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Environmental impacts shape the density-size relationship of benthic macroinvertebrates in Amazonian streams (Serra dos Carajás, Pará, Brazil)

Impactos ambientais moldam a relação densidade-tamanho de macroinvertebrados bentônicos em igarapés amazônicos (Serra dos Carajás, Pará, Brasil)

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Abstract: Aim: Streams are small lotic ecosystems essential for aquatic biodiversity and nutrient cycling. However, they are highly susceptible to anthropogenic pressures, such as the replacement of native vegetation by plantations, which can affect aquatic communities—especially benthic macroinvertebrates, due to their sensitivity to environmental changes. While most studies rely on taxonomic metrics, there is growing evidence that changes in riparian vegetation can alter size-density relationships. We hypothesized that impacted streams would exhibit shifts in macroinvertebrate size-density patterns reflecting environmental degradation. **Methods:** We sampled 15 Amazonian streams in the Serra dos Carajás region, southeastern Pará State, Brazil, an area influenced by agriculture, livestock, and mining. Sampling occurred during the dry season across two campaigns. Macroinvertebrates were collected using a kick-net, and physical-chemical variables were measured with a multiparameter probe and turbidimeter. Environmental variables were analyzed using principal component analysis, and size-density relationships were evaluated with a second-order polynomial model. **Results:** Agricultural impact altered size-density relationships. Impacted sites showed reduced macroinvertebrate density across all size classes and a concentration of individuals in intermediate sizes. These changes suggest a simplification of trophic networks and decreased energy transfer efficiency. **Conclusions:** Anthropogenic impacts significantly alter aquatic communities in Amazonian streams. The study demonstrates that agricultural activity reduces macroinvertebrate density in all size classes, signaling a widespread collapse of trophic networks. These findings highlight the vulnerability of Amazonian streams to human disturbances and underscore the importance of monitoring size-density relationships as indicators of ecosystem integrity.

Keywords: Amazon; environmental degradation; size spectra; biodiversity; streams.

Resumo: Objetivo: Os riachos são ecossistemas lóticos de pequeno porte, essenciais para a biodiversidade aquática e o ciclo de nutrientes. No entanto, são altamente suscetíveis a pressões antrópicas, como a substituição da vegetação nativa por plantações, o que pode afetar as comunidades aquáticas — especialmente os macroinvertebrados bentônicos, por serem mais sensíveis a alterações ambientais. Embora a maioria dos estudos utilize métricas taxonômicas, há evidências de que mudanças na vegetação ripária podem afetar as relações entre tamanho e densidade dos organismos. Neste estudo, testamos a hipótese de que riachos impactados apresentariam alterações nas relações tamanho-densidade de macroinvertebrados, refletindo mudanças nas condições ambientais. **Métodos:** Amostramos 15 riachos amazônicos na região da Serra dos Carajás, sudeste do estado do Pará, Brasil, uma área sujeita a atividades agropecuárias e de mineração. As coletas foram realizadas durante a estação seca, em duas campanhas. Os macroinvertebrados foram coletados com rede de arrasto (kick-net), e as variáveis físico-químicas foram medidas com sonda multiparâmetros e turbidímetro. As variáveis ambientais foram analisadas por análise de componentes principais, e as relações tamanho-densidade foram avaliadas por modelo polinomial de segunda ordem. **Resultados:** O impacto agrícola alterou as relações tamanho-densidade. Os locais mais impactados apresentaram redução na densidade de macroinvertebrados em todas as classes de tamanho, com maior concentração de indivíduos em classes intermediárias. Esses padrões sugerem simplificação das redes tróficas e menor eficiência na transferência de energia. **Conclusões:** Os impactos antrópicos alteram significativamente as comunidades aquáticas nos riachos amazônicos. O estudo demonstra que o impacto agrícola reduz a densidade de macroinvertebrados em todas as classes de tamanho, indicando um colapso generalizado nas redes tróficas. Esses resultados destacam a vulnerabilidade dos riachos amazônicos a distúrbios de origem antrópica e ressaltam a importância do monitoramento das relações tamanho-densidade como indicadores ecossistêmicos.

Palavras-chave: Amazônia; degradação ambiental; espectro de tamanho; biodiversidade; riachos.

1. Introduction

Streams play a fundamental role in maintaining the diversity of aquatic biota and in dispersing and cycling nutrients essential for the growth and development of riparian vegetation in the highland regions of the Amazon (Junk et al., 2011). These lotic ecosystems are dependent on the surrounding riparian forest, which serves to maintain water quality and soil stability, regulate hydrological cycles, and contribute to biodiversity conservation (Monteiro et al., 2008; Cardoso et al., 2018; Santos et al., 2021). However, streams are under pressure from the impacts of anthropogenic activities that cause a variety of biotic and abiotic changes across different spatial scales (Cabrera et al., 2023). One of the main anthropogenic impacts on streams is the replacement or suppression of native vegetation. As this vegetation has a relevant ecosystem function, its alteration leads to changes in the structure and functioning of stream biological communities (López-Rojo et al., 2019).

Changes in species composition and food webs of benthic macroinvertebrates are commonly observed following the loss of native vegetation, since the primary source of organic matter in streams comes from the riparian forest (Kominoski et al., 2013; Alonso et al., 2021). Although most studies on anthropogenic impacts on streams and aquatic communities focus on taxonomic metrics of benthic macroinvertebrates (Kominoski et al., 2011; Schmera et al., 2017; Sotomayor et al., 2022), there is evidence that riparian vegetation replacement affects the size and density of these organisms (Tolonen et al., 2003; Stone et al., 2005; Fierro et al., 2017; Collyer et al., 2023). Changes in feeding rates, growth and maximum body size of benthic macroinvertebrates are also expected as a result of these anthropogenic impacts (García-Girón et al., 2022). Another relevant point is that the intensification of land use near streams through activities such as mining, agriculture and grazing reduces environmental quality (Martínez et al., 2016; Poeppl et al., 2019).

Mining affects a broad size spectrum, reducing population density due to the intense discharge of toxic materials contaminating tributaries (Pomeranz et al., 2019; Zou et al., 2019). A high degree of pasture generates soil compaction due to cattle trampling, intensifying erosion, siltation and intense contribution of particles to the water (McInnis & McIver, 2001; Thomaz et al., 2020). This impact has been associated with average body size in relation to areas with low pasture (Yadamsuren et al., 2022). Agriculture, in particular, directly contributes to the loss of riparian vegetation and contamination of streams by pesticides, resulting in eutrophic rivers (Vilches et al., 2013; Wild et al., 2019). Other studies have shown that these impacts tend to favor smaller species over larger ones (Krynak & Yates, 2020; Pott et al., 2021; Collyer et al., 2023). Such disturbances reduce nutrient availability, interfere with the food chain and affect predator-prey relationships by altering aspects of the body size of aquatic organisms (García-Girón et al., 2022).

Body size is widely recognized as one of the most important biological traits for explaining metabolism, trophic interactions, and abundance distributions in food webs (Chang et al., 2014; Potapov et al., 2019). Changes in the relationship between body size or biomass and abundance (i.e., "size spectra") can be used to assess food web responses across environmental gradients (Petchey & Belgrano, 2010; Potapov et al., 2019; Pomeranz et al., 2022). The slope of this relationship is particularly important in aquatic ecosystems. A steeper slope indicates a greater abundance of small organisms relative to large ones, and may occur in environments with high predation pressure or due to disturbances that favor fast-growing species with short life cycles (Tolonen et al., 2003; Castro et al., 2018; Pomeranz et al., 2022). In contrast, a less steep slope indicates a community with a relatively higher proportion of larger organisms, indicating a more stable environment less affected by human activities (Brown et al., 2004; Castro et al., 2018). However, this parameter needs to be interpreted with caution and always considering the context of the study, because observing a pattern does not necessarily imply causation of a process (Chave, 2013).

Some studies show opposite effects of the size-density response to environmental stressors. For example, in environments impacted by agriculture, a greater abundance of larger individuals can be observed, explained by the moderate increase in nutrients favoring the growth of organisms with high metabolic needs (Juvigny-Khenafou et al., 2021). In addition, the predominance of larger organisms intensifies competitive pressure due to their greater efficiency in exploring resources, resulting in a decrease in the abundance of smaller organisms (Gjoni et al., 2017). Therefore, the type and intensity of the stressor influence the size range of the organisms (Paiva et al., 2023), promoting changes in the structure and trophic relationships of aquatic communities.

In our study, we observed the size-density relationship of aquatic macroinvertebrates, from tributary streams of the Itacaiúnas River, in areas subjected to different levels of anthropogenic impact from agricultural, livestock and mining activities. We used body size as a proxy for biomass because these traits exhibit a well-documented and consistent relationship in the literature (Atkinson et al., 2020; Nitschke et al., 2024). We studied aquatic macroinvertebrate communities in streams within the Serra dos Carajás (northern Brazil), an area notable for its extensive preserved high elevation Amazon rainforest, but increasingly impacted by mining, agriculture, and livestock activities (Oliveira et al., 2024). We tested the hypothesis that the size-density relationship of macroinvertebrate communities varies across sites impacted by human activities, expecting that smaller organisms will be more abundant in impacted areas due to greater environmental instability and reduced resource availability. We expect that streams in agriculture and mining sites have a significant impact on the strength of the density-size relationship, compared to forested streams, since the suppression of riparian vegetation reduces allochthonous resources, generating nutritional losses and, consequently, reducing the size of organisms (Collyer et al., 2023).

2. Methods

2.1. Study area

We selected 15 streams in the Serra dos Carajás, a region situated in the southeastern Amazon (Pará, Brazil). These streams are tributaries of the Itacaiúnas River, with drainage basins encompassing varying degrees of anthropogenic impact, including Conservation Units (UC), agricultural land use, and mining areas—primarily for iron extraction (Figure 1). Notably, mining activities within the UC, conducted predominantly by Vale S.A. using open-pit methods, are subject to stringent regulatory oversight by environmental agencies (e.g., ICMBio). This ensures compliance with environmental legislation, including the preservation of riparian forests and the treatment of mining effluents.

The Serra dos Carajás has an average elevation of 700 meters, featuring flattened residual plateaus deeply dissected by valleys (Dias & Paradella, 1997). According to the Köppen classification, the region exhibits an AWi climate—tropical rainy with annual precipitation ranging from 2,000 to 2,400 mm and temperatures between 24.3 °C and 28.3 °C. Climatic conditions are marked by two distinct seasons (Rolim et al., 2006): a dry season (June to November) and a rainy season (December to May). Sampling was conducted during two dry-season campaigns (August-September 2022 and June-July 2023), as macroinvertebrate sampling success rates are highest in this period (Bispo & Oliveira, 2007). The sampled streams in mining areas were located within zones of indirect mining influence, avoiding active pit sites. The predominant agricultural activity in the region is extensive livestock farming.

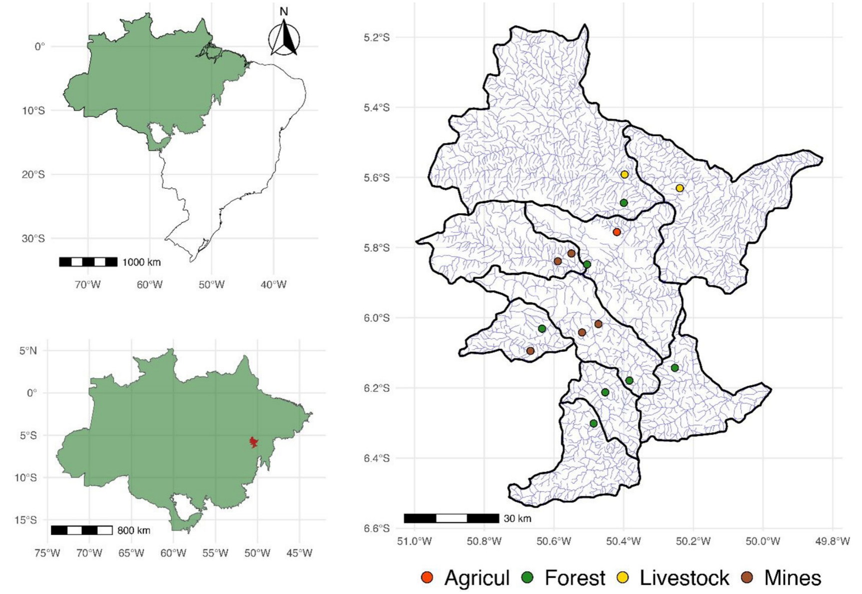

Figure 1. Sampled streams and land use classification in the Itacaiúnas River (Serra dos Carajás), Pará, Brazil. Green circles within the buffer zone indicate forested areas. Brown circles indicate areas with mining activities. Yellow circles represent pasture environments. Orange circles represent environments with agricultural ("Agricul") activity. The boundaries are of the watersheds of the Itacaiúnas River tributaries.

2.2. Data sampling

Prior to macroinvertebrate collection, we measured physical and chemical stream variables—dissolved oxygen, pH, electrical conductivity, turbidity, and temperature—at five points per stream using a multiparameter probe and turbidimeter, subsequently calculating the mean value for each variable. To evaluate the integrity of stream physical structure and riparian vegetation, we applied a modified version of the protocol by Peck et al. (2006). This protocol was selected for its ability to differentiate between distinct anthropogenic impacts, enabling us to distinguish agricultural (*w1_hoag*) from mining-related (*w1_hnoah*) disturbances. Our adaptation simplified the original protocol by reducing both the number of measured variables and the transects per stream to five.

The impact indices were estimated using the following metrics: presence of constructions such as walls (Na1), buildings (Na2), roads (Na3), highways (Na4), pipes (Na5), debris (Na6), parks (Na7), mining activities (Na8), plantations (A1), pastures (A2), and forestry (A3). Each impact was categorized by its proximity to the stream: *Absent* (no impact), *Greater than 10 meters away*, *Less than 10 meters away*, or *On the stream margin*. Metrics Na1–Na8 assessed proximal human activities linked to mining (*w1_hnoah*), while A1–A3 quantified agricultural impacts (*w1_hoag*).

The *w1_hnoah* and *w1_hoag* indices were scaled from 0 to 1, where 0 denotes no detectable impact and 1 represents a fully modified environment. Notably, some streams exhibited both agricultural and mining influences, allowing for the concurrent measurement of these combined impacts. The predominant non-agricultural activities in the region were related to mining.

Benthic macroinvertebrates were sampled using a kick-net collector (30 x 30 cm area and 500 µm mesh). In the streams, we selected five leaf litters 10 m apart for sampling. We sampled an area of 1 m^2 in each leaf litter. The leaf litter in the rapids (fast-flowing, turbulent sections of streams characterized by shallow depths, exposed bedrock or coarse substrates) was chosen as the sampling unit because this habitat usually has a greater diversity of organisms than other habitats in small streams (Bispo & Oliveira, 2007; Godoy et al., 2019). Samples were preserved in situ in 70% alcohol, and identification was performed using a stereo microscope to the lowest possible taxonomic level according to the dichotomous identification keys of Hamada et al. (2019) and Mugnai et al. (2010). For the orders Coleoptera, Ephemeroptera, Hemiptera, Lepidoptera, Megaloptera, Odonata, Plecoptera, Trichoptera and Tricladida we identified until genera level. We used the family level for Annelida, Decapoda, Diptera and Neuroptera. The body size of each individual was measured using millimeter paper attached to the Petri plate. We measured the carapace width of Decapoda, the thorax-to-abdomen distance for Diptera and Tricladida (where head boundaries were unclear), and the total body length for all other groups.

2.3. Data analysis

The physical and chemical parameters were standardized (*z* distribution, zero mean and one standard deviation for all variables) and then synthesized in a Principal Component Analysis (PCA), where we selected the number of PCs using the Broken-Stick criterion (Jackson, 1993).

Initially, we applied a base-two logarithmic transformation for the body size values, and then estimated the number of organisms that would be allocated to each size class. To define the number of size classes for the organisms we used the following Equation 1:

$$k = 1 + 3.322 \cdot Log_{10} n \quad (1)$$

where *k* was the estimated number of classes and *n* was the number of individuals measured in the stream.

We calculated the amplitude of each class using the Equation 2:

$$a = \left(max - min\right) \cdot k^{-1} \quad (2)$$

where *max* and *min* were the largest and smallest size values measured in the stream, respectively. The values of a have been rounded up.

Using the value of *a* we calculated the lower and upper limits for each size class, starting with the first with the lower limit equal to the smallest size measurement and the upper limit being *min* + *a*. For the second class, the lower limit was *min* + *a* and the upper limit *min* + 2*a*. We used the same logic for the subsequent classes. After defining the amplitudes of all the classes, we counted how many size measurements were within the class intervals. As the size classes are intervals, we used the average values of the intervals as a proxy for each class. In addition, we also applied a base-two logarithmic transformation to the densities.

To test the effect of environmental variables on size-density relationships, we used the data transformed into a second-order polynomial function (Equation 3):

$$Log_2 N_{i,j} = a + b_1 Log_2 S_{i,j} + b_2 \left(Log_2 S_{i,j}\right)^2 + c_1 W1_{HNOAG,j} + c_2 W1_{HAG,j} + d_1 PCA_{1,j} + d_2 PCA_{2,j} \quad (3)$$

In this model, $N_{i,j}$ was the abundance of class *i* in stream *j*, $S_{i,j}$ was the mean size of class *i* in stream *j*, $W1_{HNOAG,j}$ was the non-agricultural impact index in stream *j* and $W1_{HAG,j}$ was the agricultural impact in stream *j*. The values of PCA_{1j} and $PCA_{2,j}$ were relative to the eigenvectors one and two of the PCA for the physicochemical data in stream *j*, respectively. To evaluate the environmental and bionomic effects on the macroinvertebrate density classes, we ran the polynomial model for the organism density-size relationship separately for each stream. The full model included both impact types, but subsequent interpretation emphasized agricultural effects based on statistical significance (Table 1). Non-significant terms were retained to maintain model structure and avoid selective variable removal (Figure 2). Since the size-density relationship of macroinvertebrates tends to change when the stream is subject to environmental impacts. All analyses were performed using R (R Core Team, 2021).

3. Results

We identified and measured 1.936 individuals of leaf-litter-associated macroinvertebrates in the 15 streams sampled, distributed in 100 genera representing 68 families. The order with the highest abundance was Trichoptera (706 individuals), followed by Ephemeroptera (302 individuals) and Plecoptera (252 individuals). The most abundant genera included *Anacroneuria* (Perlidae, 204 individuals), *Oecetis* (Trichoptera, 190 individuals), and *Chimarra* (Trichoptera, 182 individuals). Turbidity and electrical conductivity showed the greatest variability among environmental variables, in contrast to dissolved oxygen and water temperature (Table available in Godoy & Valente-Neto, 2025).

Table 1. Environmental effects in size spectra of benthic macroinvertebrates in streams associated with Itacaiunas River (Serra dos Carajás), Pará, Brazil.

Coefficients	Estimate	Std. Error	t-value	P
Intercept	1.82	0.41	4.41	< 0.05
Size	1.92	0.29	6.62	< 0.05
Size^2	-0.39	0.05	-0.71	< 0.05
Non agricultural	0.39	0.54	0.71	0.48
Agricultural	-3.89	0.87	-4.46	< 0.05
FQ PCA1	0.03	0.07	0.44	0.66
FQ PCA2	-0.04	0.13	-0.32	0.75

The sampling units were the class size and abundance. Adjusted $R^2 = 0.40$, $F_{6,115} = 14.69$, $P < 0.05$. t-value: Statistic of Student's t-test for coefficients.

Using the Broken-Stick criterion, we selected the first two axes of the PCA, where axis 1 was associated with conductivity and temperature, and axis 2 was associated with turbidity and dissolved oxygen (Table 2; Figure 3). We observed that neither the physical nor the chemical parameters influenced the macroinvertebrate size-density relationship (Table 1). The size-density relationship of aquatic macroinvertebrates was influenced by the degree of agricultural impact on the environment of the sampled streams. We observed a reduction in the maximum value of the parabola, indicating that more impacted sites by agriculture have lower densities in all size classes. In all streams sampled, the density of individuals tended to increase in the intermediate size classes. Then it tended to decrease, indicating that the small and large size classes had lower densities (Figure 4; Table 1).

Table 2. The correlation of physical and chemical variables with PCA axes.

Variable	PC1	PC2
Temperature	0.59	0.18
pH	-0.51	-0.00
Electrical conductivity	0.58	-0.23
Turbity	0.18	0.61
DO	0.10	-0.73
Standard deviation	1.40	1.11
Broken Stick	2.28	1.28
Cumulative proportion	0.39	0.64

DO = dissolved oxygen.

4. Discussion

Our results indicate that the size-density relationship of benthic macroinvertebrates depends on the quality of the streams and the riparian forest in which they inhabit. In this regard, it is important to note that agricultural production areas had a significant impact on these communities, resulting in a reduction in the average size of the organisms. Although mining activities are widespread in the region, their effects on size-spectra appeared less pronounced than those of agriculture. This pattern may reflect: (1) stricter environmental controls in mining areas, or (2) differential biological responses to agricultural versus mining-related disturbances. Furthermore, our analysis revealed that physicochemical water variables showed no apparent influence on macroinvertebrate size-density relationships. This suggests that in these stream systems, other ecological factors - particularly habitat structure and riparian vegetation characteristics - may exert stronger control over community size structure than either water chemistry or the anthropogenic impacts we measured (Allan, 2004; Clarke et al., 2010; Nash et al., 2014). However, the absence of a clear relationship between these variables and the distribution of macroinvertebrates suggests that the influence of anthropogenic impacts may be

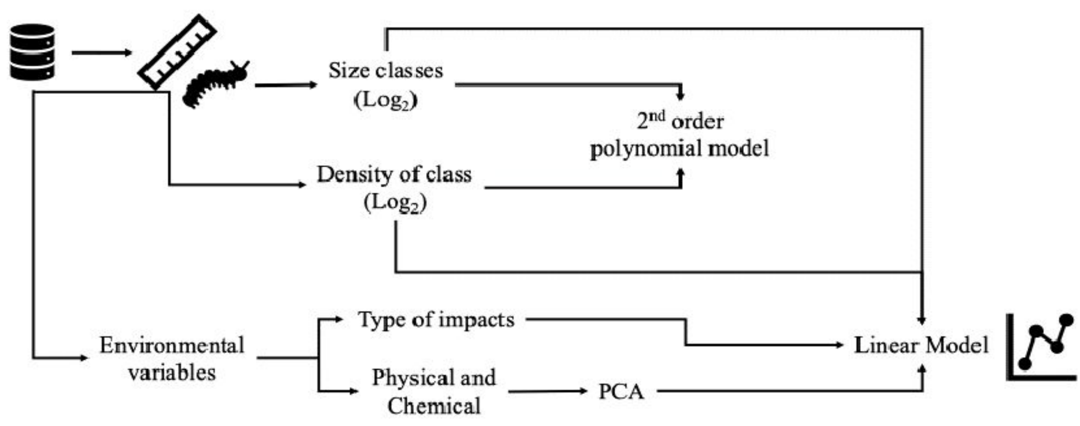

Figure 2. Conceptual model of the data analysis framework. The response variable was the density of macroinvertebrate size classes (log_2-transformed), while predictors included environmental variables (physical and chemical parameters synthesized via PCA) and anthropogenic impact types (agricultural: *w1_hoag*; mining-related: *w1_hnoah*). Size classes were log_2-binned, and their densities were modeled using a second-order polynomial regression to test the effects of body size (linear and quadratic terms), land-use impacts, and PCA-derived environmental gradients. The PCA reduced the dimensionality of physicochemical variables (e.g., dissolved oxygen, turbidity, pH), and the full model retained non-significant terms to avoid selective bias. Arrows in the diagram represent directional relationships, illustrating how predictors influence size-density patterns.

mediated by indirect mechanisms, such as changes in the availability of microhabitats or the dynamics of ecological interactions within these communities (Gjoni et al., 2017; Gjoni & Basset, 2018).

The relationship between the size of macroinvertebrates and the quality of streams is influenced by various anthropogenic and environmental factors that alter the physical and chemical characteristics of aquatic ecosystems (Cadmus et al., 2020; Nash et al., 2021). These changes can negatively affect the most sensitive organisms, reducing their fitness and increasing their mortality (Copatti et al., 2010; Godoy et al., 2018). As a consequence, these organisms face greater energy demands to cope with environmental stressors, needing to redirect energy from growth and reproduction to survival (Pomeranz et al., 2019). In our study, this ecological process is reflected in the prevalence of smaller individuals in streams with higher levels of anthropogenic impact and environmental degradation. The reduction in body size and densities observed suggests an energy trade-off consistent with the selective pressure described in the literature.

Environmental impacts affect both the biotic aspects of communities and the abiotic characteristics of water bodies, selecting many individuals that cannot complete their life cycle in degraded environments (Barreiros et al., 2023). Organisms from the Ephemeroptera, Plecoptera, and Trichoptera (EPT) orders are often considered indicators due to their sensitivity to environmental changes (Ab Hamid & Md Rawi, 2017), which may affect their persistence in impacted streams (Godoy et al., 2022). However, the theoretical description of how this impact affects the size-density relationship of macroinvertebrates is still uncertain, representing a limitation of our study.

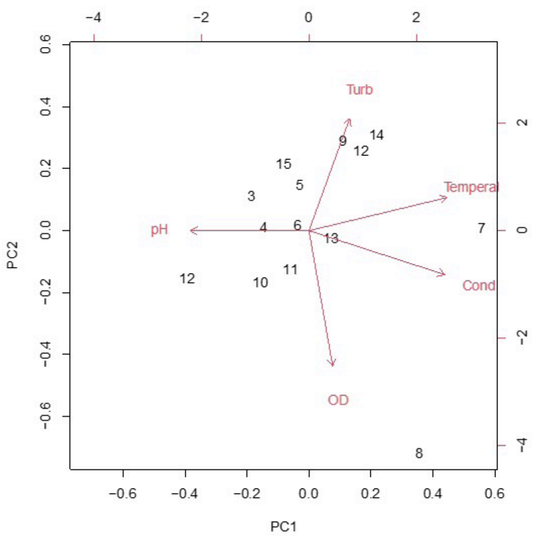

Figure 3. Physical and chemical variables related to stream environmental conditions in the Itacaiunas River region (Serra dos Carajás), Pará, Brazil. Cond = electrical condutivity; OD = oxygen dissolved; Tempera = temperature; Turb = turbidity.

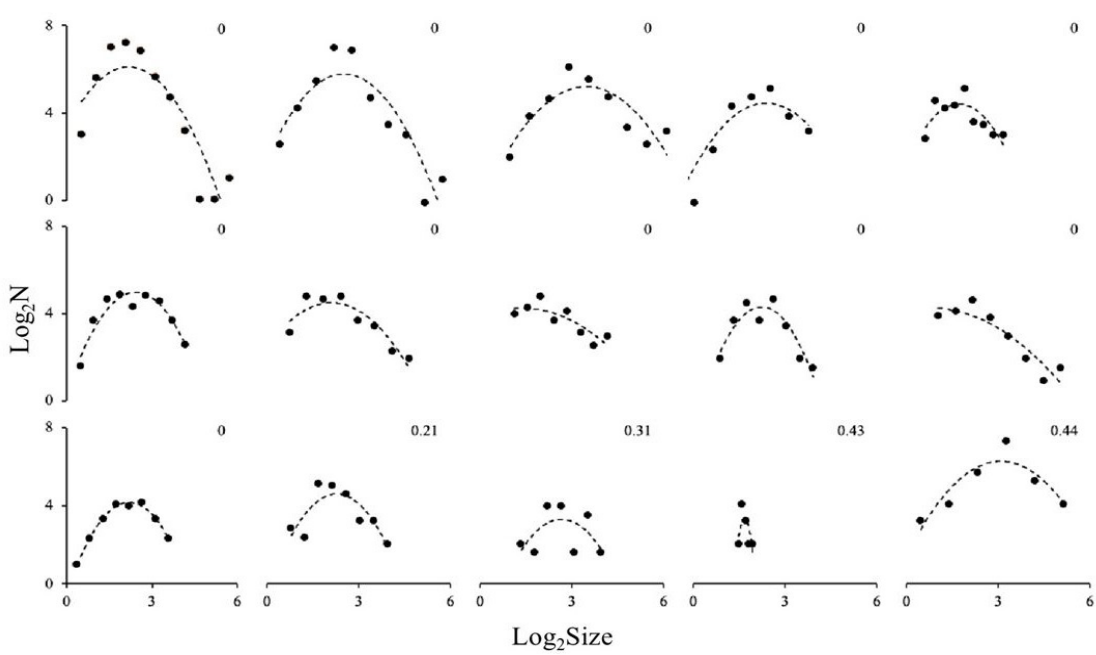

Figure 4. Size-spectra relationship in 15 streams associated with the Itacaiunas River (Serra dos Carajás), Pará, Brazil. The value in each graph indicates the influence of agricultural impacts.

Excessive energy expenditure to stay alive, along with mortality associated with environmental changes, may be the cause of the alteration in this bionomic relationship (Pomeranz et al., 2019).

Previous studies have reported distinct patterns in density-size relationship response to environmental changes. For example, studies conducted in European streams under different levels of impact showed that, in some cases, the taxonomic diversity of macroinvertebrates can be maintained but with significant structural changes in the size-density relationships (Schmid et al., 2000). These differences may be related to the specific characteristics of each ecosystem and the type of disturbance experienced, indicating that the size-density relationship may respond differently depending on local conditions (Gjoni et al., 2017). Furthermore, it is important to consider that the intensity and frequency of environmental disturbances may influence these patterns. Environments subject to constant impacts may favor only organisms with high ecological plasticity, while sporadic impacts may allow the recovery of some sensitive species over time (Pazzaglia et al., 2021).

Our findings align with Martínez et al. (2016), who observed that the replacement of native vegetation with exotic pine plantations reduced the density of smaller macroinvertebrates and overall taxonomic diversity in tropical streams. However, while their study highlighted the dominance of smaller organisms in impacted areas, our results further demonstrate a generalized reduction in density across all size classes under agricultural pressure, suggesting a broader collapse in community structure rather than a mere shift toward smaller individuals. In southeastern Brazil, the size spectrum of organisms in streams disturbed by agricultural activities showed a reduction in size spectrum slope, and the number of small organisms (Collyer et al., 2023). This result suggests the improvement of energy transfer efficiency in these systems, indicating that land use intensification alters the structure and size of aquatic macroinvertebrate communities. Additionally, this pattern of size spectrum flattening has been reported in other impacted aquatic ecosystems, reinforcing the idea that changes in community structure may be associated with shifts in energy flows within food chains (Gjoni et al., 2022).

Although our study offers valuable insights into how anthropogenic disturbances influence community size structure of benthic macroinvertebrates, some limitations must be acknowledged. Due to the observational nature of our research, we were unable to locate streams in the region with mutually exclusive agricultural (*w1_hoag*) and mining (*w1_hnoah*) impacts. Many agriculturally impacted streams were also subject to mining pressures, reflecting the region's high mining activity (Oliveira et al., 2025). In contrast, streams affected solely by mining were common both in the study area and our dataset. Nevertheless, our findings indicate that this limitation did not compromise the robustness of our results, as we still detected clear effects of agricultural impacts on aquatic macroinvertebrate community structure. The information presented helps to establish basic elements for understanding the effects of impacts on the size structure of macroinvertebrate communities in Amazonian streams.

The higher density of intermediate size classes found in our study reflects an ecological pattern in which intermediate organisms may be less subject to anthropogenic pressures due to their greater ecological flexibility and ability to cope with environmental variations. Some studies have reported a flattening of the size spectrum curve in disturbed streams, indicating that energy transfer efficiency is compromised in degraded environments, reflecting an imbalance in food chains, where the reduction in the density of extreme classes may compromise the trophic functionality and the role of larger organisms, which act as top predators or keystone species in energy flow (Harvey et al., 2018; Barnes et al., 2020). Moreover, environments with higher ecological integrity exhibit greater total biomass, which supports a broader range of size classes and promotes more efficient energy transfers along food webs (Vinson & Hawkins, 1998).

5. Conclusion

Our study tested the hypothesis that the size-density relationship of aquatic macroinvertebrates varies according to the level of anthropogenic impact, and that smaller organisms are more abundant in impacted areas due to greater environmental instability and scarcity of resources. However, the results showed that under agricultural pressure, there is a reduction in density in all size classes, including the smallest, indicating a broader negative effect on these communities, suggesting that in addition to replacement by smaller organisms, there is also a generalized collapse in abundance, possibly caused by intense habitat degradation and the simplification of food webs. These findings reinforce that agricultural activities can compromise the ecological structure of

Amazonian streams, thereby affecting the efficiency of energy transfer and the resilience of ecosystems. In order to improve our understanding about the effects of land use types on stream food webs, further studies should analyze the different types of impact in isolation, as well as include seasonal data and specific trophic interactions. We therefore emphasize the importance of conserving riparian forests as crucial strategy for mitigating the effects of anthropogenic pressure on Amazonian streams.

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Data availability

All research data analyzed in the research is available at Zenodo. Access is open. It can be accessed in: https://doi.org/10.5281/zenodo.15080061.

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