring environmental integrity. (Brasil et al. 2013; Luiza-Andrade et al. 2020). These groups are sensitive to environmental changes that occur in the landscape, in the riparian area (Seger et al. 2012) and in the environmental conditions of the stream channel, such as changes in the micro-habitats and physical-chemical parameters of water (Kikuchi & Uieda, 1998; Farias et al.

2017; Zequi et al. 2019; Paiva et al. 2021). In addition, EPT are important for the dynamics and functioning of lotic systems, acting at the base of the trophic chain, filtering particles suspended in water or fragmenting organic matter, contributing to the flow of energy at higher trophic levels (Abílio et al. 2007; Callisto & Esteves, 1995; Maneechan et al. 2015; Luiza-Andrade et al. 2020).

Aquatic insects are categorized following a trophic classification into the functional feeding groups: shredders, collectors (gatherer and filterers), scrapers and predators (Cummins 1973). This classification is intrinsically related to food resources and the characteristics and behavioral patterns organisms exhibit to obtain food (Luiza-Andrade et al. 2020). Shredders, for example, consume thick particulate organic matter (MOPG >1mm, leaves, wood and sticks), transforming it into fine particulate organic matter (MOPF<1mm), which, in turn, is a food source for the collectors-filterers. The scrapers, scrape the periphyton adhered to the substrates feeding on small algae, fungi and bacteria. On the other hand, predators feed on small invertebrates and/or small vertebrates (Cummins 1973; Cummins et al. 2005).

The River Continuum Concept (RCC; Vannote et al. 1980), in turn, predicts that rivers exhibit longitudinal gradients with ecological variations from source to mouth, where the morphological and behavioral characteristics of the aquatic assemblages reflect the physical components of these lotic systems. Therefore, the distribution of the trophic groups would be determined by the availability of food resources and the flow of allochthonous and autochthonous energy along the rivers (Luiza-Andrade et al. 2020). The Hierarchical Patch Dynamics Theory (HPD) is also an important approach, and considers that functional feeding groups in aquatic communities can be distributed among patches following the availability of resource sources and conditions present in the stream (Brasil et al. 2014).

Given the influence of riparian vegetation on trophic groups, the objective of this study is to assess the effects of changes made to the landscape on the distribution of functional feeding groups of Ephemeroptera, Plecoptera and Trichoptera (EPT), in streams of Eastern Amazon, a region with a mosaic of land uses and a prevalence of pastures. We tested the hypotheses that shredders and collectors (gatherers and filterers), naturally prevalent in preserved first-order streams (Vannote et al. 1980; Shimano et al. 2012; Brasil et al. 2014), will be more affected by in-stream environmental changes caused by deforestation of the riparian vegetation, since the changes would restrict the availability of food resources for these groups.

MATERIAL AND METHODS

Study area

The samples were collected in 30 Amazonian streams (1st to 3rd orders) distributed within the Capim River Basin, located in the municipality of Paragominas, in the Northeastern state of Pará, Brazil (between the coordinates 2º 25' - 4º 09'S and 46º 25'- 48º 54'W Gr.). The prevailing climate of the region is classified by Köppen as *Aw*, i.e., tropical humid with marked annual climatic seasons, being a rainy season from December to May and a dry season from June to November. The average annual temperature is 26.3ºC, the precipitation rate is 1,743 mm and relative humidity is 81% (Alvares et al., 2013).

The natural landscape is composed of a dense ombrophilous forest with small patches of alluvial and floodplain forests. However, due to the advance of the agricultural and mineral extraction frontier, Paragominas was included in "Arc of Deforestation" which includes Brazilian states such as Mato Grosso, Rondônia, Maranhão and Acre in response to the high deforestation rates resulting from anthropic activities (Fearnside et al. 2005). The streams were selected for comprising an environmental gradient with different anthropic disturbances/impacts, especially fragmentation or replacement of natural landscapes by matrices of different land uses, with the prevalence of agriculture, mining and timber extraction activities (Fig 1; Montag et al. 2019b; De Paiva et al. 2017; De Paiva et al. 2021).

The occupation of the municipality of Paragominas began in the mid-20th century at the peak of timber extraction in the region. Later, with the advent of mechanized agriculture, farming practices expanded rapidly in the municipality (Brito et al. 2018). As a result, the region currently has extensive land use activities, such as livestock, agriculture and timber extraction activities (Gardner et al. 2013). The region also shows great mineralogical potential, producing tons of ore (bauxite) annually (Lima & Silva, 2016).

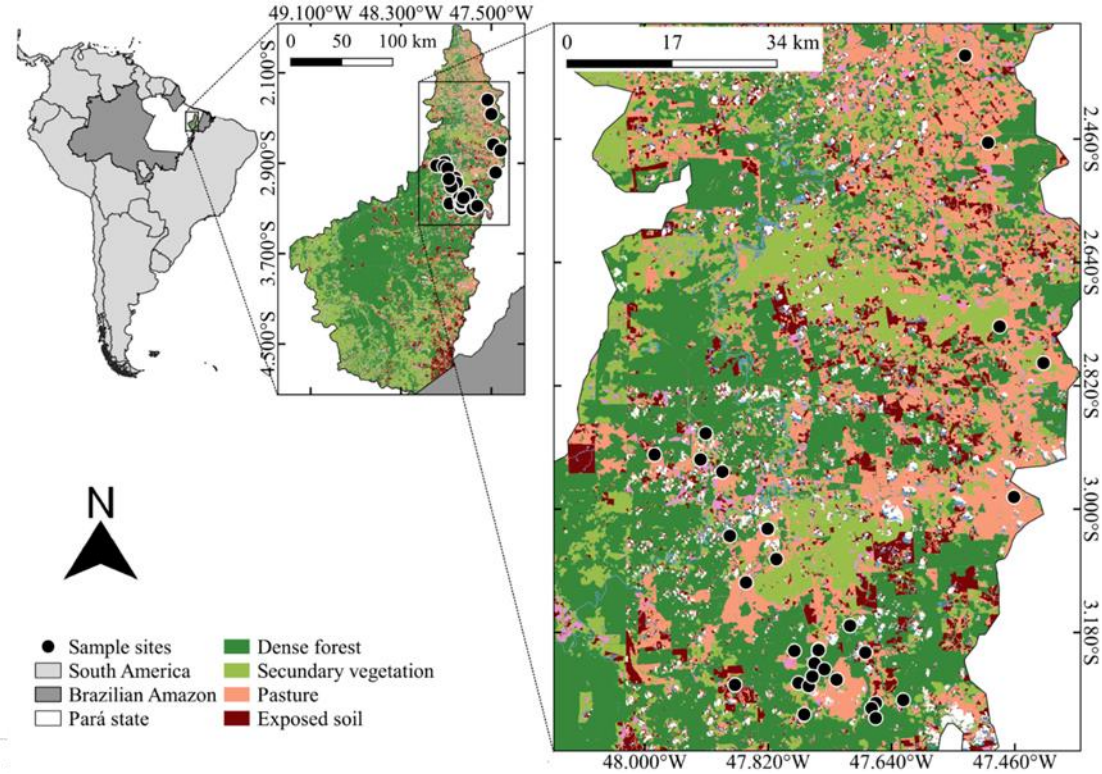

Fig 1 Distribution of the 30 streams sampled in the Capim River Basin, municipality of Paragominas, Pará, Brazil.

Biological sampling of the EPT community

The biological collections were carried out in 30 streams located within areas of anthropic changes that form a mosaic of different land uses (e.g., pasture, mining and agriculture) during the dry season, between August and September 2015 and in July 2017. Biological sampling was performed in a segment of 150 meters for each stream. Each segment was divided into 10 equidistant sections of 15 meters upstream and downstream. Each transect was named from "A" to "K" and then subdivided into fractions of 5 meters, where only the first 10 meters of each transect was collected (Faria et al. 2017; De Paiva et al. 2017).

Individuals of the EPT communities were collected using an 18 cm hand sieve with a 0.05 mm mesh size, and then pre-screened in the field and fixed in 85% alcohol (Shimano et al. 2018). Subsequently, the specimens were identified to the genus level using taxonomic keys (Salles et al. 2014; Hamada et al. 2014; Pes et al. 2014). The biological material was stored in the entomological collection of the Laboratory of Ecology and Conservation (LABECO), Federal University of Pará.

EPT functional feeding groups (FFG)

The genera EPT were categorized into functional feeding groups (FFG), namely shredder, scraper, collectors-gatherer, collector-filterer and predator, following Cummins (1973). The FFG categories are related to behavioral aspects and morphophysiological characteristics that individuals present and are used in obtaining food resources. These functional characteristics of aquatic macroinvertebrates have been widely used as a biomonitoring tool in ecological studies that seek to understand the relationships between biological communities and ecosystem processes (Luiza-Andrade et al. 2020). In addition, FFG are efficient indicators of ecosystem conditions, such as the balance between autotrophy and heterotrophy (Cummins et al. 2005; Shimano et al. 2012). The genus of each specimen collected in our study was categorized in its respective functional feeding group (Heino, et al. 2005; Shimano et al. 2012; Brasil et al. 2014).

In-stream environmental variables

The following physical characteristics of the habitat and physical-chemical characteristics of the water were measured for each stream: temperature (ºC), turbidity, pH, dissolved oxygen and conductivity, obtained utilizing multi-parameter electronic equipment, Horiba ®, model U - 51. These metrics are appointed as important to explain the structure of the aquatic insect community (Brasil et al. 2020). To measure the physical integrity of the sampled streams, a protocol adapted from Peck et al. (2006) was used, where different aspects of the physical habitat in the transverse and longitudinal profiles were measured.

Depth measurements and the percentage of fine sediment present in the thalweg were measured and the visual evaluation of the type of substrate (coarse gravel, fine gravel, sand, silt, pebble, clay, consolidated clay, large boulder, small boulder, organic matter, concrete, wood, fine debris, bank of leaves, roots, macrophytes and algae) was performed in the transversal profile, in five equidistant transversal points. The characterization of the transversal profile also included the width and depth of the channel, wet width, incision height and slope/angle of the margins.

The vegetation cover structure of the left and right margins of the riparian zone of each stream was analyzed by observing the canopy strata (>5m high), understory (0.5 to 5 m high) and undergrowth (<0.5 m high). The canopy cover was evaluated using a densiometer positioned at the center and ends of each transect (approximately 30 cm above the water column), making six measurements: center upstream, center left, center downstream, center right, left and right. These variables of the protocol of Peck et al.

(2006) have already been shown to be important predictors for aquatic biota of EPT (Faria et al. 2017; De Paiva et al. 2021), fish (Prudente et al., 2017), Odonata (Mendes et al., 2019; Oliveira-Júnior et al. 2019) and Heteroptera (Cunha et al. 2015; Guterres et al. 2019) of streams in the Brazilian Amazon.

Analysis of the landscape, land use and occupation

The geographic delimitation of the river basin was carried out to characterize the landscape using images from the Shuttle Radar Topography Mission (SRTM) project, with a spatial dimension of 30 meters and was adapted using images from Google Earth (http:/Earth.google.com) with Tau Dem 5.3 tools available in the geoprocessing software QGis 2.18.

The natural landscape, uses and land occupation were explained by monitoring multispectral images from the Landsat 8 satellite, using the Semi-Automatic Classification plug-in of the geoprocessing software HQGis 2.18. The images were obtained from the United States Geological Survey (USGS) Earth Explorer project for the years 2015 and 2017. These images provide pertinent information on the forms and organization of the elements, enabling the identification of variations in soil cover types in remnants of natural landscapes along drainage basins.

An atmospheric correction process was used to reduce the reflectance of the images. Later, the images were sorted into six types of cover and land use, namely: primary forest, secondary forest, areas deforested for long cycle (forestry) and short cycle agriculture (grain production), pasture and areas with mining activities. The classification of land cover and land use was validated using Google Earth images.

The extent of the land uses along the river basins was measured at two different scales to elucidate the structure of the benthic macroinvertebrate communities in micro-basins of Amazonian streams. The first scale consisted of the drainage area of the river basin upstream from the sampling point, and the second corresponds to the area influenced by the riparian zone (riparian buffer). The riparian buffer was 60 meters wide,being 30 meters from each margin of the stream and length of 600 meters (300 m upstream and 300 m downstream; Fig 2; Montag et al. 2019a).

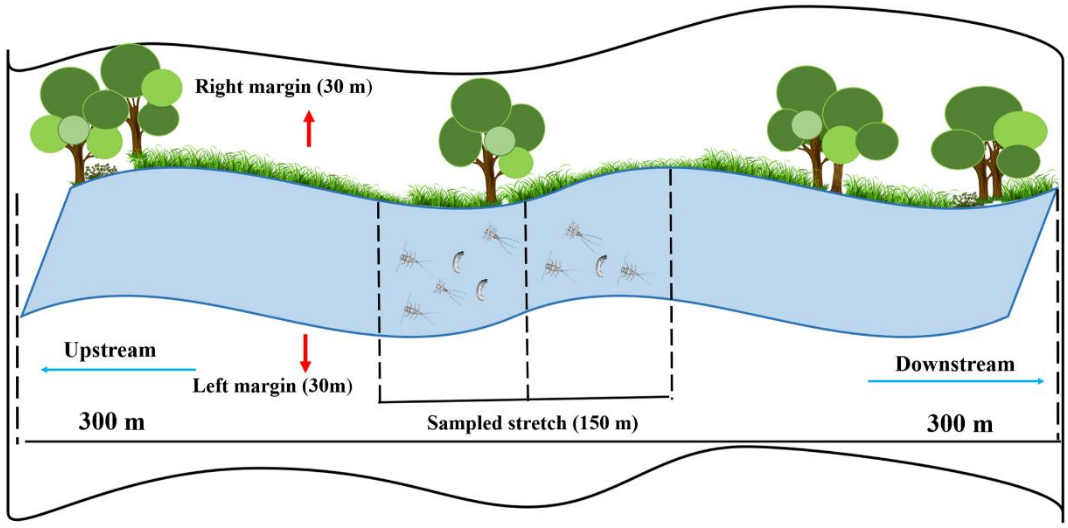

Fig 2 Schematic representation of the landscape characterization in the Rio Capim Basin, Paragominas, Pará, Brazil.

Data analysis

Each stream is considered a sample in our study, amounting to 30 samples. Hence, the abundance of the genera collected in each segment within the same stream was summed to represent a single sample. The environmental data within each stream were individually represented by the mean and standard deviation of each variable. Initially, to reduce the number of local environmental variables, we removed all variables that presented more than 70% of zero values and/or that had a coefficient of variation below 10% in all samples. Then, to select the local environmental variables related to deforestation, we conducted a multiple regression with a stepwise selection of variables using the local environmental variables and forest area the riparian zone. With this procedure, four local environmental variables were selected for being correlated with the percentages of forest in the riparian zone. Subsequently, a Principal Component Analysis (PCA) was performed with these local variables to graphically represent how each local environmental variable responded to the riparian zone forest cover gradient. The data were standardized, then the PCA was carried out with a correlation matrix. The Broken Stick (Legendre & Legendre, 1998) was used as the selection criterion for the axes.

To test the hypothesis that the shredders and collectors-gatherer will be affected by the amount of forest in the riparian zone, we performed linear regressions for each FFG. We used the abundance of each FFG as response variables and the amount of forest in the riparian zone as the explanatory variable. We also evaluated the effect of environmental changes caused by riparian zone deforestation on shredders and gatherers using a Linear Regression (LM) for each FFG. For these models, the abundance of each

FFG per sample unit was used as the response variable and the first PCA axis representing a gradient of local environmental changes related to riparian zone deforestation as the predictor variable. To compare the results of the linear models (one made for each FFG) we used Randon Forest. This method is widely used in meta-analyzes as it allows comparisons between different statistical models. For each model, a standardized effect size (R Pearson) and a confidence interval were calculated. If the confidence interval overlays the null effect line, the model is considered no effect. Models that have overlapping confidence intervals are considered equal (Borenstein et al. 2011). We tested the spatial autocorrelation of the models using Moran's Index, which is obtained from the residues of the generated models. Moran's I >0.15 indicates significant spatial autocorrelation and values ≤0.15 indicate that the models do not present spatial autocorrelation (Fig 3). All data analyses were performed in the R (R Development Core Team 2018) computational environment (RStudio interface) using the "vegan" package.

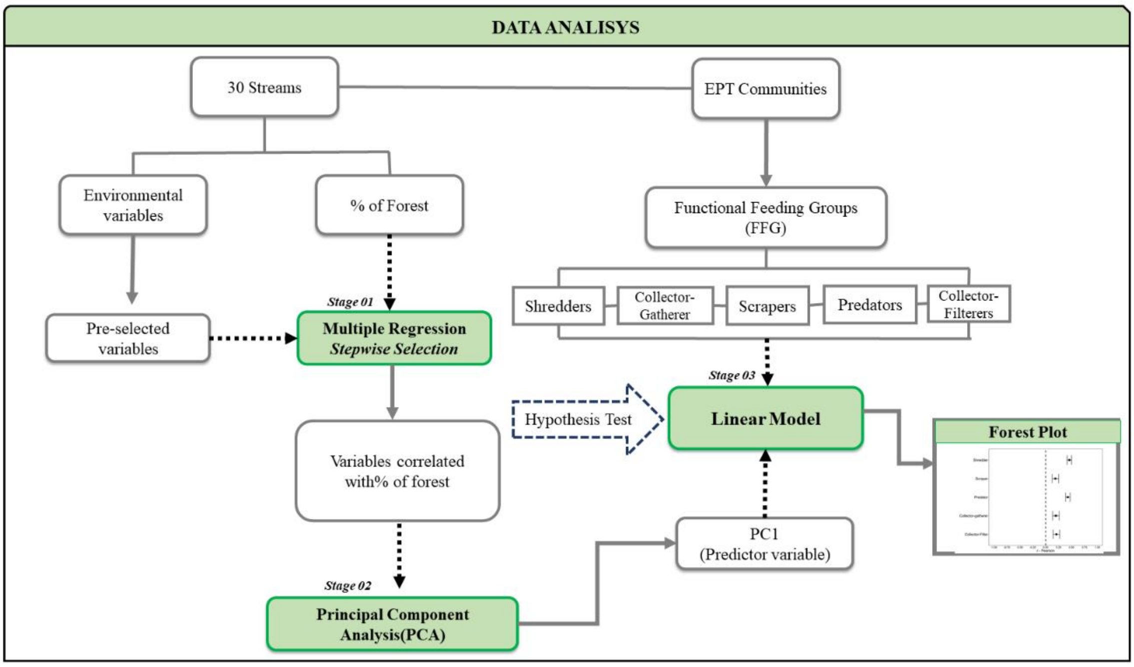

Fig 3 A conceptual framework that summarizes the analyzes carried out to evaluate the effects of changes made to the landscape on the distribution of functional feeding groups of Ephemeroptera, Plecoptera and Trichoptera (EPT), in streams of Eastern Amazon. Representation of the data analysis used in this study. The white rectangles indicate the data used for each stage of the analysis. Green rectangles indicate the analyses used for the hypothesis tests. Shredder (SH), Collector-gatherer (CG), Collector-filterer (CF), Scraper (SC) and Predator (P).

RESULTS

Environmental conditions

We analyzed the impact of deforestation in the riparian zone on local environmental variables and observed that the ratio of width to depth, woody canopy cover, sediment immersion and woody undergrowth were the environmental variables most correlated with the amount of forest in the riparian zone (Table 1). Only the first axis of the Principal Component Analysis (PCA) performed with the environmental metrics was significant, explaining 53.43% of the variation in the data (Fig 4; Table 2). A gradient where the most forested streams were distributed to the left and the deforested streams to the right was formed. The most deforested streams exhibited higher width-depth ratios (Fig 5A), lower variation in woody canopy cover (Fig 5B), lower sediment immersion (Fig 5C) and a lower amount of woody undergrowth (Fig 5D).

Table 1 Local environmental variables selected according to the land use in the riparian zone in the municipality of Paragominas, Pará, Brazil. The beta coefficients are the slope and evaluate the relative contribution of each predictor to the overall prediction of the model.

	Beta	**Std. Err. of Beta**	**t (19)**	**p-level**
Intercept			-2.009	0.060
Width and depth ratio (m)	0.925	0.181	5.110	**<0.001***
SD woody canopy cover (%)	0.969	0.252	3.849	**<0.001***
Mean sediment Immersion (%)	-0.477	0.189	-2.523	**0.021***
Mean woody undergrowth (%)	0.932	0.422	2.210	**0.040***

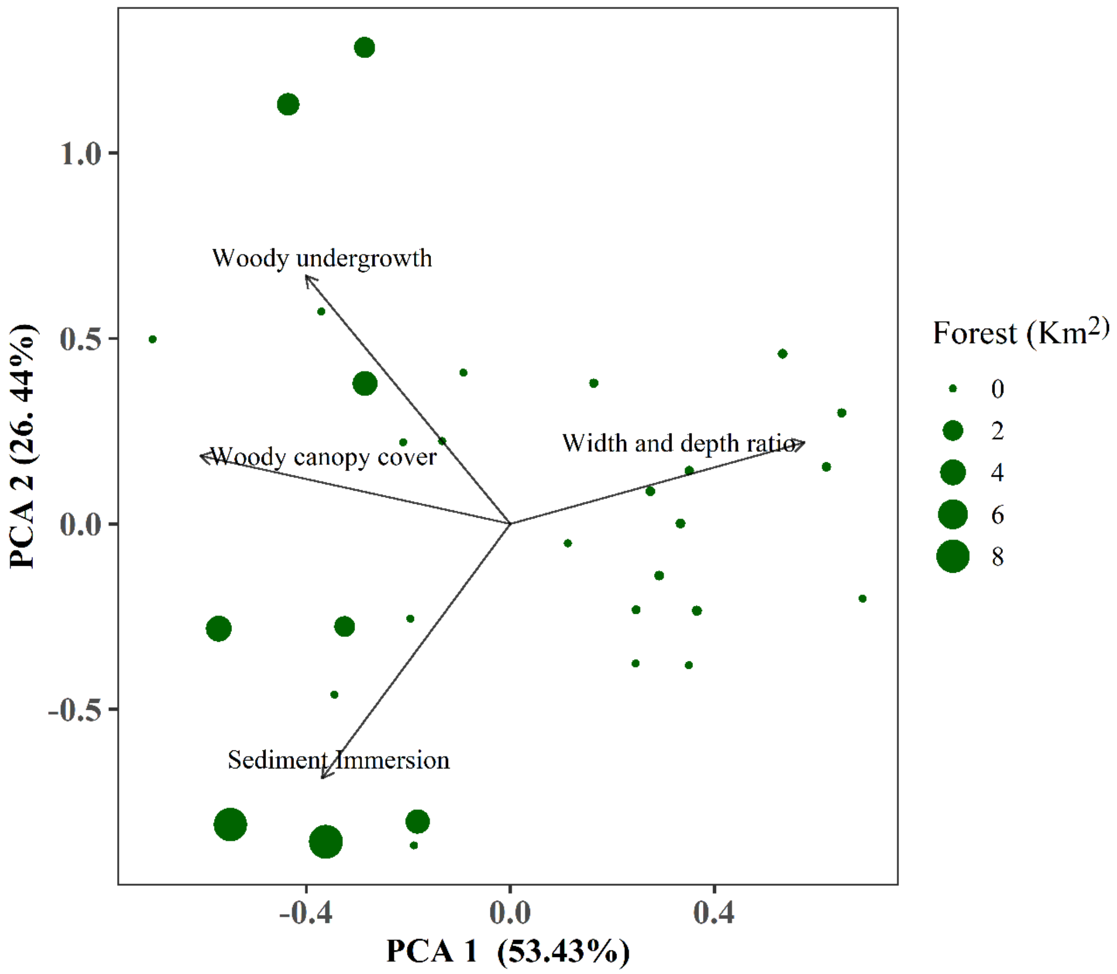

Fig 4 Principal Component Analysis (PCA) ordination of the 30 sampled streams based on four environmental variables of Amazonian streams in the municipality of Paragominas, Pará, Brazil. The size of each point in the graph represents the amount of riparian vegetation existing in each stream.

Table 2 Environmental variables of the 30 streams sampled in the Capim River basin, municipality of Paragominas, Pará, Brazil, and their correlation with the first axis of the principal components analysis (PCA). *Axis was not analyzed, because the value of the broken stick is major than the eigenvalue.

Environmental variables	**PC1**	**PC2***
Width and depth ratio	0.577	0.22
SD woody canopy cover (%)	-0.608	0.183
Mean sediment immersion (%)	-0.369	-0.686
Mean woody undergrowth (%)	-0.401	0.669
Auto value	2.13	1.057
Broken Stick	2.08	1.083
% explained	53.43	26.44
% acummulative explication	79.87	

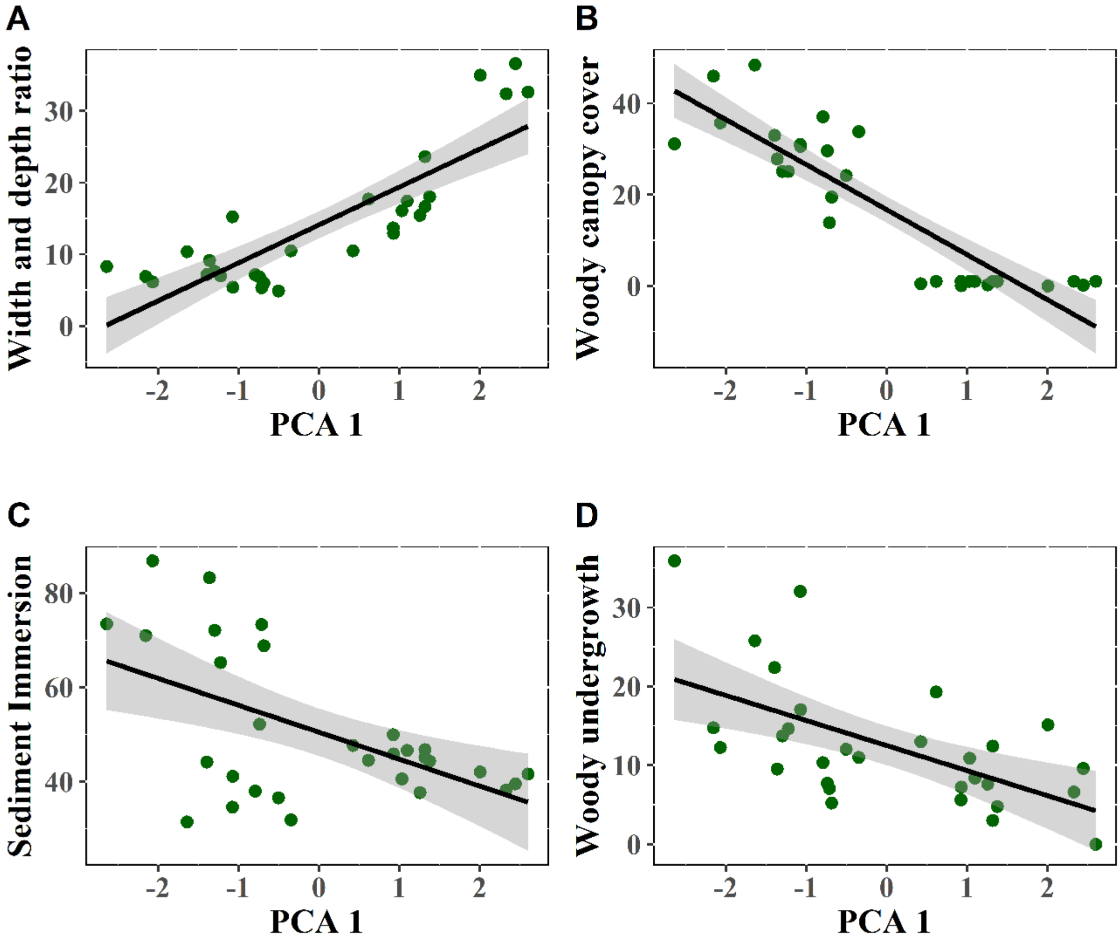

Fig 5 Relationship of the ratio of width and depth (A) variation in the woody cover canopy (B), immersion (C) and woody undergrowths (D) with the environmental gradient represented by the first axis of the Principal Component Analysis for Amazon streams sampled in the municipality of Paragominas, Pará, Brazil. The gray area corresponds to the confidence interval.

Description of the communities and Functional Feeding Groups (FFG)

A total of 4,744 specimens of aquatic invertebrates belonging to the orders (EPT) were sampled and represented 14 families and 39 genera. The order Ephemeroptera (n=24) was the most well represented in number of taxa, followed by Trichoptera (n=13) and Plecoptera (n=2). The most abundant specimens belong to the genera *Macrostemum* (n=1,338), *Miroculis* (n=689), *Ulmeritoides* (n=599), *Campylocia* (n=567), *Cernotina* (n=423), *Macronema* (n=349) and *Smicridia* (n=158), representatives of the orders Ephemeroptera and Trichoptera. The collected specimens were distributed in five functional feeding groups, with prevalence of the collector-filterer (n=1518), followed by collector-gatherers (n=1189), scraper (n=784), shredder (n=681) and predator (n=572) (Table 3).

Table 3 Genus and classification of functional feeding groups (FFG) of the Ephemeroptera, Plecoptera and Trichoptera communities sampled in Amazon streams in the municipality of Paragominas, Pará, Brazil. The reference column provides the literature source from which the FFG classification used in the study was obtained. Collector-gatherer (CG), Collector-filterer (CF), Scraper (SC), Shredder (SH) and Predator (P).

Order/ Family/ Genus	FFG	References
EPHEMEROPTERA		
Baetidae		
Americabaetis	CG	Cummins et al. 2005; Merrit et al. 2008
Aturbina	CG	Cummins et al. 2005
Callibaetis	CG	De long&Brusven, 1998
Cloeodes	SC	Baptista et al.2006
Harpagobatis	P	Mol, 1986; Shimano et al. 2012
Paracloeodes	CG	Cummins et al. 2005
Zelusia	CG	Cummins et al. 2005; Shimano et al.2012
Waltzoyphius	CG	Cummins et al. 2005
Caenidae		
Brasilocaenis	SC	Shimano et al. 2012
Caenis	SC	Francischetti et al.2001; Merrit et al. 2008
Euthyplociidae		
Campylocia	CG	Cummins et al.2005
Leptohyphiidae		
Amanahyphes	CG	Cummins et al. 2005
Traverhyphes	CG	Cummins et al. 2005
Leptophlebiidae		
Askola	SC	Polegatto & Froehlich, 2003
Farrodes	SC	Polegatto & Froehlich, 2003
Hagenulopsis	SC	Polegatto & Froehlich, 2003; Baptista et al. 2006
Hydrosmilodon	CF	Polegatto & Froehlich, 2003
Miroculis	SC	Polegatto & Froehlich, 2003
Simothraulopsis	SC	Polegatto & Froehlich, 2003
Ulmeritoides	SH	Shimano et al. 2012
Ulmeritus	SC	Baptista et al. 1998
Polymirtaciidae		
Asthenopus	CF	Salles, 2006
Campsurus	CF	Edmunds et al. 1976, Hilsenhoff, 2001
TRICHOPTERA		
Calamoreratidae		
Phylloicus	SH	Spies et al.2006
Helicopsychidae		
Helicopsyche	SC	Spies et al.2006

Continuação da tabela 3		
Order/Family/Genus	**FFG**	**References**
TRICHOPTERA		
Hydropsychidae		
Leptonema	CF	Oliveira & Nessimian, 2010
Macronema	CF	Spies et al.2006
Macrostemum	CF	Oliveira & Nessimian, 2010
Smicridea	CF	Spies et al.2006
Leptoceridae		
Nectopsyche	CG	Oliveira & Nessimian, 2010
Oecetis	P	Oliveira & Nessimian, 2010
Triplectides	F	Spies et al.2006
Odontoceridae		
Marilia	SC	Cummins et al. 2005, Oliveira & Nessimian, 2010
Philopotamidae		
Chimarra	CF	Spies et al. 2006
Polycentropodidae		
Cernotina	P	Spies et al. 2006
Cyrnellus	CG	Spies et al.2006
Polycentropus	CF	Oliveira & Nessimian, 2010
Polyplectropus	CF	Oliveira & Nessimian, 2010
PLECOPTERA		
Perlidae		
Anacroneuria	P	Oliveira & Nessimian, 2010
Macrogynoplax	P	Oliveira & Nessimian, 2010

Relationships between Environmental Conditions and the Functional feeding Groups (FFG)

None of the models generated showed spatial autocorrelation, since all of them presented Moran's I of the residues < 0.15. There was no direct relation between the forest cover of the riparian zone and the FFG: shredder (r^2=0.056; p=0.206), predator (r^2=0.046; p=0.251) collector-gatherer (r^2=0.040; p=0.289), collector-filterer (r^2=0.025; p=0.397) and scraper (r^2=0.007, p=0.649). However, the environmental gradient formed by the local variables affected by deforestation in the riparian zone (PCA 1) were predictors for all FFG: shredder (r^2=0.208; p<0.001), predator (r^2=0.183; p=0.002) collector-gatherers (r^2=0.039; p<0.01), collector-filterer (r^2=0.042; p=0.039) and scraper (r^2=0.035; p=0.031) (Table 4). The model that best explained the variation in FFG abundance was the one that considered the abundance of shredders, despite all the FFGs being significantly related to the environmental gradient (PCA 1) (Fig 6).

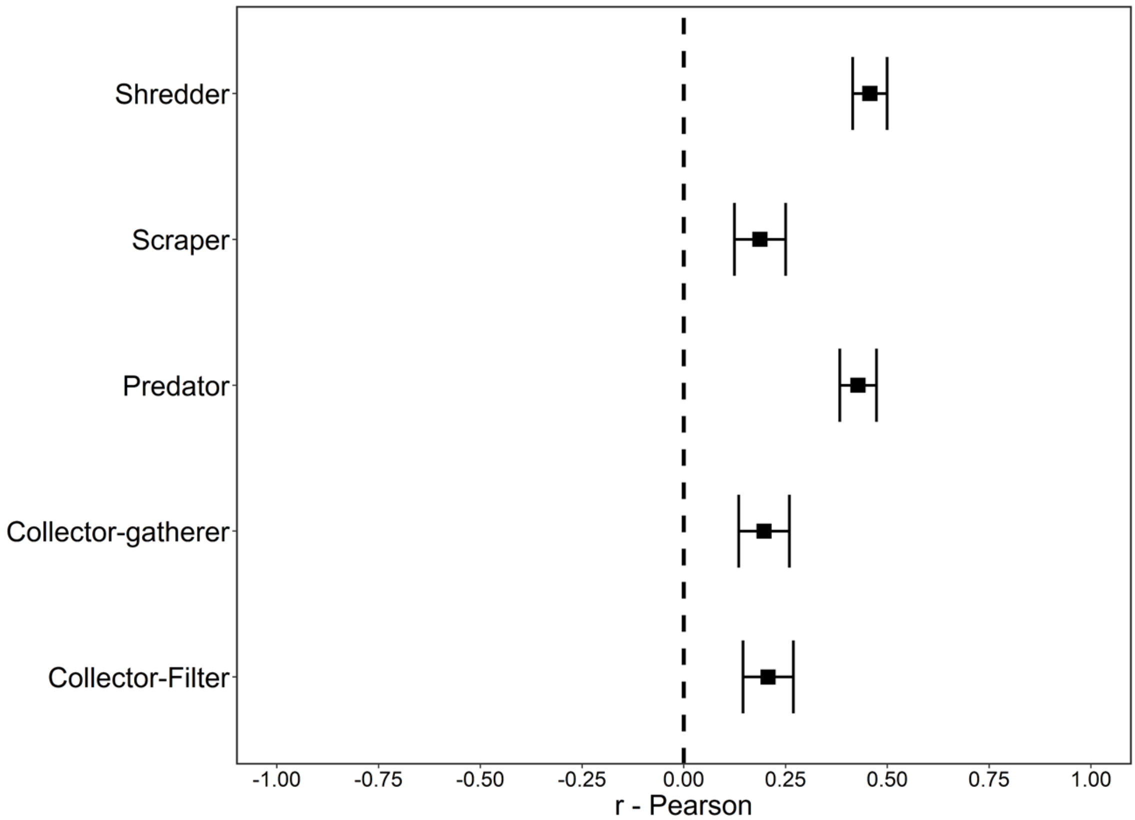

Fig 6 Forest Plot comparing the regression models of Functional Feeding Groups and the environmental gradient. The effect size was standardized with R-Pearson and the error estimate by Confidence Interval 95%.

DISCUSSION

Environmental conditions

The Amazon is one of the regions of the world with the largest extensions of native forest. Still, our results bring worrisome information on the environmental conditions of the streams. The environmental legislation includes a 30-meter zone on each bank of the stream, the riparian zone, as a permanent protection area to be kept undisturbed, and it is not being complied with in most of the sampled streams.

Studies emphasize the importance of preservation and maintenance of the riparian zone for the balance and integrity of aquatic ecosystems (Paula & Fonseca-Genners, 2010; Carvalho et al. 2018; Dalla-Corte et al. 2020). Deforestation in the riparian zone resulting from anthropogenic actions, especially agricultural activities, is one of the main factors affecting the integrity and quality of water resources in several regions of Brazil. A study of streams in areas with anthropic disturbances in southern Brazil showed the harmful impacts of deforestation of the riparian zone resulting from agricultural activities on the integrity and quality of water (Hepp et al. 2010). These effects were also detected in Southeastern Brazil, showing that livestock activities are responsible for the significant degradation of the integrity of riparian zones and, consequently, pressure on aquatic ecosystems (Tanaka et al. 2015).

The riparian zone provides essential ecosystem services for the conservation of aquatic systems, such as mitigating the entry of pollutants from anthropogenic activities that occur in the surrounding landscape and drain into the streams (Zaimes, 2007; Hepp, et al. 2010; Attanasio et al. 2012) acting as a buffer zone (Dalla-Corte et al. 2020). The removal or reduction of the riparian zone can cause alluviation of the rivers, changes in water flows, increased input of fine sediments, reduction of vegetation cover, reduced input of allochthonous organic matter from this zone and loss of habitat complexity (Paula & Fonseca-Genners, 2010; Casatti et al. 2012). These changes in natural aquatic ecosystems alter the physical characteristics of the channel (width, depth) and the physical and chemical characteristics of the water, resulting in new environmental conditions (Allan, 2004; Zaimes, 2007; Casatti et al. 2015).

Our study shows that streams located in areas with deforested riparian zone present a greater width/depth ratio. This can be associated with changes in the geomorphology of river channels, since environments with altered riparian vegetation cause the alluviation of the riverbanks and increased surface runoff and sediment deposition (Moreno & Callisto, 2005). Some ecological studies use this ratio to measure environmental impacts in drainage basins and measure habitat integrity in areas with intensive agricultural and mining activities (Callisto et al. 2014). This alluviation is very troublesome, because it often leads to a reduced amount of substrate types and an increased environmental homogeneity, with negative effects on biodiversity.

Removal of riparian vegetation cover in streams directly influences the entry of allochthonous organic matter, affecting nutrient transfer and energy flow in these aquatic systems (Paula & Fonseca-Genners, 2010; Casatti et al. 2012). In addition, the absence of woody canopy cover alters the water temperature by increasing the light contribution in the streams, and consequently changes the physical and chemical parameters of the water, resulting in an increased primary productivity rate leading to the proliferation of algae, aquatic plants and oxygen reduction (Casatti et al. 2012). The introduction of macrophytes into the system often reduces the negative effects of deforestation by increasing habitat complexity (Fares et al. 2020). However, it is of concern since the presence of macrophytes can lead to changes in functional groups as a consequence of the changes in energy input into the system.

Our results bring relevant information on the management and conservation of water resources in the Brazilian Amazon. The Brazilian Forest Code/Law nº 12.651/2012 was implemented with the objective of protecting native vegetation areas around water courses to maintain the integrity and quality of aquatic ecosystems. However, our studies show that these areas, when located in regions with influence from agricultural activities, are being degraded and/or suppressed. The changes made to areas protected by law may shed light on the greater deposition of fine sediments found in streams with the presence of riparian vegetation in the Amazon. This result may also be related to the expressive influence of cattle ranching on the sampled streams, since the cattle trampling may intensify erosion processes and soil compaction, facilitating the input of fine sediments and pollutants from adjacent activities. Furthermore, the results found to support the need for developing more efficient conservation policies to mitigate anthropogenic impacts in the riparian zones determined by the Brazilian Forestry Code and highlight the gaps in the implementation of legislation for the preservation of water resources.

Relationship between environmental conditions and Functional Feeding Groups

Environmental changes caused by the deforestation of the riparian zone creates a gradient of conditions and resources negatively related to the abundance of all FFG, especially the shredders. Therefore, our hypothesis that the shredders would have a strong relationship with environmental changes caused by riparian zone deforestation has been corroborated.

The abundance of shredders was lower in streams with higher width/depth ratios. This result may be associated with the loss of habitat complexity caused by the increased alluviation of watercourses and the deposition of sediments in channel areas with deforested riparian vegetation. These changes in aquatic ecosystems can reduce the availability of micro-habitats formed by organic substrates, which are used as a food resource by several aquatic species, especially shredders. This causes anthropized streams to present a biota similar to larger rivers, above fourth order, with a reduced dominance of shredders (Vannote et al. 1980; Dala-Corte et al. 2019). Moretti et al. (2007) showed a positive relationship between the composition of FFG and the types of habitats and resources available, showing the importance of riparian vegetation for habitat heterogeneity and to preserve the integrity of aquatic communities. The relationship between environmental conditions and FFG can be explained by the dependence of aquatic systems, especially small streams, on organic matter provided by the riparian vegetation (leaf debris, branches, trunks), an important food resource of shredders insects (Mangadze et al. 2019; Luiza-Andrade et al. 2020). The River Continuum Concept (Vannote et al. 1980) predicts that the functional groups would be related to environmental conditions and availability of organic matter of allochthonous origin, where communities would adjust to the longitudinal gradient according to their functional attributes and resource availability. The distribution of functional feeding groups follows the predictions of the River Continuum Concept in the Brazilian Cerrado, where a significant abundance of shredders has been recorded in headwaters (Shimano et al. 2012). A negative relationship between the abundance of shredders and environmental changes in streams was also recorded for the Cerrado biome (Brasil et al. 2013) and in Australian streams (Mangadze et al. 2019). These studies corroborate our results and emphasize the existence of a pattern of the response of shredders to environmental impacts in tropical streams.

The shredders were more abundant in streams with greater variation of substrate immersion in the channel. This metric is directly related to the input and deposition of sediments in the stream bed (Callisto et al. 2014). In our study, streams located in areas with native forest are located in micro-basins with intense livestock activity. Therefore, despite the presence of a preserved riparian vegetation area, cattle trampling and the degradation of streams by road construction may be the main sources of sediment input (Leal et al. 2017). Studies indicate that the presence of sediments causes negative effects on food and micro-habitat availability for the communities of EPT (Burdon et al. 2013). However, as we have shown, the amount of sediment deposited was not high enough to cause deleterious effects in these communities. Therefore, this result may be associated with the ecological adaptations and food preferences of the organisms.

The abundance of shredders was positively related to the presence of woody undergrowth. There is a general pattern where ecologically more intact forest remnants exhibit an "inverted-J" pattern, in which there is a higher density of juvenile woody plants (Bongers et al. 2010). In this condition, the greater abundance of shredders in areas with undergrowth can be explained by the fact that these places correspond to more preserved forests. Thus, the locations that are most preserved, consequently, have more forest, enable the input of food resources (organic matter) to the aquatic ecosystems (Brasil et al 2013, Mangadze et al. 2019). With this, our results emphasize the importance of maintaining the riparian vegetation for a proper functioning of the aquatic ecosystems and preservation of the associated biota.

CONCLUSION

Our results show that deforestation in the riparian zone alters the environmental conditions of the streams and the structure of the physical habitat, directly affecting the composition of the functional feeding groups of the Ephemeroptera, Plecoptera and Trichoptera (EPT) communities. Furthermore, we emphasize the effectiveness of using these groups as a tool for biomonitoring environmental integrity, and the importance of preserving and restoring the riparian forest. We also emphasize that expanding surveillance to combat illegal deforestation of the riparian zones established by the Brazilian Forestry Code can minimize the effects of anthropic activities on aquatic ecosystems, in order to conserve biodiversity and preserve water resources in the Amazon.

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Compliance with ethical standards

Conflict of interest The authors declare that the they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or vertebrate animals. All authors have approved the manuscript and agree to submission to Journal of Insect Conservation.

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CONCLUSÃO GERAL

Concluímos que o desmatamento para fins antrópicos na Amazônia altera as variáveis ambientais dos riachos, afetando diretamente a distribuição dos grupos funcionais alimentares das assembleias de Ephemeroptera, Plecoptera e Trichoptera. Além disso, nossos resultados mostram a eficiência do uso desses grupos tróficos como métrica na avaliação da integridade ambiental. Portanto, enfatizamos que a ampliação de fiscalizações e políticas ambientais podem mitigar os impactos dos diferentes usos da terra nos sistemas aquáticos, visando a preservação da biodiversidade e o desenvolvimento sustentável na Amazônia.

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