**Research Article**

# Riparian deforestation affects the structural dynamics of headwater streams in Southern Brazilian Amazonia

**Monica Elisa Bleich[1]*, Amanda Frederico Mortati[2], Thiago André[3] and Maria Teresa Fernandez Piedade[1]**

[1] Instituto Nacional de Pesquisas da Amazônia (INPA), Manaus, Amazonas, Brasil. E-mail address: monicableich@gmail.com; maua.manaus@gmail.com

[2] Universidade do Estado de Mato Grosso, Alta Floresta, Mato Grosso, Brasil. E-mail address: amortati@gmail.com

[3] Universidade Federal do Rio de Janeiro, Departamento de Botânica, Rio de Janeiro/RJ, Brasil. E-mail address: thiagojcandre@gmail.com

*Corresponding author: Caixa Postal 324 CEP: 78580-000 Alta Floresta-MT, Brasil. E-mail address: monicableich@gmail.com

**Abstract**

Comparative studies of streams with altered versus conserved riparian zones are important to evaluate the degree of alterations caused by inappropriate use of these streams' vital buffer zones. The aim of this study was to determine the impact of riparian deforestation on the habitat structure of southern Brazilian Amazonian headwater streams, as well as to provide elements for impact assessment and the monitoring of these water bodies. We selected ten sites and two headwater streams at each site; one stream was located in an area with preserved riparian vegetation (pristine streams) and the other stream in a deforested riparian zone (altered streams). Stretches of these streams were analyzed across hydrological periods (dry period, beginning of the rainy period, and end of the rainy period) for hydro-morphological aspects, water physical-chemical variables, and habitat integrity (proportion of forestation in buffer zones and habitat integrity index). Compared to pristine streams in all the hydrological periods analyzed, altered streams presented lower oxygen concentration (~1.0 mg/L), an increase of 1 ºC in water temperature, and less organic material availability. We found that riparian deforestation affects habitat structure variability among hydrological periods, making them more homogeneous. Therefore, beyond the necessary broadening of the spatial scale of studies in this region, monitoring these understudied headwater stream environments is also crucial for determining the magnitude of deforestation effects on these vulnerable aquatic ecosystems.

**Key-words**: riparian zone; environmental impact; lotic ecosystems; temporal variation; water physical-chemical conditions

**Resumo**

Estudos comparativos entre riachos com zona ripária alterada e conservada são importantes para avaliar o grau de alteração provocado pelo uso indevido desta zona tampão vital aos corpos de água. Logo, o objetivo deste estudo foi determinar o impacto do desmatamento da florestal ripária sobre a estrutura do habitat de riachos de cabeceira no sul da Amazônia, e fornecer elementos para avaliação de impacto e monitoramento desses corpos de água. Nós selecionamos 10 locais e em cada local 2 riachos, sendo um riacho localizado em área com floresta ripária preservada (riachos pristinos) e outro riacho com a floresta ripária desmatada (riachos alterados). Trechos destes riachos foram analisados durante 3 períodos hidrológicos (período de seca, enchente e vazante) para a caracterização de aspectos hidromorfologicos, variáveis físico-químicas e de controle para a integridade do habitat (proporção de floresta em área ripária e índice de integridade do habitat). Em relação aos riachos íntegros, em todos os períodos hidrológicos avaliados, os riachos alterados apresentaram menor concentração de oxigênio (~ 1,0 mg/L), aumento de 1 ºC na temperatura da água e menor disponibilidade de material orgânico alóctone. Nós detectamos que o desmatamento da floresta ripária afeta a variabilidade na estrutura do habitat entre os períodos hidrológicos, tornando-os mais homogêneos. Portanto, além de ser necessária a ampliação da escala espacial dos estudos nesta região de inúmeras nascentes hidrográficas ainda pouco estudadas, o monitoramento desses ambientes é crucial para que possam ser descritos padrões mais claros sobre a magnitude dos efeitos do desmatamento nesses sistemas aquáticos tão vulneráveis à ação humana.

**Palavras-chave:** Zona ripária; impactos ambientais; ecossistemas lóticos; variação temporal; condições físico-químicas da água.

Received: 11 July 2014; Accepted 18 September 2014; Published: 15 December 2014

Copyright: © Monica Elisa Bleich, Amanda Frederico Mortati, Thiago André and Maria Teresa Fernandez Piedade. This is an open access paper. We use the Creative Commons Attribution 4.0 license http://creativecommons.org/licenses/by/3.0/us/. The license permits any user to download, print out, extract, archive, and distribute the article, so long as appropriate credit is given to the authors and source of the work. The license ensures that the published article will be as widely available as possible and that your article can be included in any scientific archive. Open Access authors retain the copyrights of their papers. Open access is a property of individual works, not necessarily journals or publishers.

Cite this paper as: Bleich, M. E., Mortati, A. F., André, T. and Piedade, M. T. F. 2014. Riparian deforestation affects the structural dynamics of headwater streams in Southern Brazilian Amazonia. *Tropical Conservation Science* Vol.7 (4): 657-676. Available online: www.tropicalconservationscience.org

## Introduction

Patterns and processes in streams are determined by ecological and hydrological connectivity [1-5], in which habitat heterogeneity plays an important role [6]. Climatic and geological conditions can affect the supply of nutrients [7], while riparian zone and watershed conditions control light entry as well as litter and debris buildup [8], thus determining stream autotrophy and heterotrophy [7]. Stream habitat heterogeneity is also required to maintain the diversity of ecosystem processes and maintain habitat integrity [6, 9]. Therefore, the human-induced simplification of natural habitats can alter the functioning of aquatic ecosystems at spatial [6] and time scales [16], given that habitat quality has a significant effect on patterns of species richness and abundance [10] and, consequently, on the trophic relationships of water systems [11].

Since watersheds directly influence aquatic ecosystems [12], degradation of the riparian stream zone, as well as loss of connectivity to downstream ecosystems, threatens the biological integrity of river networks [13]. In South Amazonia, this situation derives mainly from the damming of streams and rivers, often with the purpose of storing water for cattle. Although vast areas in Southern Brazilian Amazonia have been suffering intense changes in land use [14], mainly due to large-scale soybean agriculture and pasture establishment [15], the consequences of deforestation on the structure of stream ecosystems have been investigated only in a few regions. For example, studies conducted in the state of Rondônia (Madeira River basin) showed that replacing riparian forest with pastures for grazing affects the hydrology, nutrient concentrations, and benthic habitats of streams, particularly in micro and meso spatial scales. In a small watershed of two stream pairs in the upper Jamari basin, suspended material, particulate organic carbon, and organic nitrogen concentrations are higher in pasture than in forested streams, but only in the dry period [16]. In a broader scale study, tributaries along the Madeira basin exhibit high nitrogen and phosphate concentrations within watersheds with at least 75% of degraded area, in the dry period [17]. These watersheds also exhibit changes in structural dynamics, from water flow to aquatic habitats [18].

In the Ji-Paraná basin, pasture presence is a major factor affecting the chemical composition of streams' superficial waters, since a 10% increase of pasture area can produce three times higher phosphate and one and a half times higher dissolved organic nitrogen concentrations, and the stormflow volume in pasture increased seventeen times that of forested sites [19, 20]. In the upper Jamari basin, tributaries showed an increase in runoff, while differences in stream flow responses between the early and late rainy season were related to the convertion of forest to pasture. At the Ji-Paraná basin, streams subjected to pasture land cover have changed aquatic habitat complexity, from a channel composed of runs and pools and forest leaf detritus (50% cover) to a channel covered with grass (63%), mainly with slow-moving water [21]. In the Tocantins and Araguaia rivers, large-scale deforestation contributes to a 25% increase in river flow [22]. In upper Xingu watersheds, covered by plantations in Brazilian Mato Grosso state, Hayhoe et al. [15] reported a reduction in evapotranspiration as well as an increase in flow and seasonal variability compared to forested watersheds; this pattern could be mirrored in the agriculture-dominated landscapes of the Southern Brazilian Amazon, causing important alterations in regional hydrology.

Laurance et al. [23] reported that particularly in South America, tropical ecosystems face unprecedented anthropogenic pressures, which affect biodiversity and ecosystem services. Given the steady increase in deforestation in the different ecosystems of the Amazon and the huge network of rivers of various orders that cut across the region, the degradation of water bodies has been continuously increasing. These environments need to be rehabilitated in order to restore their multiple functions and ecosystem services. Comparative studies of streams with altered versus conserved riparian zones can assess the degree of change and establish Amazonian stream degradation indicators. Amazonian aquatic ecosystems vary throughout the rainfall and dry period cycle [24], making the tracking of habitat conditions at different stages of the water cycle critical. In Central Amazonian streams, Espirito-Santo et al. [30] recorded higher numbers of individuals and species in the dry season. Without temporal analysis there is a strong risk of inaccurate ecological conclusions and inadequate management options for biological conservation, even in environments that are not subject to the annual flooding pulse. As deforestation is the main environmental impact in Southern Brazilian Amazonia, we propose a 'simplification' hypothesis: i.e. streams with altered riparian zones should present more homogeneous structural characteristics and loss of variation among hydrological periods. To test this hypothesis, we quantified the structural variations of a set of headwater streams with and without riparian deforestation. We determine the impact of the removal of riparian forest cover on habitat structure and provide guidance for impact assessment and the monitoring of these water bodies.

## Methods

*Study Site*

Sampling was conducted between 2010 and 2011 in Teles Pires River basin streams (9°30′28″–10°17′07″ S, 55°59′59″–56°44′37″ W), Northern Mato Grosso state, Brazilian Amazonia (Fig. 1), located between 238 and 296 m above sea level. The annual rainfall distribution in this region has two well-defined seasons, with June, July, and August being the driest months. The variation in rainfall in the studied region was used to define hydrological periods for further analysis.

Since the '[70s, the Teles Pires River drainage has been damaged by mining and wood removal, and since the '90s, cattle raising, which is currently the predominant activity in the lower portion of the basin, especially at Alta Floresta and Paranaíta municipalities. Analysis by Trancoso et al. [14] across hydrographic basins of the Brazilian Amazon pointed to Southern tributaries as the most deforested, and the Tapajós River as the one with proportionally the greatest area lost.

*Sampling Design*

Ten sites were selected based on their hydrographic relationships and spatial location (Fig. 1). At each site, we selected two headwater streams, one located in an area with preserved riparian vegetation (pristine streams) and the other with riparian deforestation (altered streams). Each stream surveyed consisted of a 50 m stretch of a chosen stream, where the hydro-morphological and water physical-chemical variables were measured.

To control the differential effects of deforestation on streams, even within the same category (pristine or altered streams), we sampled habitat integrity assessing forested proportion on linear buffer zones and habitat integrity index. We sampled stretches during three periods between July 2010 and May 2011: dry period (July and August 2010), beginning of the rainy period (November and December 2010), and end of the rainy period (April and May 2011). The three sets of samples were collected in the same stretches, with the same equipment, same number of collectors and same sampling time on each survey occasion.

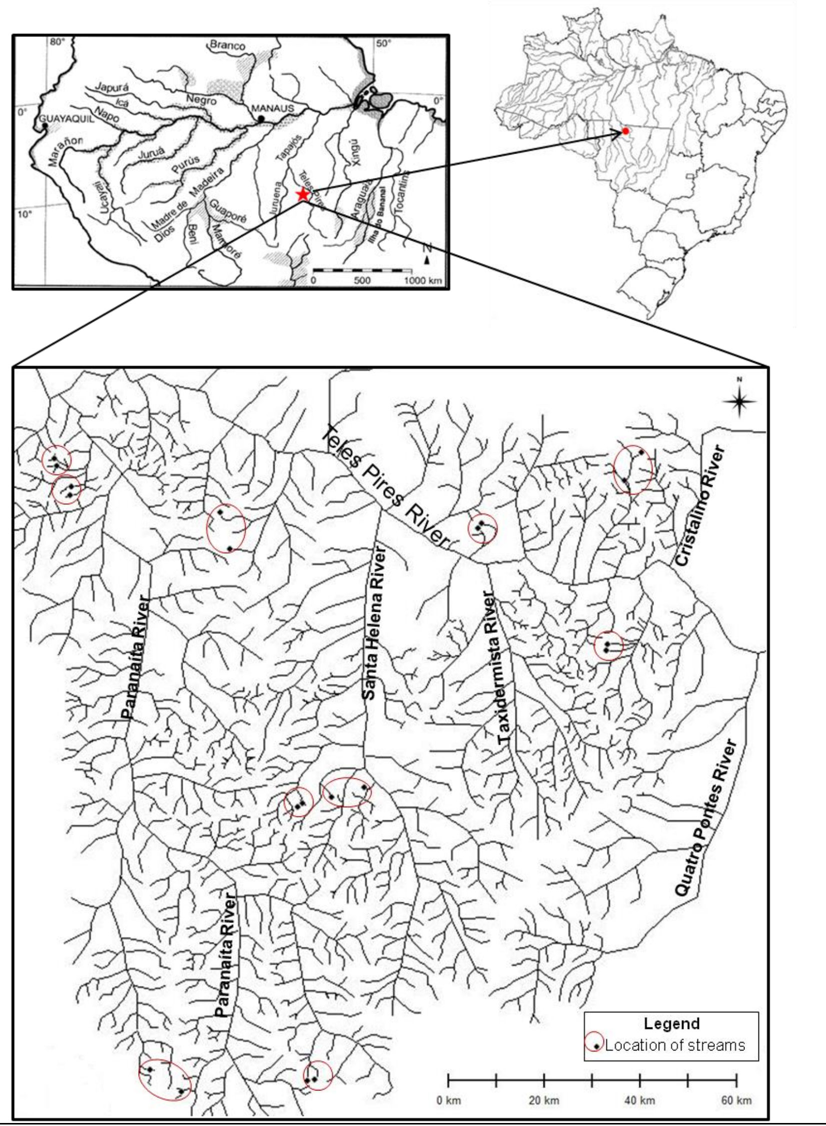



**Fig. 1. Location of 10 study sites (red circle), at each site one pristine stream and an altered stream, along the southern boundary of the Brazilian Amazon.**

Stream riparian zones were evaluated regarding their proportional forested area, canopy gap density, surrounding pasture, secondary forest, and exposed soil. We analyzed Spot-5 satellite images (Satellite Probatoire Pour l'Observation de La Terre) from 2009 for linear buffer zones vectorization of varying width (50, 100, and 200 m) along each 150 m stream stretch using ArcGis 9.3 [25]. Altered streams have median values of pasture above 80% in buffer zones, while pristine streams do not present pasture cover at the 50 m and 100 m buffer zones, with only minor alterations at the 200 m buffer zone (Table 1).

The habitat integrity index (HII) was obtained from the protocol described in Nessimian et al. [26], which standardizes each observed value by dividing by the maximum possible value for each variable. Then, the index is calculated from the average of the 12 items evaluated. Index values closer to 1 indicate greater integrity. Our version of the index (Appendix 1) was modified because some features of the Nessimian et al. [26] model, deleveloped for headwater streams in Central Amazonia, were not appropriate to assess the habitat integrity for our samples in Southern Brazilian Amazonia. Essentially, we adjusted entry cases related to the nature of the fragmentation and secondary succession processes (variable 1: land use pattern beyond the riparian zone and variable 2: width of riparian forest) and the nature of the bottom elements (variable 9: stream bottom). In streams with riparian deforestation, we recorded a median habitat integrity index value of 0.52, indicating that these streams can be classified as altered. The median HII value for pristine streams was 0.98. Among altered streams, 50% presented riparian forest remnants narrower than 50 m wide, and in the other 50%, the forest was absent, with only a few pioneer trees and shrub species detected in 30% of these streams.

We used the 50 m stretches to measure stream structural characteristics: mean canopy openness above water, mean channel width, mean water column depth, mean surface water speed, mean discharge, and the proportional cover of benthonic substrates (organics and inorganics), as modified from Mendonça et al. [27]. For channels, we also recorded stream bottom type (sandy, sandy/rocky, sandy/pebbly, sandy/clayey, or clayey) and channel margin type (well delimited or loose).

Canopy openness (CO) was estimated with three equidistant digital photographs of the canopy per stretch using an Olympus FE-120 (6.3–18.9mm) camera, which were converted to monochromatic (black and white) images using an image editor (ArcGis 9.3) [25]. CO (%) was calculated as the mean of the proportion of white pixels from the total amount of pixels per image [27, 28]. Mean channel width was measured at three points (0, 25, and 50 m of stretch), establishing three transects. Thus, depth was measured at nine equidistant points along each transect. We recorded the type of substratum touched by a measuring stick at each point. Benthonic substrate categories were small inorganic (sand and clay), big inorganic (rock and pebble), and organic (trunk: wood with diameter >10 cm; litter: leaves and small branches; and roots: fine roots from riparian vegetation). The proportion of benthonic substrate cover was calculated as the proportion of points of each substrate type in relation to all substrate measurements in each stretch, modified from Mendonça et al. [27]. For sediment sampling, three replicates at each transect per stream were collected with a plastic container (100 mL) and dried in an oven at 60 °C. Benthic organic matter (OM) (%) was estimated from the difference between the dry weight (105 ºC) and the organic matter calcined in a muffle (550 ºC) [29]. Mean surface water speed was measured at each transect and estimated by recording the time it took for a 40 mm diameter floating plastic disc to drift 1 m downstream [30]. We estimated stream mean discharge according to Mendonça et al. [27], as follows: $Q = Am \times Vm$, where Q = mean discharge, Vm = mean water surface speed, and Am = mean cross-sectional area of the stream at each of the three transects. Submerged leaf litter bank characteristics were estimated by their presence, respective retention devices (RD) (rock, trunk, branch, root, sand), and volume (n= 5; $m^3$) from the greater length, width, and depth of each bank.

Conductivity, pH, and concentration of dissolved oxygen in the water were measured using portable Hanna Instruments (HI 7662, HI 8424, and HI 9147-04, respectively). A thermometer attached to the portable oxygen meter was used to record the water temperature. For each stretch, we collected three water samples, which were kept refrigerated for further analysis (up to 12 hours after sampling) of the suspended material and nutrient concentrations. We quantified the concentration (mg/L) of the suspended material (SM) by filtering 500–2,000 mL of water through a fiberglass filter (GF/C 52mm Whatman) that was previously calcined in a muffle furnace at 450 °C for 4h and weighed, and subsequently drying and re-weighing the SM. The dissolved nutrients (mg/L) analyses were made in water filtered (100 mL) through a calcined (450 ºC) fiberglass filter (GF/C 52mm Whatman). Ammonia [$NH_3^-$] was determined using the Indophenol blue method, Nitrite [$NO_2^-$] and Nitrate [$NO_3^-$] by the N-(1-Naphthyl) ethylenediamine (NTD) method and Orthophosphate [$PO_4^{3-}$] by the Molybdenum blue method, according to APHA [31] and using a spectrophotometer (Quimis, Q798U2M model).

Table 1. Median values of the riparian zone characteristics of pristine (P) and altered (A) streams of Southern Brazilian Amazonia, from linear buffer zones of varying width (50, 100, and 200 m) surrounding each stream stretch.

| Riparian Zone | 50 m width | | 100 m width | | 200 m width | |
|---|---|---|---|---|---|---|
| (%) | P | A | P | A | P | A |
| Forest | 96.03 | 0.00 | 94.71 | 0.00 | 93.15 | 3.79 |
| Secondary forest | 0.00 | 9.53 | 0.00 | 7.03 | 0.00 | 2.51 |
| Gap | 3.49 | 0.00 | 3.48 | 0.00 | 2.62 | 0.29 |
| Pasture | 0.00 | 81.36 | 0.00 | 81.38 | 0.00 | 84.56 |
| Exposed soil/roads | 0.00 | 4.13 | 0.67 | 4.79 | 1.84 | 3.48 |

### *Data analyses*

Stream structural characteristics were assessed by analyzing median values for each hydrological period surveyed: dry period (dry), beginning of the rainy period (rain/begin), end of the rainy period (rain/end), as well as all periods together. Variation between pristine and altered streams and among hydrological periods was compared by non-parametric multivariate analysis of variance (NPMANOVA) with 999 permutations (Adonis function, Vegan package) [32], e.g. Landeiro et al. [60], and Gower distance (Gowdis function, FD package) in the R language [33, 59]. Stream structural characteristics were summarized by entering a similarity matrix (Gower distance) into a non-metric multi-dimensional scaling (NMDS) ordination analysis (metaMDS function, Vegan package) [59]. The ordination analysis resulted in a two dimensional solution (stress = 0.18). Differences for each variable between pristine and altered streams were tested by Wilcoxon paired analysis (wilcox.test function, Stats package), and differences for each variable between hydrological periods were tested by Kruskal-Wallis analysis (kruskal.test function, Stats package, and *a posteriori* with the kruskalmc function, pgirmess package) [59]. To test the association between the HII and each of the streams' structural variables and water characteristics, we performed a Spearman correlation (rs), using the corr.test function from the Psych package [59].

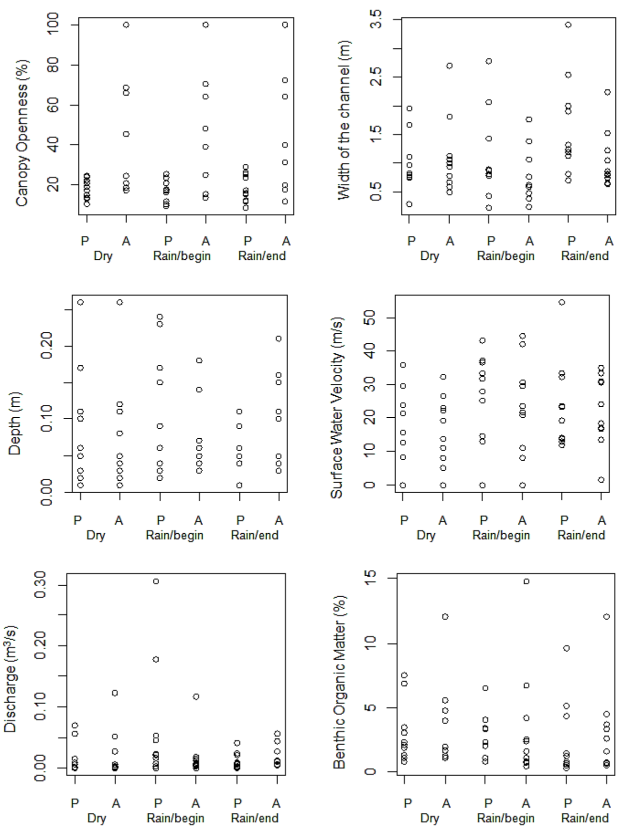
## Results

Multivariate analysis revealed that riparian forest deforestation affects the variation between hydrological periods (NPMANOVA, $F [2,29] = 1.57$, $R^2 = 0.10$, $p = 0.07$), making altered streams more homogeneous throughout the rainy to dry period. Habitat structure of pristine streams varied significantly between hydrological periods (NPMANOVA, $F [2,29] = 2.96$, $R^2 = 0.18$, $p = 0.001$). Although the median variable values varied in altered streams, the differences between hydrological periods were significant only for nitrite concentration (Kruskal-Wallis, $p = 0.005$; dry–rain/begin, $p < 0.05$), dissolved oxygen (Kruskal-Wallis test, $p = 0.022$; rain/begin–rain/end, $p < 0.05$) and water temperature (Kruskal-Wallis, $p = 0.001$; dry–rain/begin and dry–rain/end, $p < 0.05$).

The variations in habitat structure between pristine and altered streams are presented in Figs. 2–5 and Appendix 2, and the variation summaries by NMDS in Fig. 6. The HII was significantly lower (53%) in altered than in pristine streams (Wilcoxon, $p < 0.01$), and canopy openness was greater over the channel of altered streams in all hydrological periods studied (~ 30%) (Wilcoxon, $p < 0.02$). The end of the rainy period was the period in which riparian deforestation had an impact on the largest number of variables affecting stream habitat structure. During this period, altered streams had a relatively lower proportion of litter (31.3%) and trunks (100%) in the substrate (Wilcoxon, $p < 0.05$), a smaller number of retention devices (14.3%) for submerged leaves (Wilcoxon, $p < 0.04$), a greater proportion of big inorganic particles (94.4%) (Wilcoxon, $p < 0.05$), a greater concentration of dissolved nitrate in the water (32.3%) (Wilcoxon, $p < 0.05$), and higher water temperature (1.1 °C; 3.9%) (Wilcoxon, $p < 0.03$). Moreover, altered streams had lower oxygen concentrations (~1.0 mg/L), an increase of 1 °C in water temperature and lower availability of allochthonous organic material than pristine streams in all hydrological periods evaluated, plus twice the concentration of suspended material in the water during the dry and rain/begin periods.

The HII is significantly correlated to: canopy openness; proportions of small inorganic particles and big inorganic particles; trunk; litter in the bottom susbtrate; volume of litter banks; number of retention devices; water temperature; and suspended material (Appendix 3).

The canopy/vegetation cover over the course of the altered streams had a median aperture of 56.2% (Fig. 2, Appendix 2). These streams had only a few centimeters of water column depth, a narrow channel, and a mean water surface velocity of 22.5 m/s (Fig. 2, Appendix 2). The bottom of altered streams was predominantly sandy (40%) and sandy-pebbly (40%), followed by sandy-rocky (20%); 70% of streams had a defined margin, with no flooding of the riparian zone in any of the streams; these characteristics were similar to those recorded in pristine streams, where the sandy bottom predominated (40%), followed by sandy-rocky (30%), sandy clay (20%), and sandy-pebbly (10%), as well as a defined margin in 80% of streams. In the benthic substrate of altered streams, small inorganic particles predominated (59.3%), and there was a smaller proportion of big inorganic particles and litter (Fig. 3, Appendix 2). In the sediment, 2.4% organic matter was recorded, with the highest median concentration recorded during the dry period (2.9%) (Fig. 2, Appendix 2). Submerged leaf litter banks were recorded in 80% of altered streams, and the highest recorded litter bank volume was during the dry period (Fig. 3, Appendix 2). Among the retention devices for submerged leaf banks are rocks, trunks, branches, roots, and sand. Altered stream waters are transparent, slightly acidic, with low nutrient concentrations, and a 0.14 mg/L concentration of orthophosphate; among the different forms of inorganic nitrogen, nitrate was the most prominent (median amount = 0.56 mg/L) (Figs. 4 and 5, Appendix 2), which was similar to what was observed for pristine streams.



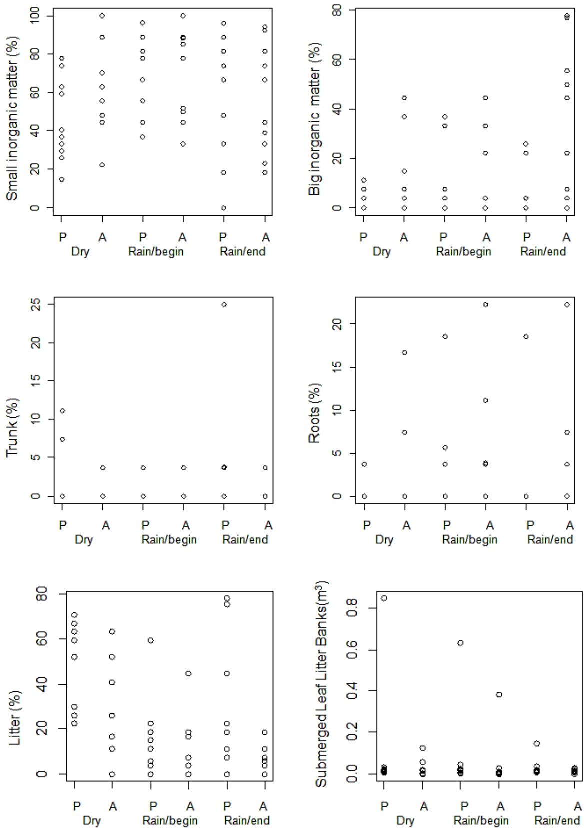
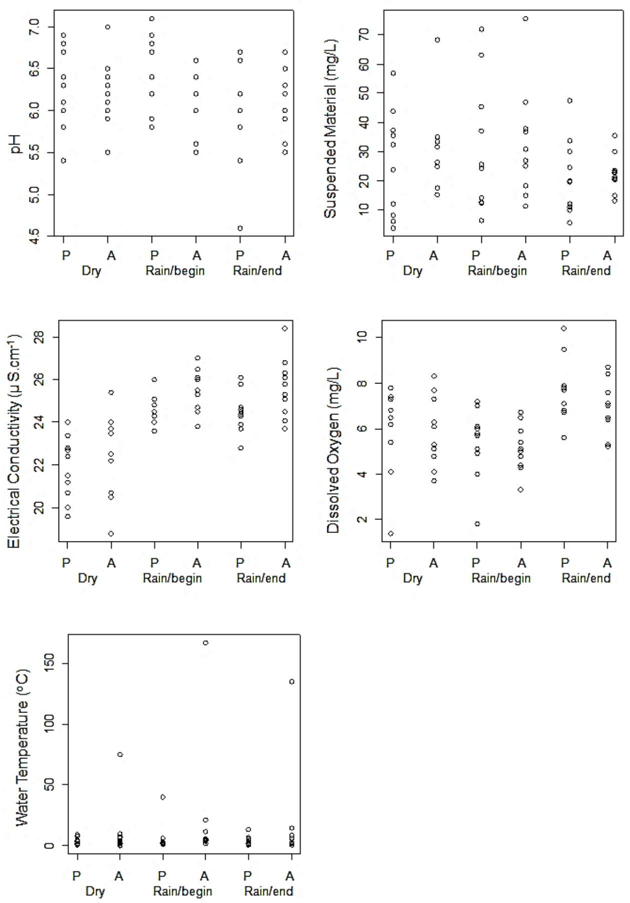




**Fig. 2. Variation range of canopy openness and channel structure of the pristine (P) and altered (A) streams across hydrological periods (Dry; Rain/begin; Rain/end) in Southern Brazilian Amazonia.**

**Fig. 3. Variation range of the benthonic substrate composition and leaf litter bank volume of the pristine (P) and altered (A) streams across hydrological periods (Dry; Rain/begin; Rain/end) in Southern Brazilian Amazonia.**

In altered streams we recorded an increase in the number of retention devices during rain/begin and rain/end periods (Appendix 2). Nevertheless, during the dry period there was an increase in the proportion of litter in the benthic substrate and in the concentration of organic matter in the sediment, with the largest concentrations found. During the rain/begin period, the highest concentrations of nutrients (except for nitrate) were recorded in altered streams, as well as the highest concentration of suspended material (median = 4.6 mg/L), the highest proportion of small inorganic particles in the substrate (median = 81.5%), and the lowest concentration of dissolved oxygen in the water (median = 5.0 mg/L). During the rain/end period, we recorded the highest concentration of dissolved oxygen (median = 6.7 mg/L), the lowest proportion of litter in the substrate (median = 4.6%), and the lowest concentration of suspended material in the water (value median = 2.38 mg/L); during the dry period, on the other hand, we recorded the lowest water temperature (median = 23.0 $^{o}$C).



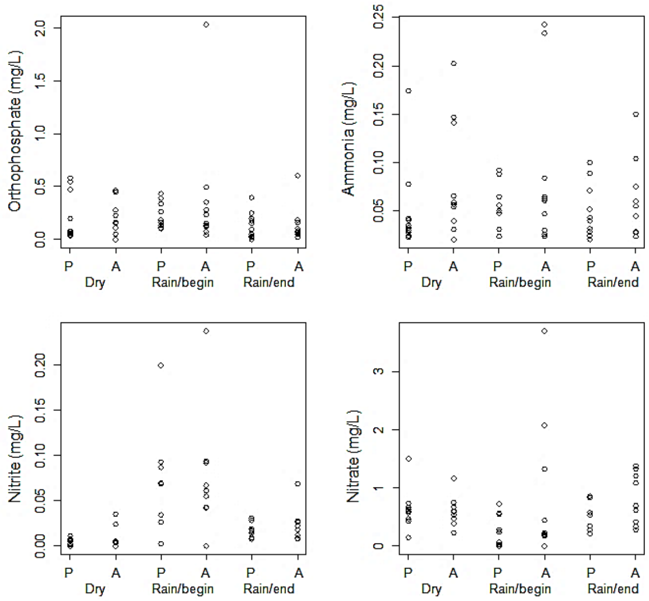




**Fig. 4. Variation range of the physical-chemical features of the water of the pristine (P) and altered (A) streams across hydrological periods (Dry; Rain/begin; Rain/end) in Southern Brazilian Amazonia.**

**Fig. 5. Variation range of the water nutrient concentrations of the pristine (P) and altered (A) streams across hydrological periods (Dry; Rain/begin; Rain/end) in Southern Brazilian Amazonia.**

## Discussion

The partial or total deforestation of Southern Amazonian riparian forest analysed in this study led to the loss of variability in headwater stream habitat structure across hydrological periods, making habitat conditions more homogeneous and simplified throughout the year. Streams naturally present spatial and temporal variations in their physical, biological, and ecosystem processes [34]. In addition, stream systems are sensitive to a series of stress factors [35], including a reduction in riparian forest cover, which, as shown in this study, reduces stream integrity.

Only in altered streams did we record changes in important variables, including a reduction in oxygen concentration (~1.0 mg/L), increased water temperature (1 °C), higher canopy openness (median value > 50%), the predominance of sand and the lower availability of litter and trunk in the substrate, materials that help to form the submerged leaf banks, which provide food and shelter for aquatic fauna [65]. Small patches of diverse substrates are common in streams, but in this study we recorded a predominance of sand, a type of substrate that occurs most often in large rivers [36].

These results indicate alterations in habitat quality and show the influence of the riparian forest on headwater streams, as well as its role in mitigating the thermal impact of land use. Support for this finding comes from evidence that forested streams in the Xingú River basin in Mato Grosso also had lower water temperatures (4 °C colder) than those recorded in streams with soybean plantations in the watershed [37]. In addition, the water temperature in watershed streams with soybean plantations varied more (daily and seasonally) than in forested watershed streams [38]. As in Amazonian streams, tropical streams in agriculture and forest catchments in Kenya also showed differences in physico-chemical and organic matter characteristics, and suspended material and total dissolved nitrogen were higher during the wet than dry season [61]. Masese et al. [61] showed increased concentrations of major ions, turbidity, suspended material, conductivity, temperature and dissolved nitrogen in streams in agriculture landscapes compared with those in forest, as well as lower temperature in forest streams, due to high canopy cover (above 80%). The natural riparian vegetation protects streams from direct insolation and contributes to a reduction in the local temperature, important for conserving aquatic biota [61, 62].

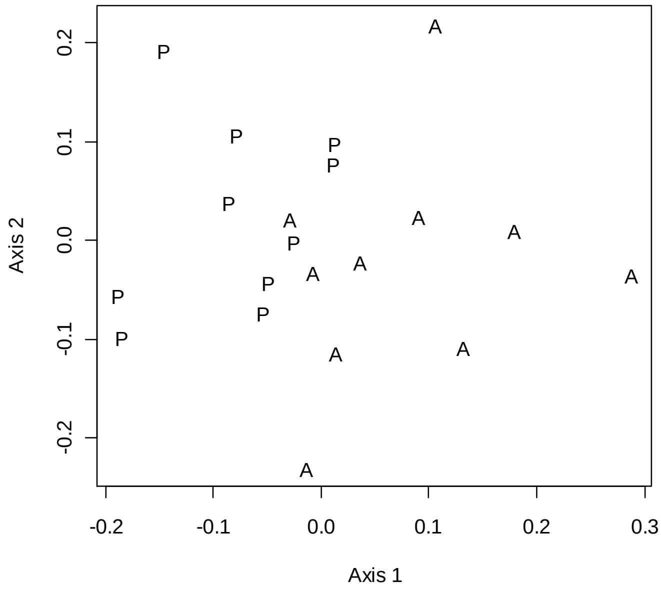



**Fig. 6. Non-metric multi-dimensional scaling (NMDS) plot of stream structural characteristics of pristine (P) and altered (A) streams in Southern Brazilian Amazonia.**

Variations between hydrological periods result from differences in precipitation, which is very important in the Amazon, as it influences structural and functional aspects of ecosystems, notably bodies of water [24, 30, 39, 40]. Therefore, changes in stream structural dynamics between hydrological periods due to riparian deforestation can compromise habitat availability for aquatic biota [28, 41] as well as habitat function [42]. The heterogeneity of the physical habitat of streams, as well as the structural complexity, promote and maintain biological diversity [35], and are necessary for maintaining the diversity and integrity of ecosystem processes [6]. The reduction in environmental heterogeneity can also increase the impact of invasive species on native ones [43].

The cumulative effect of this homogenization in large Amazonian rivers can be dramatic, given that the riparian zone of headwater streams can cover an area of the Amazon greater than one million $km^2$ [44]. The riparian zone of streams plays an important role in maintaining the integrity of the aquatic habitat conditions [45], including reducing runoff [19] and supplying organic material, which in these ecosystems is a key element in the food chain [8]. Habitat quality affects biodiversity and can benefit from the connectivity between habitats [10, 46], especially in fragmented landscapes [47]. As well as providing corridors connecting forest fragments [48], the rehabilitation of riparian forests of the numerous streams in southern Amazonia can help minimize the negative effects of this region's deforestation, such as a significant decline in local and regional biodiversity [11]. In Mato Grosso, Dias-Silva et al. [63] found that alteration in riparian areas can lead to significant changes in Heteroptera composition, and Juen et al. [49] found that even partial environmental changes affect the composition of Odonata in streams, indicating that ecosystem services may be lost.

In Rondônia, forest streams had more leaves in the benthic substrate (>38%) than did streams with pasture in their riparian zones [50], where habitat structure was greatly altered; the benthic habitat was dominated by *Paspalum repens* (>55%), and low dissolved oxygen concentration was recorded, indicating that Amazonian streams are susceptible to cattle ranching in the riparian zone [21]. In contrast to streams in the state of Rondônia [16, 51], in this study we did not record a predominance of *P. repens* in the stream channel, and nitrate concentrations were higher (for forms of inorganic nitrogen), both in pristine and altered streams; the nitrate concentration was also higher in altered than in pristine streams during the rain/end period. In Rondônia, the nitrate concentration was the lowest among forms of inorganic nitrogen and smaller in altered than in pristine streams [16, 51]. Biggs et al. [17] reported that phosphorus and nitrate in streams are affected by soil properties, and that nitrate concentrations increase with deforestation, since high concentrations of nitrate are found in streams draining forested watersheds in sandy soils. This is a possible explanation for the higher nitrate concentration observed during the rain/end period in the streams contemplated in the present study.

Although riparian zone conditions determine the habitat structure and organic material input to the streams, the input of nutrients as well as sediments and hydrology are influenced by regional conditions [52], which can affect the detection of significant differences in nutrient concentrations and hydromorphological variables between the pristine and altered streams evaluated in this study. Biggs et al. [17] reported that nutrient concentrations in Amazonian streams in Rondônia varied according to regional changes in the soil's texture and nutritional status, and that no nutrient alterations or differences were recorded between forest and pasture streams with 66 to 75% deforestation during the dry and rainy seasons [16]. In this study, we found that the riparian forest, when up to 200 m wide, protects the habitat structure of headwater streams from the effects of anthropogenic activities in the watershed. On the other hand, when there is more than 80% deforestation in the riparian zone (even if there is secondary vegetation being regenerated), human activity has an effect on stream habitat structure.

Heterogeneity in habitat conditions is a critical factor for maintaining species diversity [11], and should be taken into consideration when defining measures for biodiversity conservation [53]. Godbold et al. [54] emphasize the importance of diversified/complex habitats in maintaining ecosystem multifunctionality, where different species affect different functions [55, 56] and can therefore minimize the effects of perturbations.

## Implications for conservation

Deforestation of the southern Amazonian riparian forest led to the loss of variability in headwater stream habitat structure across hydrological periods. According to Castello et al. [57], human activities can alter aquatic ecosystems and make them vulnerable; a paradigm shift is necessary to conserve the Amazon, one that expands the focus beyond the forest to aquatic ecosystems. Restoring the structural complexity of altered streams is a great challenge, as it requires more than simply introducing physical elements into stream channels [35] or planting tree species in the riparian zone.

Another important issue is assessing the impact and monitoring the effectiveness of stream rehabilitation within riparian forest rehabilitation programs. Impact assessment in aquatic systems commonly uses sensitive organisms such as macroinvertebrates, but some of these organisms may not be sensitive to degradation in Amazonian streams or to variations between dry and rainy periods [58]. In this study, we identified the association between HII and canopy openness, litter bank volume, number of retention devices, proportion of benthic substrate components, and water temperature. Measuring HII is inexpensive and our results show its sensitivity to riparian deforestation. Correlations between stream integrity and riparian zone structural variables and aquatic habitat quality demonstrate that the consequences of the degradation process are currently occurring at Southern Amazonia, independently of the natural variability that this system holds. Alterations between hydrological periods indicate that this process occurs in a heterogeneous and unpredictable way through time.

We recommend conducting evaluations during the rainy/end period, between the months of April and May, which is when differences between altered and pristine streams are most pronounced in Southern Brazilian Amazonia. Yates et al. [64] reported that structural indicators were associated with crop cultivation and agricultural land cover, and functional indicators were associated with gradients of waste-water treatment and urban land cover, demonstrating that selecting the most sensitive indicators of stream conditions would benefit aquatic ecosystem assessment programs. This highlights the need for establishing robust and inexpensive indicators of habitat structure that are not linked only to species; this will facilitate and cheapen monitoring rehabilitation efforts targeting altered streams, such as those of the southern Amazon. Although necessary, these rehabilitation efforts are poorly funded in Brazil.

## Acknowledgments

We are thankful for financial support by FAPEMAT/Universal/Brazil (469087/2009) and for logistical support provided by Universidade do Estado do Mato Grosso (UNEMAT) and Instituto Nacional de Pesquisas da Amazônia (INPA). This study was funded with a PhD fellowship from the Brazilian National Research Council (CNPq) to MEB during manuscript elaboration. We are thankful to several UNEMAT students who helped with field and laboratory data collection.

## References

[1] Ward, J.V. 1989. The four-dimensional Nature of lotic ecosystems. *J. N. Am. Benthol. S.* 8: 2-8.

[2] Ward, J.V. 1998. Riverine landscapes: biodiversity patterns, disturbance regimes, and aquatic conservation. *Biol. Conserv*. 83: 269-278.

[3] Pringle, C.M. 2001. Hydrologic connectivity and the management of biological reserves: a global perspective. *Ecol. Appl*. 11: 981-998.

[4] Ward, J.V., Tockner, K., Arscott, D.B., Claret, C. 2002. Riverine landscape diversity. *Freshwater Biol*. 47: 517-539.

[5] Wiens, J.A. 2002. Riverine landscapes: taking landscape ecology into the water. *Freshwater Biol*. 47: 501-515.

[6] Cardinale, B.J., Palmer, M.A., Swan, C.M., Brooks, S. and Poff, N.L. 2002. The influence of substrate heterogeneity on biofilm metabolism in a stream ecosystem. *Ecology* 83: 412-422.

[7] Minshall, G.W., Petersen, R.C., Cummins, K.W., Bott, T.L., Sedell, J.R., Cushing, C.E. and Vannote, R.L. 1983. Interbiome Comparison of Stream Ecosystem Dynamics. *Ecol. Monogr.* 53: 1-25.

[8] Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R. and Cushing, C.E. 1980. The river continuum concept. *Can. J. Fish. Aquat. Sci*. 37: 130-137.

[9] Cooper, S.D., Barmuta, L., Sarnelle, O., Kratz, K. and Diehl, S. 1997. Quantifying spatial heterogeneity in streams. *J. N. Am. Benthol. S.* 16: 174-188.

[10] Chisholm, C., Lindo, Z. and Gonzalez, A. 2010. Metacommunity diversity depends on connectivity and patch arrangement in heterogeneous habitat networks. *Ecography*, DOI: http://dx.doi.org/10.1111/j.1600-0587.2010.06588.x.

[11] Urban, M.C. 2004. Disturbance heterogeneity determines freshwater metacommunity structure. *Ecology* 85: 2971–2978.

[12] Hynes, H.B.N. 1975. The stream and its valley. *Verh. Int. Ver. Limnol*. 19: 1–15.

[13] Meyer, J.L., Strayer, D.L., Wallace J.B., Eggert, S.L., Helfman, G.S. and Leonard, N.E. 2007. The contribution of headwater streams to biodiversity in river networks. *J. Am. Water Resour. Assoc*. 43: 86-103.

[14] Trancoso, R., Carneiro Filho, A., Tomasella, J., Schietti, J., Forsberg, B.R. and Miller, R.P. 2009. Deforestation and conservation in major watersheds of the Brazilian Amazon. *Environ. Conserv*. 36: 277-288. DOI: 10.1017/S0376892909990373.

[15] Hayhoe, S.J., Neill, C., Porder, S., McHorney, R., Lefebvre, P., Coe, M.T., Elsenbeer, H. and Krusche, A.V. 2011. Conversion to soy on the Amazonian agricultural frontier increases streamflow without affecting stormflow dynamics. *Glob. Chang. Biol*. 17: 1821–1833. DOI: 10.1111/j.1365-2486.2011.02392.x.

[16] Neill, C., Deegan, L.A., Thomas, S.M. and Cerri, C.C. 2001. Deforestation for pasture alters nitrogen and phosphorus in small Amazonian streams. *Ecol. Appl*. 11: 1817-1828.

[17] Biggs, T.W., Dunne, T. and Martinelli, L.A. 2004. Natural controls and human impacts on stream nutrient concentrations in a deforested region of the Brazilian Amazon basin. *Biogeochemistry* 68: 227–257.

[18] Krusche, A.V., Ballester, M.V.R., Victoria, R.L., Bernardes, M.C., Leite, N.K., Hanada, L., Victoria, D.C., Toledo, A.M., Ometto, J.P., Moreira, M.Z., Gomes, B.M., Bolson, M.A., Gouveia Neto, S., Bonelli, N., Deegan, L., Neill, C., Thomas, S., Aufdenkampe, A.K. and Richey, J.E. 2005. Efeitos das mudanças do uso da terra na biogeoquímica dos corpos d'água da bacia do rio Ji-Paraná, Rondônia. *Acta Amaz*. 35: 197-205.

[19] Chaves, J., Neill, C., Germer, S., Gouveia Neto, S., Krusche, A. and Elsenbeer, H. 2008. Land management impacts on runoff sources in small Amazon watersheds. *Hydrol. Process*. 22, 1766-1775. DOI: 10.1002/hyp.6803.

[20] Germer, S., Neill, C., Krusche, A.V. and Elsenbeer, H. 2010. Influence of land-use change on near-surface hydrological processes: Undisturbed forest to pasture. *J. Hydrol*. 380: 473–480. DOI: 10.1016/j.jhydrol.2009.11.022.

[21] Deegan, L.A., Neill, C., Haupert, C.L., Ballester, M.V.R., Krusche, A.V., Victoria, R.L., Thomas, S.M. and Moor, E. 2011. Amazon deforestation alters small stream structure, nitrogen biogeochemistry and connectivity to larger rivers. *Biogeochemistry* 105: 53-74. DOI: 10.1007/s10533-010-9540-4.

[22] Coe, M.T., Costa, M.H. and Soares-Filho, B.S. 2009. The influence of historical and potential future deforestation on the stream flow of the Amazon River - Land surface processes and atmospheric feedbacks. *J. Hydrol*. 369: 165-174. DOI: 10.1016/j.jhydrol.2009.02.043.

[23] Laurance, W.F., Sayer, J. and Cassman, K.G. 2014. Agricultural expansion and its impacts on tropical nature. *Trends Ecol. Evol*. 29: 107-116. DOI: 10.1016/j.tree.2013.12.001.

[24] Junk, W.J., Bayley, P.B. and Sparks, R.E. 1989. The flood pulse concept in river-floodplain-systems. *Can. Spec. Publ. Fish. Aquat. Sci*. 106: 110-127.

[25] ESRI – Environmental Systems Research Institute. 2006. ArcGIS Professional GIS for the desktop, version 9.3.

[26] Nessimian, J.L., Venticinque, E.M., Zuanon, J., De Marco Jr. P., Gordo, M., Fidelis, L., Batista, J.D. and Juen, L. 2008. Land use, habitat integrity, and aquatic insect assemblages in Central Amazonian streams. *Hydrobiologia* 614: 117-131. DOI: 10.1007/s10750-008-9441-x.

[27] Mendonça, F.P., Magnusson, W.E. and Zuanon, J. 2005. Relationships between habitat characteristics and fish assemblages in small streams of Central Amazonia. *Copeia* 4: 751-764.

[28] Bunn, S.E., Davies, P.M. and Mosisch, T.D. 1999. Ecosystem measures of river health and their response to riparian and catchment degradation. *Freshwater Biol*. 41: 333-345.

[29] Allen, S.E. 1989. *Chemical analysis of ecological materials*. Blackwell Scientific Publications, London.

[30] Espirito-Santo, H.M.V., Magnunsson, W.E., Zuanon, J., Mendonça, F.P. and Landeiro, V.L. 2008. Seasonal variation in the composition of fish assemblages in small Amazonian forest streams: evidence for predictable changes. *Freshwater Biol*. 54: 536–548. DOI:10.1111/j.1365-2427.2008.02129.x.

[31] APHA – American Public Health Association. 1998. *Standard methods for the examination of water and wastewater*. United Book Press, Baltimore, Maryland.

[32] Anderson, M.J. 2001. A new method for non-parametric multivariate analysis of variance. *Austral Ecol*. 26: 32-46.

[33] Oksanen, J., Kindt, R., Legendre, P., O'Hara, R.B. and Stevens, M.H.H. 2011. Vegan: Community Ecology Package. R Package Version 1.8–8. http://cran.r-project.org.

[34] Winemiller, K.O., Flecker, A.S. and Hoeinghaus, D.J. 2010. Patch dynamics and environmental heterogeneity in lotic ecosystems. *J. N. Am. Benthol. S.* 29: 84–99. DOI: 10.1899/08-048.1.

[35] Palmer, M.A., Menninger, H.L. and Bernhardt, E. 2010. River restoration, habitat heterogeneity and biodiversity: a failure of theory or practice? *Freshwater Biol*. 55: 205–222. DOI: 10.1111/j.1365-2427.2009.02372.x.

[36] Thorp, J.H., Thoms, M.C. and Delong, M.D. 2006. The riverine ecosystem synthesis: biocomplexity in river networks across space and time. *River Res. Appl*. 22: 123-147. DOI: 10.1002/rra.901.

[37] Macedo, M.N., Coe, M.T., DeFries, R., Uriarte, M., Brando, P.M., Neill, C. and Walker, W.S. 2013. Land-use-driven stream warming in southeastern Amazonia. *Philos. Trans. R. Soc. B* 368: 20120153, DOI: 10.1098/rstb.2012.0153.

[38] Neill, C., Coe, M.T., Riskin, S.H., Krusche, A.V., Elsenbeer, H., Macedo, M.N., McHorney, R., Lefebvre, P., Davidson, E.A., Scheffler, R., Figueira, A.M.S., Porder, S. and Deegan, L.A. 2013. Watershed responses to Amazon soya bean cropland expansion and intensification. *Philos. Trans. R. Soc. B* 368: 20120425, DOI: 10.1098/rstb.2012.0425.

[39] Junk, W.J. and Piedade, M.T.F. 2005. The Amazon River Basin. In: *The World's Largest Wetlands: Ecology and Conservation.* Fraser, L.H. and Keddy, P.A. (Eds.), pp. 63-117. Cambridge University Press, Cambridge.

[40] Rueda-Delgado, G., Wantzen, K.M. and Beltran Tolosa, M.B. 2006. Leaf-litter decomposition in an Amazonian floodplain stream: effects of seasonal hydrological changes. *J. N. Am. Benthol*. *S*. 25: 233–249.

[41] Burdon, F.J., McIntosh, A.R. and Harding, J.S. 2013. Habitat loss drives threshold response of benthic invertebrate communities to deposited sediment in agricultural streams. *Ecol. Appl*. 23: 1036–1047.

[42] Silva-Junior, E.F., Moulton, T.P., Boëchatc, I.G. and Gückerc, B. 2014. Leaf decomposition and ecosystem metabolism as functional indicators of land use impacts on tropical streams. *Ecol. Indic*. 36: 195-204. DOI: 10.1016/j.ecolind.2013.07.027.

[43] Melbourne, B.A., Cornell, H.V., Davies, K.F., Dugaw, C.J., Elmendorf, S., Freestone, A.L., Hall, R.J., Harrison, S., Hastings, A., Holland, M., Holyoak, M., Lambrinos, J., Moore, K. and Yokomizo, H. 2007. Invasion in a heterogeneous world: resistance, coexistence or hostile takeover? *Ecol. Lett.* 10: 77–94. DOI: 10.1111/j.1461-0248.2006.00987.

[44] Junk, W.J. 1993. Wetlands of Tropical South America. In: *Wetlands of the world.* Whigham, D., Hejny, S. and Dykyjova, D. (Eds.), pp. 679-739. Dr. W. Junk Publ, Dordrecht.
[45] Naiman, R.J. and Decamps, H. 1997. The ecology of interfaces: Riparian Zones. *Annu. Rev. Ecol. Syst*. 28: 621–658.
[46] Laurance, W.F., Useche, D.C., Rendeiro, J., Kalka, M. and Bradshaw, C.J.A. 2012. Averting biodiversity collapse in tropical forest protected areas. *Nature* 1, DOI: http://dx.doi.org/10.1038/nature11318.
[47] Loreau, M., Mouquet, N. and Gonzalez, A. 2003. Biodiversity as spatial insurance in heterogeneous landscapes. *Proc. Natl. Acad. Sci. U.S.A.* 100: 12765-12770.
[48] Bleich, M.E. and Silva, C.J. 2013. Caracterização dos fragmentos florestais amazônicos remanescentes na microbacia hidrográfica do rio Taxidermista I em Alta Floresta, MT. *Biotemas* (UFSC) 24: 41-51. DOI: http://dx.doi.org/10.5007/2175-7925.2013v26n4p45.
[49] Juen, L., Oliveira-Junior, J.M.B. Shimano, Y., Mendes, T.P. and Cabette, H.S.R. 2014. Composição e riqueza de Odonata (Insecta) em riachos com diferentes níveis de conservação em um ecótone Cerrado-Floresta Amazônica. *Acta Amaz*. 44: 223–233.
[50] Neill, C., Deegan, L., Thomas, S., Hauper, C.L., Krusche, A.V., Ballester, V.M. and Victoria, R.L. 2006. Deforestation alters hydraulic and biogeochemical characteristics of small lowland Amazonian streams. *Hydrol. Process*. 20: 2563-2580.
[51] Thomas, S.M., Neill, C., Deegan, L.A., Krusche, A.V., Ballester, V.M. and Victoria, R.L. 2004. Influences of land use and stream size on particulate and dissolved materials in a small Amazonian stream network. *Biogeochemistry* 68: 135-151.
[52] Allan, J.D., Erickson, D.L. and Fay, J. 1997. The influence of catchment land use on stream integrity across multiple spatial scales. *Freshwater Biol.* 37: 149-161.
[53] Tews, J., Brose, U., Grimm, V., Tielborger, K., Wichmann, M.C., Schwager, M. and Jeltsch, F. 2004. Animal species diversity driven by habitat heterogeneity/diversity: the importance of keystone structures. *J. Biogeogr*. 31: 79–92.
[54] Godbold, J.A., Bulling, M.T. and Solan, M. 2011. Habitat structure mediates biodiversity effects on ecosystem properties. *Proc. R. Soc. B* 278: 2510–2518. DOI: 10.1098/rspb.2010.2414.
[55] Hector, A. and Bagchi, R. 2007. Biodiversity and ecosystem multifunctionality. *Nature* 448: 188–191. DOI: 10.1038/nature05947.
[56] Pasari, J.R., Levia, T., Zavaletaa, E.S. and Tilmanb, D. 2013. Several scales of biodiversity affect ecosystem multifunctionality. *Proc. Natl. Acad. Sci. U.S.A*. 110: 10219–10222. DOI: 10.1073/pnas.1220333110/-/DCSupplemental.
[57] Castello, L., McGrath, D.G., Hess, L.L., Coe, M.T., Lefebvre, P.A., Petry, P.; Macedo, M.N., Reno, V.F. and Arantes, C.C. 2013. The vulnerability of Amazon freshwater ecosystems. *Conserv. Letters* 0: 1–13. DOI: 10.1111/conl.12008.
[58] Couceiro, S.R.M., Hamada, N., Forsberg, B.R., Pimentel, T.P. and Luz, S.L.B. 2012. A macroinvertebrate multimetric index to evaluate the biological condition of streams in the Central Amazon region of Brazil. *Ecol. Indic*. 18: 118–125. DOI: 10.1016/j.ecolind.2011.11.001.
[59] R Development Core Team. 2011. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org.
[60] Landeiro, V.L., Bini, L.M., Melo, A.S., Pes, A.M.O. and Magnusson, W.E. 2012. The roles of dispersal limitation and environmental conditions in controlling caddisfly (Trichoptera) assemblages. *Freshwater Biol*. DOI: 10.1111/j.1365-2427.2012.02816.x.
[61] Masese, F.O., Kitaka, N., Kipkemboi, J., Gettel, G.M., Irvine, K. and McClain, M.E. 2014. Litter processing and shredder distribution as indicators of riparianand catchment influences on ecological health of tropical streams. *Ecol. Indic*. 46: 23–37. DOI: 10.1016/j.ecolind.2014.05.032.

[62] Monteiro Júnior, C.S., Couceiro, S.R.M., Hamada, N. and Leandro Juen, L. 2013. Effect of vegetation removal for road building on richness and composition of Odonata communities in Amazonia, Brazil. *Inter. J. Odonat*. DOI:10.1080/13887890.2013.764798.
[63] Dias-Silva, K., Cabette, H.S.R., Juen, L. and De Marco Jr, P. 2010. The influence of habitat integrity and physical-chemical water variables on the structure of aquatic and semi-aquatic Heteroptera. *Zoologia* 27: 918–930. DOI: 10.1590/S1984-46702010000600013.
[64] Yates, A.G., Brua, R.B., Culp, J.M., Chambers, P.A. and Wassenaar, L.I. 2014. Sensitivity of structural and functional indicators depends on typeand resolution of anthropogenic activities. *Ecol. Indic*. 45: 274–284. DOI: 10.1016/j.ecolind.2014.02.014.
[65] Walker, I. 1987. The biology of streams as part of Amazonian forest ecology. *Experientia* 43: 279-287.

Appendix 1. Habitat characteristics used in evaluation of sampling sites for habitat integrity index calculations adapted from Nessimian *et al*. (2008).

| Characteristic | | Condition | Score |
|---|---|---|---|
| 1 | Land use pattern beyond the riparian zone | Forest fragment | 6 |
| | | Secondary forest – old | 5 |
| | | Secondary forest - open, degraded | 4 |
| | | Pasture | 3 |
| | | Perennial agriculture | 2 |
| | | Exposed soil or annual agricultural activity | 1 |
| 2 | Width of riparian forest | Forest width over 200 m | 6 |
| | | Forest width between 101 and 200 m | 5 |
| | | Forest width between 51 and 100 m | 4 |
| | | Forest width less than 50 m | 3 |
| | | Riparian forest absent, but some shrub and pioneer trees | 2 |
| | | Riparian forest and shrub vegetation absent | 1 |
| 3 | Completeness of riparian forest | Riparian forest intact without breaks in vegetation | 4 |
| | | Breaks occurring at intervals of 50 m | 3 |
| | | Breaks frequent with gullies and scars at every 50 m | 2 |
| | | Deeply scarred with gullies all along its length | 1 |
| 4 | Vegetation of riparian zone 10 m of channel | More than 90% plant density by non-pioneer trees or shrubs | 4 |
| | | Mixed pioneer species and mature trees | 3 |
| | | Mixed grasses and sparse pioneer trees and shrubs | 2 |
| | | Grasses and few tree shrubs | 1 |
| 5 | Retention devices | Channel stream with rocks, trunk, branches or roots | 3 |
| | | Retention devices loose, moving with floods | 2 |
| | | Absence of retention devices | 1 |
| 6 | Channel sediments | Little or no channel enlargement resulting from sediment accumulation | 4 |
| | | Some gravel bars of coarse stones and little silt | 3 |
| | | Sediment bars of rocks, sand and silt common | 2 |
| | | Channel divided into braids or stream channel corrected | 1 |

Appendix 1 continued

| Characteristic | | Condition | Score |
|---|---|---|---|
| 7 | Bank structure | Banks stable, with rock and soil held firmly by shrubs or tree roots | 4 |
| | | Banks firm but loosely held by grasses and shrubs | 3 |
| | | Banks of loose soil held by a sparse layer of grass and shrubs | 2 |
| | | Banks unstable, easily disturbed, with loose soil or sand | 1 |
| 8 | Bank undercutting | Little, not evident or restricted to areas with tree root support | 4 |
| | | Cutting only on curves and at constrictions | 3 |
| | | Cutting frequent, undercutting of banks and roots | 2 |
| | | Severe cutting along channel, banks falling | 1 |
| 9 | Stream bottom | Heterogeneous bottom, with the presence of organic and inorganic material | 3 |
| | | Uniform bottom, organic matter absent, predominantly sand or stone | 2 |
| | | Uniform bottom of sand and silt loosely held together | 1 |
| 10 | Riffles and pools, or meanders | Irregularly spaced | 3 |
| | | Long pools separating short riffles, meanders absent | 2 |
| | | Meanders and riffle/pools absent or stream corrected | 1 |
| 11 | Aquatic vegetation | When present, consists of moss and few aquatic herbaceous | 4 |
| | | Algae dominant in pools, vascular plants along edge | 3 |
| | | Algal mats present, some vascular plants, few mosses | 2 |
| | | Algal mats cover bottom, vascular plants dominate channel | 1 |
| 12 | Detritus | Mainly consisting of leaves and wood | 4 |
| | | Few leaves and wood, fine organic debris | 3 |
| | | No leaves or woody debris, coarse and fine organic matter | 2 |
| | | Fine anaerobic sediment, no coarse debris | 1 |

Appendix 2. Median habitat structure values for pristine (P) and altered (A) streams, southern Brazilian Amazon. CO= Canopy openness; OM= Benthic organic matter; Litter banks= Submerged leaf litter banks (volume); RD= Retention devices; SM= Suspended material; HII= habitat integrity index.

| **Hydrological period** | **Dry** | | **Rain/begin** | | **Rain/end** | | **All periods** | |
|---|---|---|---|---|---|---|---|---|
| **Variables** | **P** | **A** | **P** | **A** | **P** | **A** | **P** | **A** |
| Width | 0.90 | 0.97 | 0.85 | 0.69 | 1.29 | 0.84 | 1.04 | 0.81 |
| Depth | 0.06 | 0.06 | 0.05 | 0.04 | 0.08 | 0.10 | 0.06 | 0.05 |
| Water velocity | 14.15 | 22.57 | 16.45 | 21.31 | 29.71 | 21.25 | 20.25 | 22.46 |
| Discharge | 0.01 | 0.01 | 0.002 | 0.01 | 0.10 | 0.01 | 0.01 | 0.01 |
| CO | 18.13 | 55.58 | 17.15 | 56.24 | 16.39 | 52.04 | 17.1 | 56.24 |
| Small inorganic | 38.9 | 55.56 | 77.8 | 81.48 | 70.37 | 55.56 | 64.81 | 59.26 |
| Big inorganic | 1.85 | 5.56 | 0.00 | 3.70 | 1.85 | 33.32 | 0.00 | 5.63 |
| Root | 0.00 | 0.00 | 0.00 | 1.85 | 0.00 | 0.00 | 0.00 | 0.00 |
| Trunk | 0.00 | 0.00 | 0.00 | 0.00 | 3.70 | 0.00 | 0.00 | 0.00 |
| Litter | 55.56 | 21.30 | 16.57 | 7.41 | 14.81 | 4.63 | 22.22 | 7.41 |
| OM | 2.19 | 2.92 | 2.80 | 1.98 | 1.01 | 2.10 | 2.05 | 2.14 |
| Litter banks | 0.10 | 0.009 | 0.08 | 0.005 | 0.03 | 0.006 | 0.01 | 0.006 |
| RD | 2.20 | 2.50 | 3.00 | 3.00 | 3.5 | 3.00 | 3.00 | 3.00 |
| Conductivity | 28.05 | 25.58 | 24.95 | 28.85 | 19.8 | 21.95 | 24.05 | 24.10 |
| pH | 6.2 | 6.24 | 6.4 | 6.30 | 5.9 | 6.21 | 6.21 | 6.23 |
| Oxygen | 6.63 | 5.65 | 5.75 | 5.05 | 7.4 | 6.75 | 6.75 | 5.98 |
| Temperature | 21.9 | 23.02 | 24.15 | 25.40 | 24.45 | 25.55 | 24.0 | 24.60 |
| SM | 1.43 | 3.57 | 2.28 | 4.65 | 2.8 | 2.38 | 2.28 | 4.00 |
| Orthophosphate | 0.08 | 0.16 | 0.22 | 0.19 | 0.12 | 0.09 | 0.16 | 0.14 |
| Ammonia | 0.03 | 0.06 | 0.05 | 0.06 | 0.04 | 0.05 | 0.04 | 0.06 |
| Nitrite | 0.004 | 0.003 | 0.07 | 0.06 | 0.02 | 0.02 | 0.01 | 0.02 |
| Nitrate | 0.60 | 0.58 | 0.15 | 0.21 | 0.44 | 0.65 | 0.50 | 0.56 |
| HII | 0.98 | 0.52 | 0.98 | 0.52 | 0.98 | 0.52 | 0.98 | 0.52 |

Appendix 3. Spearman correlation among HII and stream structural characteristics in the southern Brazilian Amazon. CO= Canopy openness; OM= Benthic organic matter; Litter banks= Submerged leaf litter banks (volume); RD= Retention devices; SM= Suspended material.

| Variables | Spearman Correlation | P-value |
|---|---|---|
| Width | 0.01 | 0.95 |
| Depth | -0.14 | 0.55 |
| Water velocity | -0.32 | 0.18 |
| Discharge | -0.11 | 0.64 |
| CO | -0.85 | 0.00 |
| Small inorganic | -0.41 | 0.07 |
| Big inorganic | -0.46 | 0.04 |
| Root | -0.22 | 0.35 |
| Trunk | 0.61 | 0.00 |
| Litter | 0.75 | 0.00 |
| OM | -0.11 | 0.63 |
| Litter banks | 0.45 | 0.05 |
| RD | 0.53 | 0.02 |
| Conductivity | -0.18 | 0.45 |
| pH | -0.21 | 0.38 |
| Oxygen | 0.19 | 0.43 |
| Temperature | -0.55 | 0.01 |
| SM | -0.41 | 0.07 |
| Orthophosphate | -0.03 | 0.90 |
| Ammonia | -0.21 | 0.37 |
| Nitrite | -0.08 | 0.73 |
| Nitrate | -0.25 | 0.29 |