INSTITUTO NACIONAL DE PESQUISAS DA AMAZÔNIA - INPA
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EFEITOS DE ALTERAÇÕES NA ZONA RIPÁRIA SOBRE A INTEGRIDADE DE IGARAPÉS AMAZÔNICOS NO BAIXO RIO TELES PIRES, NORTE DE MATO GROSSO

MONICA ELISA BLEICH

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SINOPSE:

Foram estudados os efeitos de alterações da cobertura florestal ripária sobre a integridade de igarapés de cabeceira no sul da Amazônia. Esses efeitos foram avaliados por meio da hidrologia, morfologia, características físico-químicas da água e produtores primários aquáticos, e sua variação entre os períodos hidrológicos de seca, enchente e vazante.

Palavras-chave: estrutura do habitat, produção primária, ecossistemas lóticos, variação temporal, degradação, desmatamento.

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"É impossível fazer mal somente aos outros."

J. Hermógenes

RESUMO

Na bacia Amazônica existem muitos riachos, localmente denominados de igarapés, inseridos em paisagens heterogêneas, considerando as variações naturais das condições geomorfológicas, os períodos hidrológicos e a degradação promovida pelo desmatamento, principalmente na borda sul da bacia. Logo, o objetivo do presente estudo foi avaliar os impactos de alterações na cobertura florestal ripária sobre a estrutura do ecossistema em igarapés de cabeceira no baixo rio Teles Pires, norte de Mato Grosso. Foram selecionados dez locais na bacia do Rio Teles Pires, afluente do rio Tapajós, e em cada um deles foram selecionados dois igarapés de cabeceira (primeira ou segunda ordens), um igarapé localizado em área com a floresta ripária conservada (igarapé íntegro) e outro igarapé com a zona ripária antropizada, com alterações da cobertura florestal ripária (igarapé alterado). Foi considerada como alteração na zona ripária dos igarapés a remoção parcial ou total da floresta. Foram avaliadas variáveis indicadoras da integridade do habitat (proporção de floresta em zonas tampão, índice de integridade do habitat), variáveis hidromorfológicas dos igarapés, variáveis físico-químicas da água, e a produção primária autóctone (algas e herbáceas aquáticas) nos períodos hidrológicos de seca, início do período chuvoso e final do período chuvoso. Foi registrada a variação entre os períodos hidrológicos e a heterogeneidade espacial na estrutura dos igarapés de cabeceira íntegros. As alterações na cobertura florestal ripária afetaram a variabilidade na estrutura do habitat dos igarapés entre os períodos hidrológicos, tornando-os mais homogêneos, e contribuindo para uma menor disponibilidade de material orgânico no substrato bentônico. Além disso, a ausência de cobertura florestal na zona ripária contribuiu para o aumento da produção primária autóctone nos igarapés de cabeceira no sul da Amazônia, embora algas e herbáceas aquáticas tenham respondido de forma diferenciada aos períodos de seca e chuvoso. A partir da comparação entre igarapés íntegros e alterados foi possível estabelecer indicadores de alterações nos igarapés de cabeceira, os quais podem ser utilizados na avaliação de impactos ambientais nestes ambientes, assim como no monitoramento e em ações de reabilitação de igarapés degradados no sul da Amazônia.

Effects of the zone riparian changes on the amazonian streams integrity in the lower Teles Pires river, north of Mato Grosso

ABSTRACT

In the Amazon basin there are many streams, locally called streams, embedded in heterogeneous landscapes, considering the natural variations of geomorphological conditions, rainfall periods and degradation promoted by deforestation, mainly on the southern Amazon basin. Therefore, the aim of this study was to evaluate the impacts of the riparian forest cover changes on the structure streams in the lower Teles Pires River, north of Mato Grosso. Ten sites in the basin of the Teles Pires River, tributary of the Tapajos river, and each of them two headwater streams were selected; a stream located in area with riparian forest preserved (pristine stream) and another stream with the riparian zone disturbed with changes in the riparian forest cover (altered stream). As changes in the riparian zone of the streams, partial or total removal of the forest were considered. Indicator variables of habitat integrity (proportion of forest buffer zones, habitat integrity index), hydromorphological variables streams, physico-chemical parameters, and the autochthonous primary production (algae and aquatic herbaceous) were evaluated in drought, rain/begin and rain/end (hydrological periods). The variation between the hydrological periods and spatial heterogeneity in the structure of pristine headwater streams were recorded. Changes in riparian forest cover affected the variability in habitat structure of the streams between the hydrological periods, making them more homogeneous, and contributing to a lower availability of organic material in benthic substrate. In addition, the absence of forest cover in the riparian zone contributed to the rise of primary production allochthonous in headwater streams in southern Amazonia, although aquatic plants and algal biomass have responded differently to periods of drought and rainy. From the comparison between pristine and altered streams indicators of changes in the headwaters were identified, which can be used in the assessment of environmental impacts in these environments as well as in monitoring and rehabilitation of degraded streams actions in the southern Amazon.

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INTRODUÇÃO GERAL

A numerosa trama de pequenos cursos de água na bacia amazônica é alimentada pela elevada precipitação pluviométrica, que por sua vez contribui para a enorme massa de água lançada ao mar pelo rio Amazonas (Junk e Piedade, 2005). O rio Amazonas recebe descargas provenientes de sistemas heterogêneos, entre eles os ambientes de águas brancas, águas pretas e águas claras de diferentes regiões, inclusive aquelas oriundas do Brasil Central (Sioli, 1991). A heterogeneidade nas características climatológicas e hidrológicas da bacia Amazônica está ligada às condições geomorfológicas e geográficas, as quais mudam nos limites setentrional e meridional da bacia, onde há períodos secos bem definidos (Salati, 1985). Enquanto nos Andes a precipitação pluviométrica pode atingir 6000 mm e na Amazônia Central varia de 1800 a 3000 mm, na periferia da bacia ocorre uma redução no volume de chuvas, podendo a precipitação oscilar entre 1200 e 1800 mm (Junk e Piedade, 2005). As mudanças sazonais no regime hidrológico são importantes na região tropical, em virtude das pequenas variações de luz e temperatura observadas ao longo do ano (Thorp *et al.,* 2006).

Entre os tributários da bacia amazônica, as variações naturais nas tipologias de água e respectivas áreas úmidas, as quais apresentam condições diferenciadas de fertilidade e produtividade, refletem as condições geológicas e fisiográficas, além da influência do regime hidrológico (Sioli, 1984; Junk *et al*., 1989; Junk *et al*., 2011). A heterogeneidade de condições na bacia Amazônica influencia a estrutura da comunidade terrestre (ter Steege *et al*., 2013), e esta, por sua vez, pode influenciar o ecossistema aquático, principalmente a floresta ripária em riachos de cabeceira (Vannote *et al*., 1980). Os riachos/igarapés de biomas florestais dependem da proteção dada pela floresta ripária, seja com relação à interceptação da luz ou ao aumento da infiltração da água das chuvas, que reduz o escoamento superficial, remove ou armazena sedimentos e nutrientes, além de manter as margens estáveis (Gregory *et al*., 1991; Ramírez *et al*., 2008). Além disso, os riachos de florestas são sistemas heterotróficos (Vannote *et al*., 1980), que dependem da matéria orgânica alóctone fornecida para o ecossistema aquático (McClain e Elsenbeer, 2001; Wantzen *et al*., 2008).

A heterogeneidade na escala do habitat é responsável por grande parte da biodiversidade associada aos sistemas aquáticos (Ward, 1998). Contudo, as atividades antrópicas na Amazônia podem ter afetado a estrutura funcional de muitos corpos de água (Lewis Jr, 2008), especialmente no entorno dos grandes centros urbanos e em áreas na periferia da bacia Amazônica. Principalmente a rede hidrográfica que drena a porção sul periférica da região Amazônica vem sofrendo há várias décadas intensa mudança da forma de uso da terra, pela agricultura, pecuária e garimpo. Este é o caso da bacia do rio Tapajós, que apresenta a maior porcentagem de perda de área total reportada para a Amazônia (Trancoso *et al*., 2009). Esses processos de mudança de uso da terra têm levado à degradação crescente das florestas ripárias e à perda de nascentes hidrográficas, bem como à interrupção da conectividade à jusante, ameaçando a integridade biológica das redes hidrográficas (Meyer *et al*., 2007). Isto decorre do fato de que os ecossistemas aquáticos são fortemente influenciados pela bacia de drenagem (Hynes, 1975; Ward, 1998), e pela interface entre a floresta e o riacho, ou seja, pela zona ripária que abriga condições particulares (Gregory *et al*., 1991).

A integridade dos riachos pode ser afetada por alterações nas condições físico-químicas da água, na estrutura física do hábitat, no regime de fluxo de água e nas fontes de energia, entre elas a entrada de luz, material orgânico alóctone e produção primária autóctone, e interações bióticas (Karr e Chu, 2000). Logo, os efeitos da alteração da zona ripária por atividades antrópicas sobre a estrutura do habitat de igarapés de cabeceira podem ser aferidos por meio de medidas de parâmetros hidromorfológicos, limnológicos, e pelas respostas dos produtores primários autóctones e alóctones. O diagnóstico desse conjunto de variáveis poderá subsidiar o entendimento da estrutura funcional dos ecossistemas aquáticos. Além disso, atualmente são também usados protocolos para avaliar vários atributos do habitat, por meio dos quais podem ser gerados índices de integridade do habitat (Nessimian *et al*., 2008).

Embora vastas áreas ao sul da região Amazônica venham sofrendo intensas mudanças da forma de uso da terra, apenas algumas regiões têm sido contempladas com estudos que avaliaram as consequências da remoção da cobertura florestal sobre os igarapés de cabeceira. Esses estudos concentram-se no

Estado de Rondônia, e mostram que a remoção da floresta ripária altera a luminosidade, o balanço de nutrientes e modifica a produtividade do perifíton (Neill *et al*., 2001; Biggs *et al*., 2004; Thomas *et al*., 2004; Neill *et al*., 2006; Germer *et al*., 2009; Deegan *et al*., 2011). Além disto, são também reportadas mudanças na hidrologia dos igarapés, aumentando a frequência e o volume das enxurradas (Chaves *et al*., 2008; Germer *et al*., 2010). Entretanto, estudos relacionados a estas questões ainda inexistem em igarapés de cabeceira na bacia do Rio Teles Pires, Alto Tapajós, onde os processos de mudança de uso da terra têm sido intensos, especialmente nas últimas três décadas, quando a região foi efetivamente colonizada (Soares-Filho, 1995). A partir de estudos comparativos entre igarapés íntegros e alterados é possível gerar indicadores de integridade biológica para riachos de cabeceira no sul da Amazônia, por meio dos quais será possível classificar os riachos e identificar alterações, além de subsidiar programas de reabilitação e uso sustentável desses ambientes.

OBJETIVOS

Objetivo Geral

Determinar os impactos decorrentes de alterações na cobertura florestal ripária sobre a estrutura do ecossistema em igarapés de cabeceira no baixo rio Teles Pires, norte de Mato Grosso.

Objetivos específicos

1. Caracterizar nos períodos hidrológicos de seca, início do período chuvoso e final do período chuvoso, a estrutura do habitat de igarapés de cabeceira com a floresta ripária conservada (igarapés íntegros), determinando ainda a proporção de floresta em zonas tampão no entorno dos igarapés e o Índice de Integridade do Habitat;

2. Avaliar se as alterações na cobertura florestal ripária de igarapés de cabeceira (riachos alterados) influenciam a estrutura do habitat nos períodos hidrológicos de seca, início do período chuvoso e final do período chuvoso, bem como o Índice de Integridade do Habitat;

3. Caracterizar a produção primária autóctone (algas e herbáceas aquáticas) nos períodos hidrológicos de seca, início do período chuvoso e final do período chuvoso e testar se há diferença nesses valores de produção primária entre igarapés íntegros e igarapés alterados pela remoção da cobertura florestal ripária.

Capítulo I

Bleich, M.E.; Mortati, A.F.; Andre, T.; Piedade, M.T.F. Structural dynamics of pristine headwater streams from southern Brazilian Amazon.
River Research and Applications (no prelo)

Structural dynamics of pristine headwater streams from southern Brazilian Amazon

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Abstract

Amazonian headwater streams trail a heterogeneous landscape, with marked natural variation of geomorphological conditions and hydrological periods. Southern Brazilian Amazon is subjected to high degradation pressure mainly from deforestation. Hence, we characterize pristine headwaters structure (hydro-morphology and water physical-chemical variables) and variation among hydrological periods (dry, beginning of the rainy period and end of the rainy period), to define reference conditions for conservation-oriented classification, monitoring, and rehabilitation of the southern Brazilian Amazon streams. Stretches of 10 pristine streams from the Teles Pires River, a major tributary of the Tapajós River, were analyzed for hydro-morphology, water physical-chemical variables, and controlled for habitat integrity (forested proportion on buffer zones and habitat integrity index). We found variation among hydrological periods and spatial heterogeneity on pristine stream structure. Most variables showed great variation ranges at the same hydrological period and high variation coefficient values, reflecting the natural environmental heterogeneity among streams protected by a riparian forest. Variation among hydrological periods and spatial heterogeneity between streams in this region, combined with current high levels of deforestation, indicate the need for the conservation of a high proportion of streams and their respective riparian forests. Here we have presented reference range values for monitoring and rehabilitation programs integrated in Amazonian aquatic conservation efforts.

Key words: riparian zone; habitat structure; lotic ecosystems; temporal variation; hydrological regime; water physical-chemical conditions

Introduction

The Amazonian hydrological basin is fed by a huge network of small streams that trail diverse and complex Amazonian landscapes (Junk and Piedade, 2005). Hence, these streams are themselves highly heterogeneous (McClain and Elsenbeer, 2001). Stream heterogeneity is ruled by a set of biogeochemical processes; water chemistry is primarily controlled by soil characteristics, landscape, and rainfall patterns (McClain and Elsenbeer, 2001; Stallad and Edmond, 1983). Natural variation on water characteristics is visually exemplified by their colors, which in the Amazon basin can be white, black or transparent (Sioli, 1984).

Amazon basin climatological and hydrological conditions differ drastically across the North-South axis with a marked dry season in the South (Sioli, 1984; Salati, 1985; Junk et al., 2011). In Central Amazonia, the rainy season occurs from December through May, with annual rain precipitation varying between 1800 and 3000 mm. At the basin's periphery there is an overall strong rainfall reduction, with values ranging between 1200 and 1800 mm. At the Andean foothills precipitation can reach as high as 6000 mm (Junk and Piedade, 2005). At the Tapajós headwaters, higher rainfall is historically recorded between October and April (Salati, 1985) with mean water column depth at Tapajós River mouth varying up to 7 m between dry and rainy seasons (Sioli, 1984).

Besides the influence from hydrological regime, geological, and physiographic natural variations (Sioli, 1984; Bustillo et al., 2011), Amazon basin tributaries are susceptible to antropic alterations. Water cycle change in Southern and Eastern portions of the Amazon basin indicate a transition towards a perturbation-dominated flow generated by agricultural expansion and climatic variability (Davidson et al., 2012). Once streams are directly influenced by the drainage basin (Hynes, 1975), perturbations triggered by land use modification might modify habitat structure (Biggs et al., 2004; Neill et al., 2006; Coe et al., 2009; Bleich et al., 2009; Germer et al., 2010; Clapcott et al., 2012). Consequently, headwater stream degradation, or even loss, affects ecological connectivity to adjacent ecosystems and threatens biological and functional integrity of hydrographic networks (Meyer et al., 2007).

South and Southeast tributaries are responsible for most of the water contribution to the Amazon basin (Sioli, 1991). Riparian forest these tributaries have been suffering intense alterations for several decades, in the form of land use change by agriculture, cattle rearing and mining operations. In fact, a comprehensive and broad analysis by Trancoso et al. (2009) across hydrographic basins of the Brazilian Amazon pointed to Southern tributaries as the most deforested, and the Tapajós River the one with the highest area lost proportionally.

Channel morphology, discharge, substrate type, litter bank dimensions, riparian vegetation cover and canopy cover are important in providing or controlling habitat structure because a habitat characterization approach is whether it contains useful information for interpreting controls on biota or impacts of human activity; all these habitat attributes vary naturally and may be directly or indirectly altered by anthropogenic activities (Kaufmann et al., 1999).

In such context, the definition of natural spatial heterogeneity and variability between hydrological periods in unperturbed headwater streams is urgent and necessary for the assignment of reference conditions to environmental integrity. In particular, this information is crucial for maintenance and/or rehabilitation of the structure and function of these intrinsically dynamic water bodies (Stoddard et al., 2006; Hawkins et al., 2010). Although transparent water 'igapós' are placed within the most susceptible and exposed environments in the Amazon, this water physiognomy is the least known, as available studies are limited to just a few sites in the Brazilian Amazon (Junk and Furch, 1980; Bernardes et al., 2004; Neill et al., 2001; Umetsu et al., 2007; Espírito-Santo et al., 2008). From undamaged environment characteristics it is possible to specify a transparent water stream condition range, and thus further identify degraded habitats and the most sensitive structural variables of riparian zone alteration. Considering these aspects, the knowledge of understory-protected stream structure in the Amazon basin's South border is essential to define reference conditions to structural integrity of headwater streams. Furthermore, since values of structural integrity may change in a temporal basis here we characterize pristine headwater stream structure (hydro-morphology and water physical-chemical variables) and evaluate natural variation among hydrological periods (dry period, beginning of the rainy period and the end of the rainy period), in order to define reference conditions for the classification of streams of the southern Brazilian Amazon. We propose a variation among hydrological periods hypothesis; pristine streams presenting more heterogeneous structural characteristics and variation among hydrological periods even in environments that are not subject to the annual flooding pulse. We postulate that without temporal analysis there is a strong risk of inaccurate ecological conclusions and inadequate management options for biological conservation.

Methods

Study Site

The study was carried out between 2010 and 2011 in Teles Pires River basin (9°30′28″ - 10°17′07″ S 55°59′59″ - 56°44′37″ W; 238 – 296 m a.s.l.), Northern Mato Grosso state, Brazilian Amazonia (Figure 1; Supplementary Table 1).

The Teles Pires River runs through ‘Cerrado’ biome at its Southern portion and flows North through the Cerrado-Amazonia transition zone until it reaches full Amazonian domain at Northern Mato Grosso, close to its encounter with the Juruena River to form the Tapajós River. At the interfluve Juruena - Teles Pires Rivers the drainages have dendritic to sub-dendritic patterns, with mean to high densities, promoting an irregular topography and interfluvial spacing from 1.750 to 3.750 m, drainage depth below 20 m, and continuous lightly convex slopes with angles below 5%, normally not developing alluvial plains, with the exceptions of greater order drainages (SEPLAN, 2000a).

Annual rainfall is seasonal with a dry period from June to August (SEPLAN, 2000b); within the study period, rainfall during the dry period (July and August 2010) was of 5 mm (ANA, 2011). During the beginning of the rainy period, between October and December 2010, mean rainfall was 363 mm and during the end of the rainy period, between April and May 2011, mean rainfall was 158 mm. Mean air temperature in the dry period was 28 oC, and during the beginning and end of the rainy period was 26.3 ^{o}C (ANA, 2011). This rainfall variation in the study area was used to define hydrological periods for further analysis.

Experimental Design

Ten headwater streams were selected based on their hydrographic relationships and spatial location in an area with preserved riparian vegetation (pristine streams) (Figure 1). 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 (ESRI, 2006). The habitat integrity index (HII) was obtained from the protocol described in Nessimian et al. (2008) and modified by Bleich et al. (2014). The index is calculated from the average of the 12 items evaluated, which standardizes each observed value by dividing by the maximum possible value for each variable. Index values closer to 1 indicate greater integrity. Bleich et al. (2014) 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). Pristine streams do not present human activity at the 50 m and 100 m linear buffer zones, with only minor alterations at the 200 m buffer zone (Table 1) and the habitat integrity index varied from 0.85 to 1.00, with median value of 0.98 (VC = 4.45%).

Each stream surveyed consisted of a 50 m stretch of a chosen stream, where stream structural characteristics (hydro-morphological and water physical-chemical) variables were measured. 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.

We used the 50 m stretches to measure: mean canopy openness above water, mean channel width, mean water column depth, mean surface water speed, mean discharge, proportional cover of benthonic substrates, benthic organic matter, submerged leaf litter bank (presence, respective retention devices and volume), conductivity, pH, dissolved oxygen in the water, water temperature, suspended material and nutrient concentrations. 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) (ESRI, 2006). CO (%) was calculated as the mean of the proportion of white pixels from the total amount of pixels per image (Bunn et al., 1999; Mendonça et al., 2005). 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. (2005). 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) (Allen, 1989).

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 (Espírito-Santo et al., 2008). We estimated stream mean discharge according to Mendonça et al. (2005), as follows: Q = Am X 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; m3) from the greater length, width, and depth of each bank.

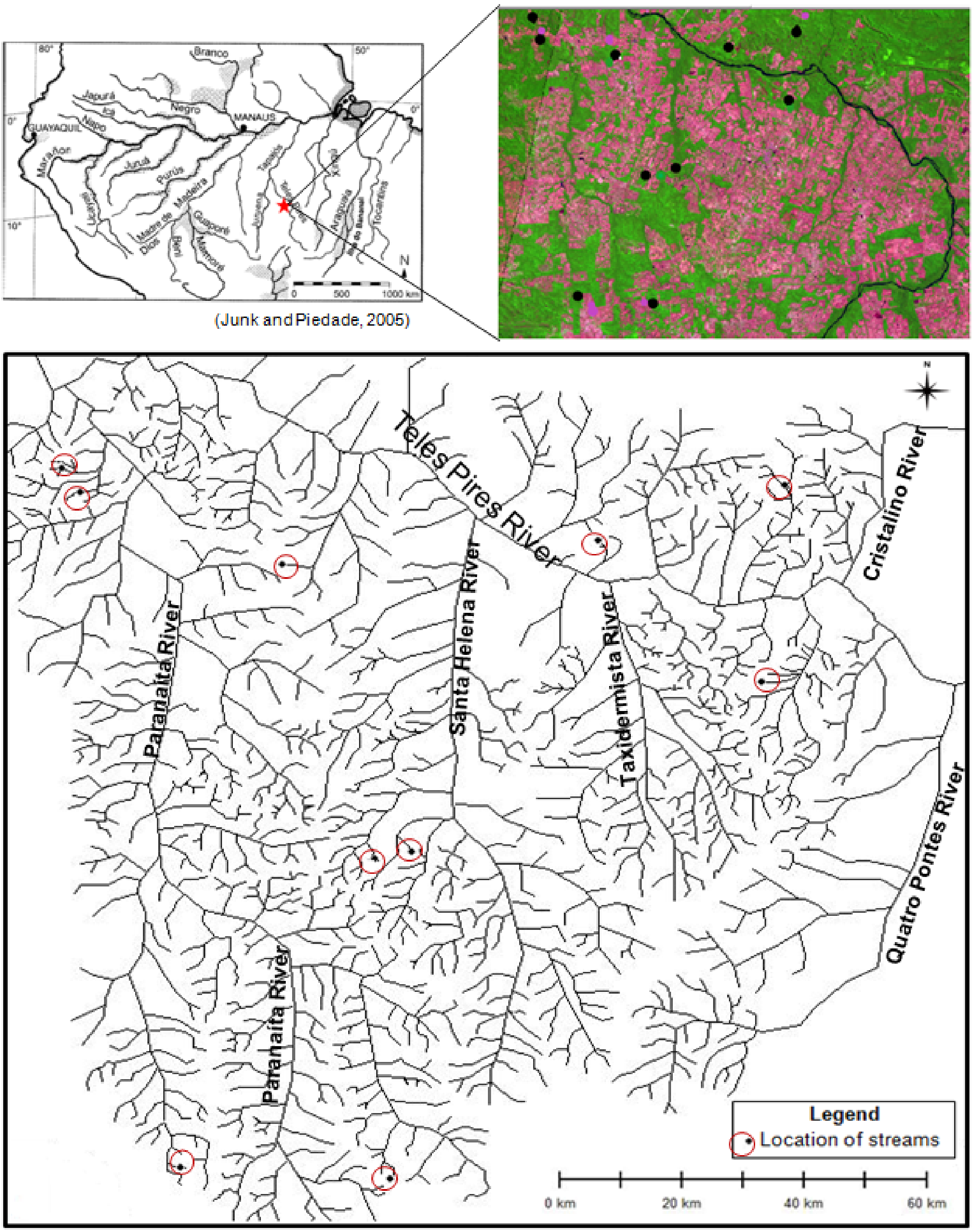

Figure 1. Location of 10 pristine streams along the southern boundary of the Brazilian Amazon.

Table 1. Riparian zone characteristics of the 10 pristine streams of the southern Brazilian Amazon.

Riparian Zone	50 m width			100 m width			200 m width		
	Min.	Max.	Median	Min.	Max.	Median	Min.	Max.	Median
Forest	92.11	98.94	96.03	78.07	98.34	94.71	57.56	97.72	93.15
Secondary Forest	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.47	0.00
Gap	1.06	7.7	3.49	1.66	6.12	3.48	1.4	5.21	2.62
Pasture	0.00	0.00	0.00	0.00	19.59	0.00	0.00	37.93	0.00
Exposed soil/roads	0.00	3.65	0.00	0.00	4.24	0.67	0.00	3.17	1.84

Min. = Minimum value; Max. = Maximum value.

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 [NH3-] was determined using the Indophenol blue method, Nitrite [NO2-] and Nitrate [NO3-] by the N-(1-Naphthyl) ethylenediamine (NTD) method and Orthophosphate [PO43-] by the Molybdenum blue method, according to APHA (1998) and using a spectrophotometer (Quimis, Q798U2M model).

Data analyses

Streams structural characteristics (each variable) were assessed by the analysis of median values (10 streams) and the variation coefficient (% VC= standard/mean*100) for each hydrological period surveyed (dry, rain/begin, rain/end), as well as all periods together. Streams structural characteristics variation among hydrological periods was compared by non-parametric multivariate analysis of variance (NPMANOVA) with 999 permutations (Adonis function, Vegan package), and Gower distance (Gowdis function, FD package) (Anderson, 2001; Oksanen et al., 2011) in the R language (R Development Core Team, 2011). 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) (R Development Core Team, 2011. The ordination analysis resulted in a two dimensional solution (stress = 0.17). Differences for each variable among hydrological periods were tested by Kruskal-Wallis analysis (kruskal.test function, Stats package, and a posteriori the kruskalmc function, pgirmess package).

Results

Most variables showed great variation ranges at the same hydrological period and high variation coefficient values, reflecting the natural environmental heterogeneity among streams protected by a riparian forest (Table 2, Figures 2). The hydrological periods effect on streams structure was detected by NPMANOVA ($F(2,29)= 2.96$; $R2= 0.18$; $p= 0.001$) (Table 3) and the variation summaries by NMDS in Figure 3. Stream structural variables that differed between hydrological periods were: proportion of small inorganic particles substrate (Kruskal-Wallis, $p= 0.051$; Dry-Rain/begin $p<0.05$), litter (Kruskal-Wallis, $p= 0.007$; Dry-Rain/begin $p<0.05$), water temperature (Kruskal-Wallis, $p= 0.0002$; Dry-Rain/begin $p<0.05$; Dry-Rain/end $p<0.05$), water dissolved oxygen (Kruskal-Wallis, $p= 0.009$; Rain/begin-Rain/end $p<0.05$), nitrate (Kruskal-Wallis, $p= 0.013$; Dry-Rain/begin $p<0.05$), and nitrite concentrations (Kruskal-Wallis, $p<0.0001$; Dry-Rain/begin $p<0.05$; Dry-Rain/end $p<0.05$).

Median values for channel width, depth, current velocity and discharge of the sampled streams were respectively 1.04 m, 0.06 m, 20.25 m/s and 0.01 m3/s. Among hydrological periods, the greatest recorded discharge was at the end of the rainy period (0.02 m3/s). In the end of the rainy period width of streams increased 30.2%, depth increased 25%, water velocity 52.4% and flow 90% in relation to the dry period where lowest median values were reported. The prevailing bottom type was sandy (40%), followed by clayey/rocky (30%), sandy/clayey (20%) and sandy/pebbly (10%). Eighty percent of the streams had defined margins, indicating absence of riparian zone flood at the beginning or the end of the rainy period. Small inorganic particles were the most abundant benthonic substrate (65%) followed by litter (22%). The highest proportion of litter (56%) was registered at the dry period and the lowest at the end of the rainy period (15%), when the higher proportion of small inorganic particles (70%) was registered. In the dry period the proportion of litter in the substrate was 73.3% greater than in the receding water. Benthic organic matter represented 2% of stream sediment, and the highest median value was recorded at the beginning of the rainy period (3%), being 63.9% greater in the flood than in the receding water.

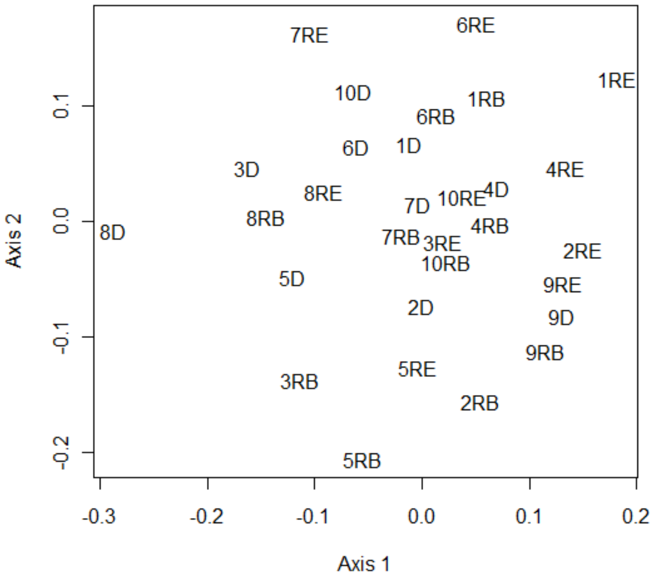

Figure 2. Non-metric multi-dimensional scaling (NMDS) plot of stream structural characteristics of pristine streams in Southern Brazilian Amazonia.

Table 2. Habitat conditions of the pristine streams of the southern Brazilian Amazon.

Hydrological period	Dry		Rain/begin		Rain/end		All periods	
Variables	Med	VC	Med	VC	Med	VC	Med	VC
Width	0.9	50.4	0.85	69.6	1.29	51.6	1.04	58.5
Depth	0.06	88.3	0.05	103.4	0.08	78.1	0.06	86.7
Water velocity	14.15	74.0	16.45	63.3	29.71	50.7	20.25	63.9
Discharge	0.01	156.6	0.002	185.1	0.1	152.7	0.01	190.5
CO	18.13	27.1	17.15	31.2	16.39	38.2	17.1	31.8
Small inorganic	38.9	47.3	77.8	28.0	70.37	54.9	64.81	45.3
Big inorganic	1.85	129.1	0.0	177.7	1.85	141.0	0.0	168.6
Root	0.0	316.2	0.0	211.4	0.0	316.2	0.0	286.4
Trunk	0.0	164.6	0.0	316.2	3.7	154.8	0.0	196.1
Litter	55.56	43.1	16.57	95.9	14.81	103.4	22.22	81.7
OM	2.19	77.9	2.8	61.0	1.01	124.0	2.05	85.3
Litter banks	0.1	270.8	0.08	251.6	0.03	153.8	0.01	276.7
RD	2.2	55.9	3.0	38.5	3.5	27.8	3.0	41.8
Conductivity	28.05	69.5	24.95	72.0	19.8	60.3	24.05	69.0
pH	6.2	7.9	6.4	6.3	5.9	10.2	6.21	8.7
Oxygen	6.63	32.6	5.75	29.3	7.4	18.2	6.75	29.6
Temperature	21.9	6.7	24.15	2.9	24.45	3.9	24.0	7.0
SM	1.43	96.9	2.28	196.4	2.8	100.5	2.28	167.0
Orthophosphate	0.08	104.99	0.22	52.39	0.12	93.4	0.16	84.3
Ammonia	0.03	90.41	0.05	50.50	0.04	55.2	0.04	65.6
Nitrite	0.004	92.33	0.07	79.74	0.02	46.2	0.01	138.1
Nitrate	0.60	54.93	0.15	113.48	0.44	45.8	0.50	70.8

Med= Median value; VC= Variation coefficient; CO= Canopy openness; OM= Benthic organic matter; Litter banks= Submerged leaf litter banks; RD= Retention devices; SM= Suspended material.

Table 3. PERMANOVA results from Gower dissimilarity of habitat conditions related to the hydrological periods of the pristine streams of the southern Brazilian Amazon.

	Df	Sums of Squares	Mean Squares	*F* Model	R^2	Pr(>F)
All hydrological periods	2	0.18	0.09	2.96	0.18	0.001*
Residuals	27	0.82	0.03		0.82	
Total	29	0.99			1	
Periods: Dry- Rain/begin	1	0.14	0.14	3.57	0.16	0.002*
Residuals	18	0.70	0.04		0.83	
Total	19	0.84			1	
Periods: Dry- Rain/end	1	0.13	0.13	3.28	0.15	0.005*
Residuals	18	0.70	0.04		0.85	
Total	19	0.82			1	
Periods: Rain/begin- Rain/end	1	0.10	0.09	2.43	0.12	0.009*
Residuals	18	0.71	0.04		0.88	
Total	19	0.80			1	

* significance of 5%; Periods= hydrological periods.

Streams had clear, transparent, slightly acidic (median value: pH = 6.2) and well oxygenated (median value: 6.8 mg/L) waters, with low conductivity (median value: 24.05 µS.cm-1), low suspended material concentration (median value: 2.28 mg/L), and water temperature of 24oC (median value). Streams had low water nutrients concentration with median values of 0.16 mg/L of phosphate, 0.04 mg/L of ammonia, 0.01 mg/L of nitrite, and 0.50 mg/L of nitrate.

Lowermost median values for water nitrite concentration (0.004 mg/L), phosphate (0.08 mg/L), suspended material (1.43 mg/L), and temperature (22 oC) were registered during the dry period, in which were also recorded the highest median values for electric conductivity (31.30 µS.cm-1) and nitrate concentration (0.60 mg/L). Highest phosphate (0.22 mg/L) and nitrite concentrations (0.07 mg/L) were registered at the beginning of the rainy period. At the end of the rainy period, highest dissolved oxygen (7.40 mg/L) and suspended material concentration (2.80 mg/L) were registered, as well as the lowest values of water pH (5.94) and electric conductivity (19.80 μS.cm-1).

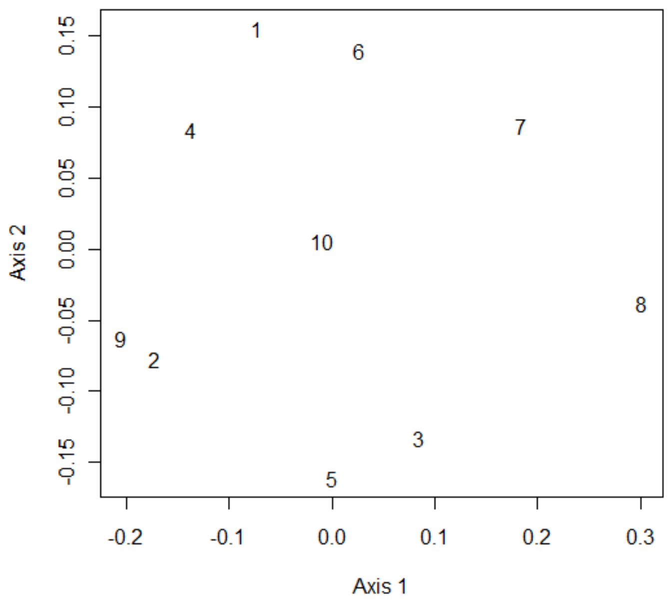

Figure 3. Non-metric multi-dimensional scaling (NMDS) plot from median values (hydrological periods) of stream structural characteristics of pristine streams in Southern Brazilian Amazonia.

In the end of the rainy period the electrical conductivity was 70.6% lower in relation to the dry period; the concentration of MS increased 48.9%, and the water temperature of streams increased 10.4%. On the other hand, for pH difference was 95.2% between these hydrological periods. The increase in concentration of nutrients assessed in the beginning of the rainy period, relative to the dry period was 40% for ammonia, 94.3% for nitrite, and 63.6% for the orthophosphate. However, nitrate increased 75% in the dry period. All surveyed streams displayed submerged leaf litter banks for all analyzed periods. Their median volume was 0.01 m3, with the greatest value recorded in the dry period (0.10 m3) (70% higher) and the smallest at the beginning of the rainy period (0.02 m3). Three types of leaf litter banks retention devices were frequently recorded among rocks, trunks, branches, roots and sand. The lowest median value of number of retention devices was registered at the dry period (2.0). Canopy presented 17.10% of annual median openness above watercourses, and the higher values were recorded at the dry period (median = 18.13%), 9.6% higher than at the end of the raining period.

Discussion

The headwater streams of the southern Brazilian Amazon had high habitat integrity and extremely variable conditions. The effects of hydrological periods on streams structure were detected and also a natural environmental heterogeneity among streams protected by a riparian forest. This spatial-temporal heterogeneity is a prevailing characteristic of lotic ecosystems (Ward, 1989).

Environmental spatial heterogeneity can influence the distribution of species (Hynes, 1975; Vannote et al., 1980; Poff and Ward, 1990; Shimano et al., 2013) and temporal heterogeneity over physical conditions can influence organisms and ecological processes (Palmer and Poff, 1997). Water chemistry of large rivers is influenced by all tributaries in the dense stream net (Junk et al., 2011), which in turn is influenced by the terrestrial systems to which they are connected (Hynes, 1975; Sioli, 1984). Hydro-chemical variability, including seasonality is therefore expected to be higher is headwaters when compared to large rivers (Junk et al., 2011; Sioli, 1984). Therefore, accounting for stream structural heterogeneity permits an improved understanding of structural and functional variations of downstream systems (Karr et al., 1986; Wipfli et al., 2007). The heterogeneity analyzed in this pioneering study is a fundamental guide for conservation efforts concerning Amazonian streams, the predominant unit in the region's lotic ecosystems (McClain and Elsenbeer, 2001; Ballester et al., 2003), and highly vulnerable to human-induced alterations.

Within variables that symbolize pristine stream structure, organic material has emphasized significance because headwater streams tend to accumulate organic matter from the native riparian forest. This mechanism is controlled by riparian vegetation and correlates to nutrient and particle concentrations, as well as to downstream water temperature (Minshall et al., 1983). The median proportion of submerged leaf litter within the three hydrological periods in southern Brazilian

Amazon (22%), resembles the values registered in pristine streams of Central Amazonia (Mendonça et al., 2005), as well as habitat varieties in benthonic substrate (Espírito-Santo et al., 2008; Carvalho et al., 2011; Couceiro et al., 2012). Small headwater streams are beneath a dense canopy layer (median canopy openness <20%), so riparian forest shading limits their primary productivity (Vannote et al., 1980). However, energy as well as nutrient input depends of external terrestrial sources, mainly from leaves and debris that support associated trophic chains (Walker, 1987; McClain and Elsenbeer, 2001; Wantzen et al., 2008). Consequently, leaf litter and debris inside streams and organic material in benthonic sediment (2.08% - median value between hydrological periods) are indicative of the integrity of analyzed streams and are also important factors for habitat availability and energy for aquatic biota (Boyero and Bosch, 2004; Bührnheim and Cox-Fernandes, 2003; Williams, 1980; Williams and Smith, 1996).

Structural variables confirmed water typologies classification of streams (Sioli, 1984; Sioli, 1991) as clear transparent waters tested were nutrient-poor and suspended materials and electrical conductivity below 30 µS.cm-1. These characteristics reflect lixiviated ancient conditions and flow through nutrient-poor landscapes, and are compatible with recorded stream variation for transparent water bodies in the Amazon, whose broad ranges of electrical conductivity (4 to 40 µS.cm-1) and pH (4.5 – 7.8) are indicative of geological dependency (Sioli, 1984; Junk and Piedade, 2005). For instance, in Central Amazonia (Reserva Ducke, Manaus-AM) transparent water streams have acidic waters (pH<5.6) and electrical conductivity between 2.1 and 85.4 µS.cm-1 (Espírito-Santo et al., 2008). Clear streams and rivers investigated at 'Parecis formation' by Junk and Furch (1980) are chemically deficient in electrolytes (Ca and Mg), with water pH lower than 6.0 and low electric conductivity (3 – 6 µS.cm-1). At Ji-Paraná River basin in general, suspended material concentration in rivers and streams are of 3.0 mg/L (Bernardes et al., 2004), similar values to the ones shown here. On the other hand, in nutrient-rich rivers, suspended material concentration is far greater, as such that readings below 20 mg/L are considered low and readings are only considered high when reaching above 100 mg/L (Nittrouer et al., 1986). A color based classification highlights macro-scale differentiation on Amazonian water characteristics (Junk et al., 2011); however, within each typological category there is also local variability, as observed for the streams analyzed here.

Additionally, intra-annual variability in habitat conditions found in Teles Pires headwater streams can be attributed to rainfall variations seen with a dry season as long as three months (SEPLAN, 2000b). This variability between hydrological periods appears similar to other Amazon systems, although there is no inundation of the riparian zone in the streams studied here. Variation in habitat conditions influenced by hydrological/rainfall periods are commonly found in major Amazonian rivers (Junk and Piedade, 2005; Bustillo et al., 2011; Junk et al., 2011). For instance, in the Madeira River in Western Amazonia the increase in suspended material concentration is influenced by the up-rise of the river discharge and results in a great annual range of mean suspended material concentration (between 1 and 294 mg/L) (Leite et al., 2011). At the Ji-Paraná River, also in Western Amazonia, suspended material concentration is higher during the rainy season and a significant difference between dry and rainy seasons was also recorded (Bernandes et al., 2004). Such hydrological period effects were also seen in Central Amazonia streams (Espírito-Santo et al., 2008), Southwest (Neill et al., 2001, Biggs et al., 2004) and South Amazonia rivers (Umetsu et al., 2007). The Teles Pires River and one of its black water tributaries, the Cristalino River, have maximum recorded electrical conductivity of 25 µS/cm, and a pH range between 5.4 and 7.2 (Umetsu et al., 2007). They also presented higher values of some conditions during the rainy season, such as acidity, dissolved oxygen, and suspended material concentration (varying annually between 7 and 22 mg/L in the Teles Pires River; and 2.7 and 5.8 mg/L in the Cristalino River). Although these are relatively big rivers, conditions were found to be similar to the ones described here. This suggests that even smaller streams might follow general patterns presented by better-known Amazonian rivers.

The streams studied here are conserved as evidenced by high habitat integrity index values (and variation coefficient below 5%), despite surrounding landscape alterations. Hence, our results can be taken as reference for impact monitoring and evaluation in future regional conservation efforts. Besides habitat integrity index and the structural variables represented here, monitoring could and should account biotic and multimetric indexes. Biological monitoring based on multimetric evaluation indexes of biological integrity is a powerful tool used to diagnose, prevent or reduce human-induced environmental impacts (Karr and Chu, 2000). A multimetric approach accounts for several aspects of ecosystem structure and function, making it robust and better suited than exclusively biological indexes (Barbour et al., 1996), but requires complementary descriptive studies on structure and function of aquatic systems (Buss et al., 2003), especially in pristine environments. Use of mulimetric approaches in Brazil to evaluate habitat integrity (e.g. Baptista et al., 2011; Couceiro et al., 2012; Baptista et al., 2013) is an important advance, considering the infant stage of aquatic biodiversity conservation at national level: National Water Resources Policy law is from 1997 (Federal Law 9.433/97 Brasil, 1997). However, evaluations of environment impacts on aquatic ecosystems have been restricted to providing environmental licenses that authorize activities with degradation potential. Sadly, such evaluation is not even needed for some activities, cattle for example, including in riparian zones. Impacts on regional streams in South Amazonia are obvious and expected to increase.

The advance of Brazilian Amazon degradation, especially by deforestation occurring along Southern and Eastern borders (Rosa et al., 2013), stresses the urgent need for the identification of habitat structural diversity both in time as in space. Reference stream conditions allow a more precise evaluation regarding impacts generated by riparian zone use and alteration. Results presented here allow the assessment of stream integrity in a region with extremely high human pressure, highlighted by the ~20% forested area loss, the highest within the whole Amazon basin (Trancoso et al., 2009). Considering projections estimated by Soares-Filho et al. (2006), by 2050 total forested area loss in the Tapajós River basin might reach absurd values close to 65% as the advance of agricultural activities is projected to destroy 40% of the total Amazon Forest. Our results are intended to support and encourage high quality monitoring and effective rehabilitation of hundreds of already degraded southern Brazilian Amazon, with the intent of changing future dark scenarios for biodiversity conservation.

Conclusion

The effects of hydrological periods on streams structure and spatial heterogeneity between streams were detected. This condition combined with current high levels of deforestation in southern Brazilian Amazon, indicate the need for the conservation of a high proportion of streams and their respective riparian forests.

Acknowledgments

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Supplementary Table 1. Geographical coordinates of the pristine streams of the southern Brazilian Amazon.

Streams	Geographical coordinates	
	S	W
1	09º43’45.1’’	56º01’23.9’’
2	09º30’28.3’’	55º59’59.3’’
3	10º16’21.6’’	56º37’18.1’’
4	10º17’07.9’’	56º24’54.0’’
5	09º35’49.6’’	56º30’59.7’’
6	09º34’11.1’’	56º11’29.4’’
7	09º55’10.0’’	56º23’00.8’’
8	09º55’40.2’’	56º25’16.1’’
9	09º29’20.2’’	56º44’37.7’’
10	09º30’57.7’’	56º43’25.2’’

Capítulo II

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

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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 ^{o}C 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 prístinos) 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 hidromorfológicos, 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 ^{o}C 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.

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.

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

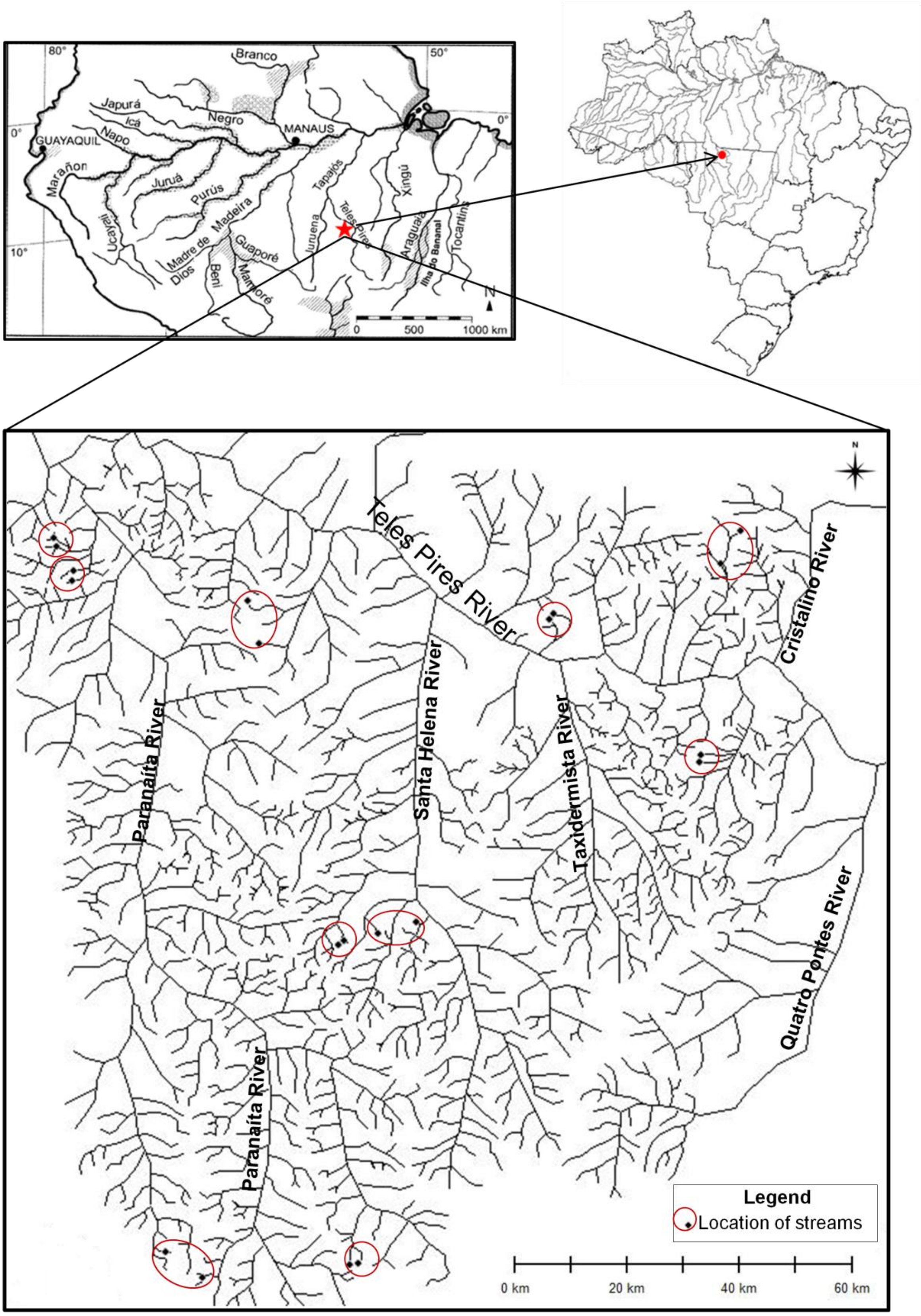

Fig. 1. Location of 10 study sites (red circle), at each site one pristine stream and an altered stream, along the southern boundary of the Brazilian Amazon.

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 X 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).

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].

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

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.

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).

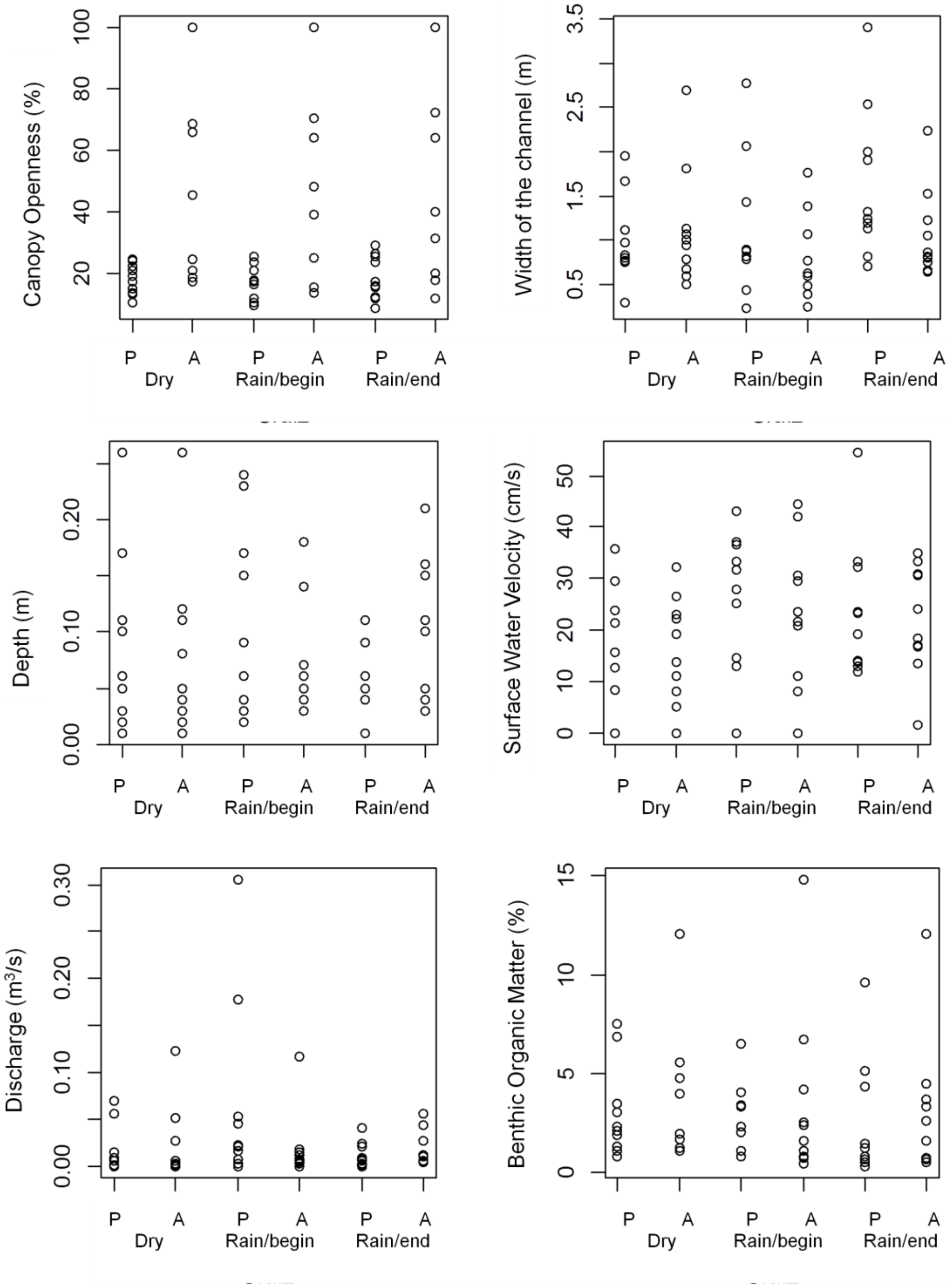

Fig. 2. Variation range of canopy openness and channel structure of the pristine (P) and altered (A) streams across hydrological periods (Dry; Rain/begin; Rain/end) in Southern Brazilian Amazonia.

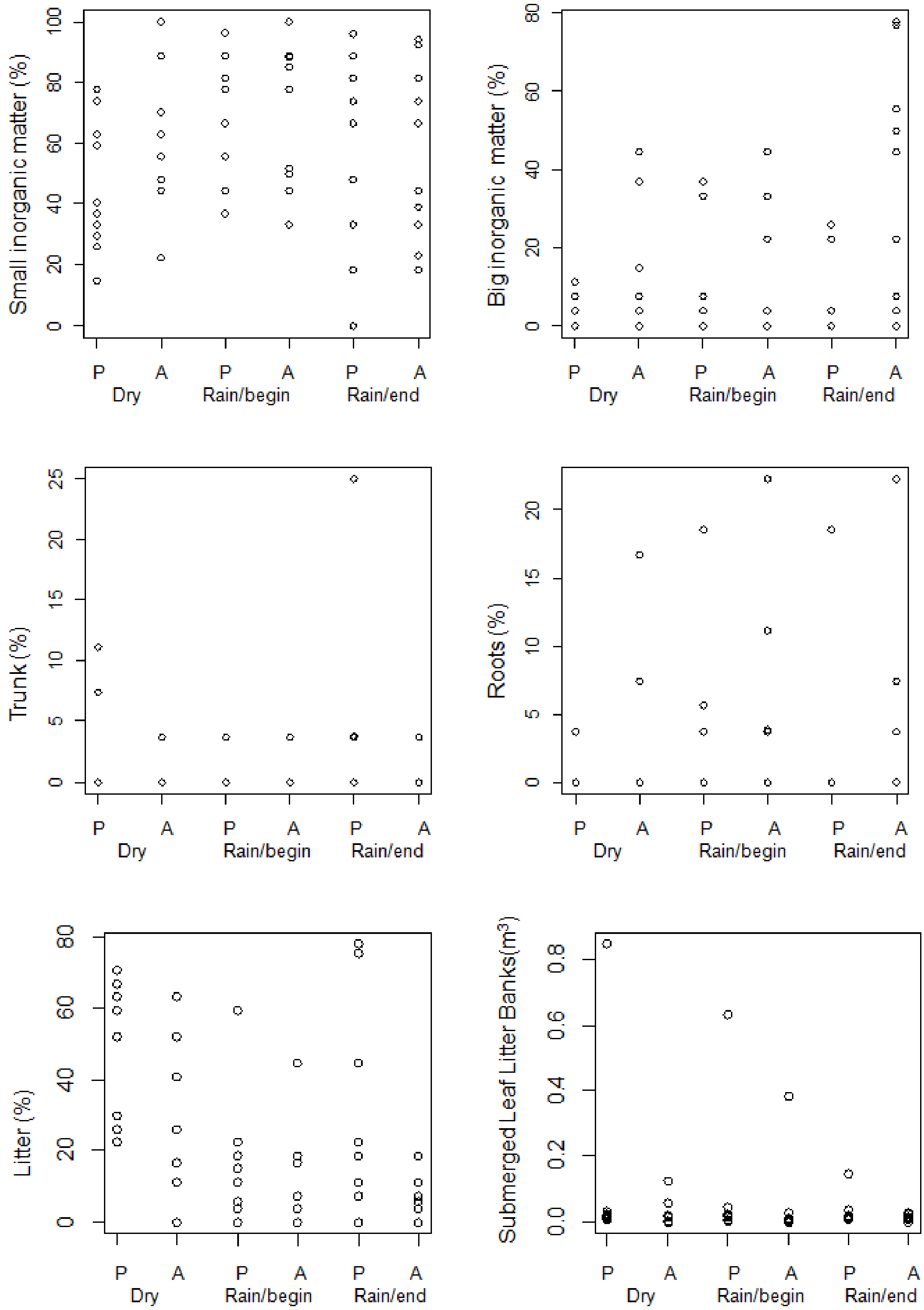

Fig. 3. Variation range of the benthonic substrate composition and leaf litter bank volume of the pristine (P) and altered (A) streams across hydrological periods (Dry; Rain/begin; Rain/end) in Southern Brazilian Amazonia.

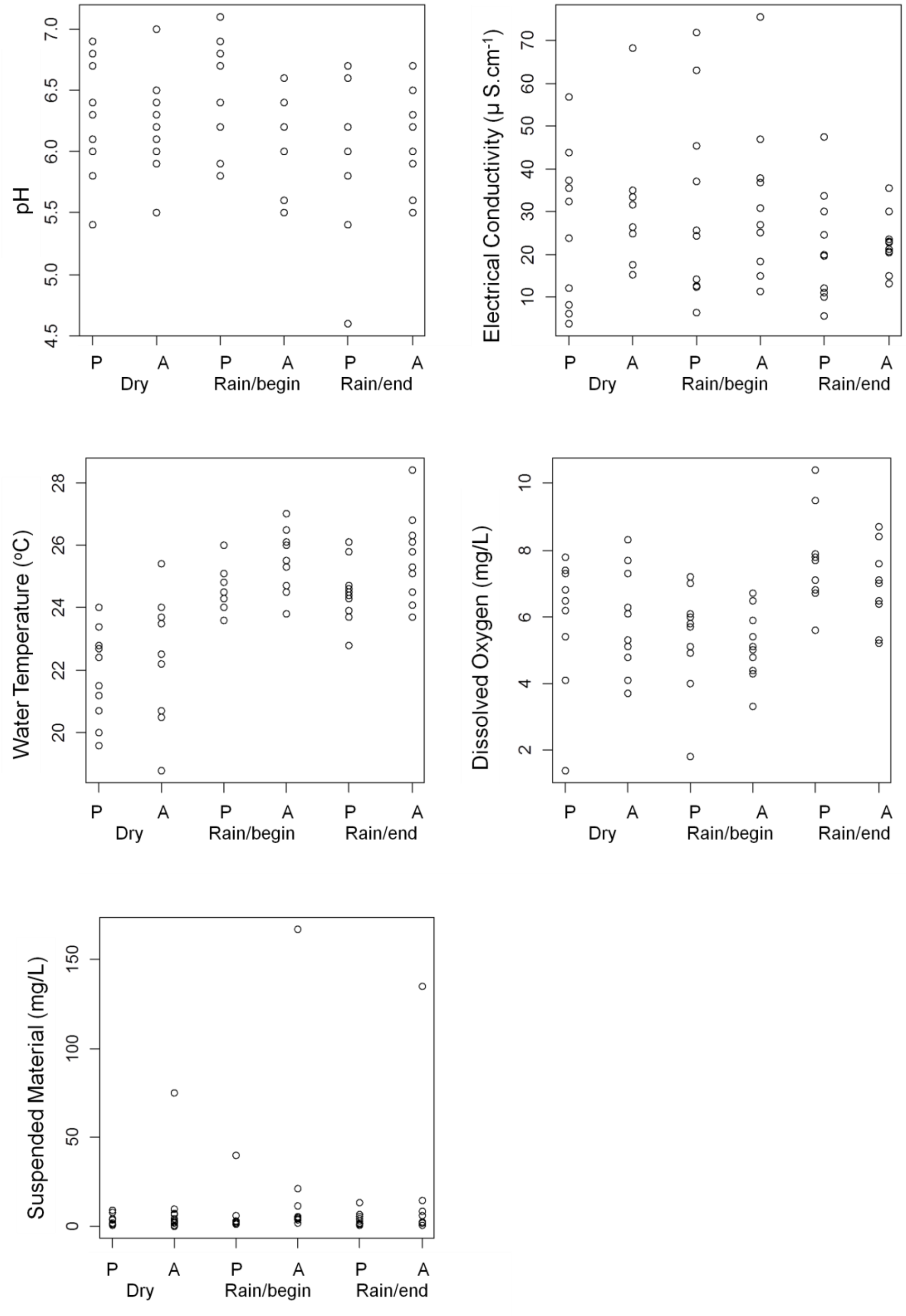

Fig. 4. Variation range of the physical-chemical features of the water of the pristine (P) and altered (A) streams across hydrological periods (Dry; Rain/begin; Rain/end) in Southern Brazilian Amazonia.

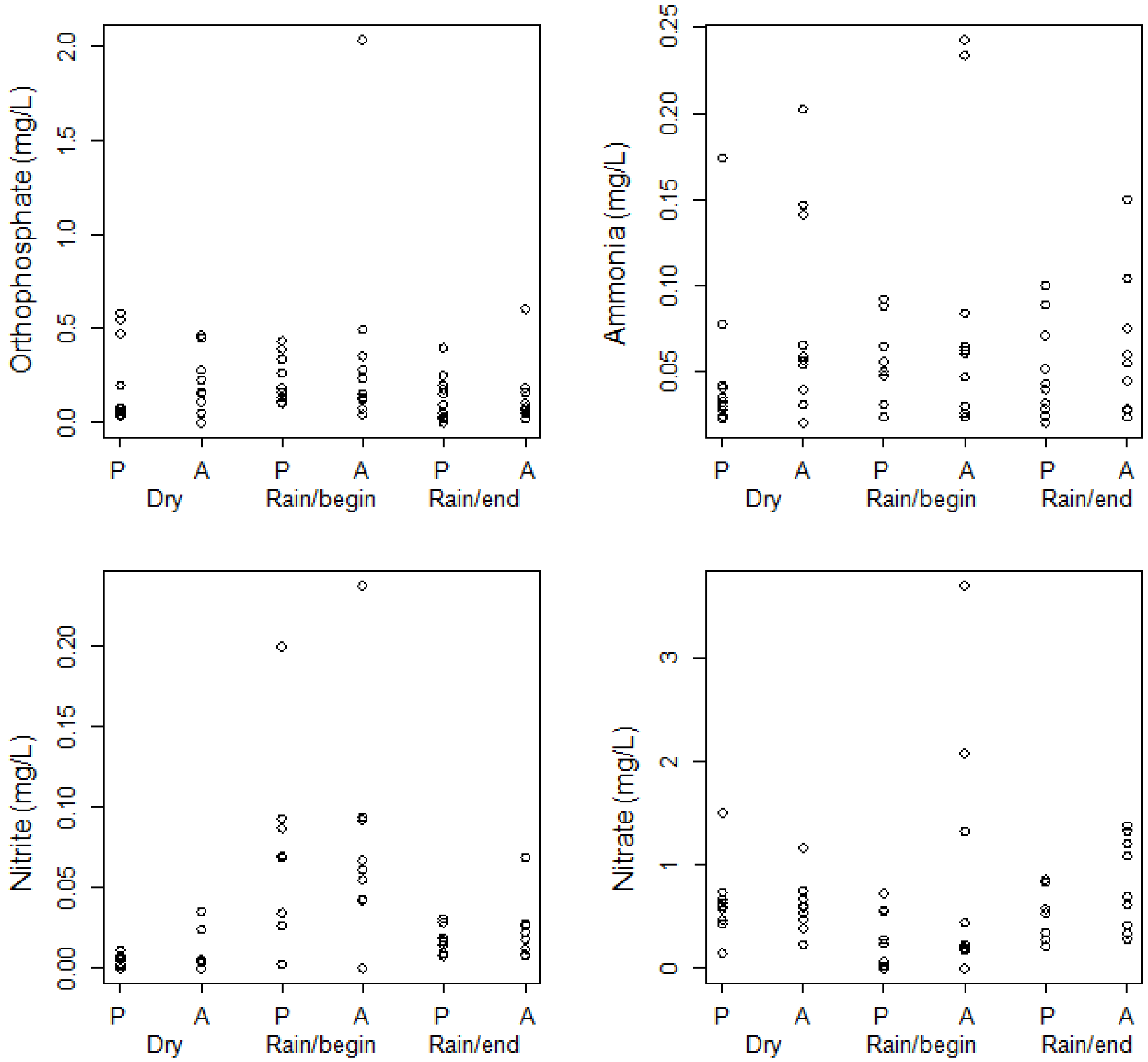

Fig. 5. Variation range of the water nutrient concentrations of the pristine (P) and altered (A) streams across hydrological periods (Dry; Rain/begin; Rain/end) in Southern Brazilian Amazonia.

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).

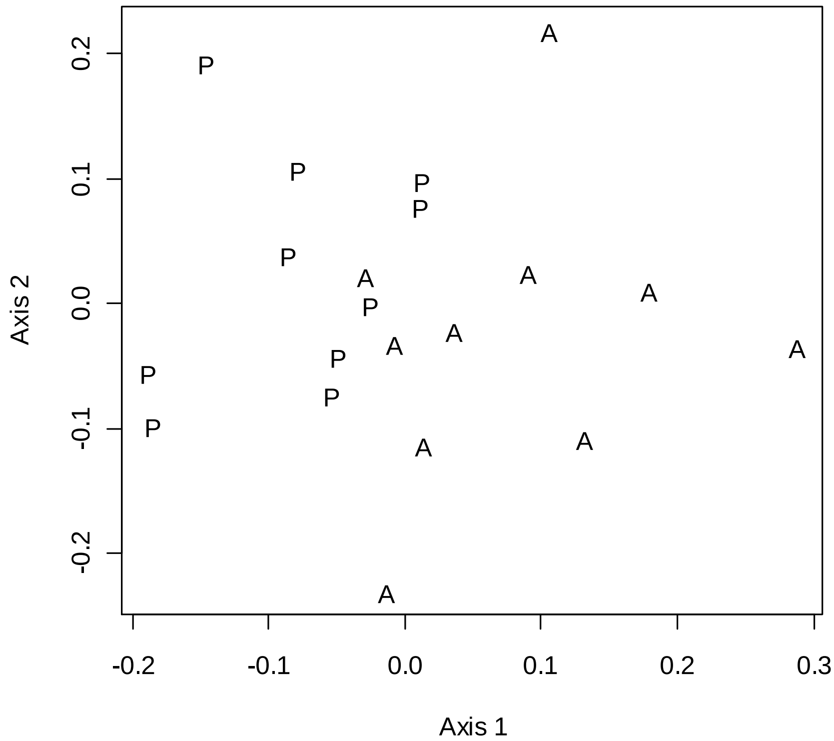

Fig. 6. Non-metric multi-dimensional scaling (NMDS) plot of stream structural characteristics of pristine (P) and altered (A) streams in Southern Brazilian Amazonia.

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 ^{o}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].

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.

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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

Capítulo III

Bleich, M.E., Piedade, M.T.F., Mortati, A.F. & André, T. Autochthonous primary production in southern Amazon headwater streams: Novel indicators of altered environmental integrity. *Ecological indicators* (no prelo)

Autochthonous primary production in southern Amazon headwater streams: Novel indicators of altered environmental integrity

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Abstract

The riparian forest reduces the amount of light entering streams, which limits autochthonous primary production. The aim of this study was to evaluate the temporal variation of autochthonous primary production in pristine and altered streams, with the goal of identifying indicators of change in environmental integrity in the southern Brazilian Amazon. We evaluated the free algal biomass in the water column, the presence of periphyton, and the richness and cover of aquatic herbaceous plants in 20 streams (10 pristine and 10 altered, i.e., with riparian deforestation) during the dry period, at the beginning of the rainy period, and at the end of the rainy period. In altered streams, we recorded the presence of macroscopic periphyton and the amount of algal biomass varied between the dry and flood seasons. Variations in hydrological periods did not contribute to changes in algal biomass in pristine streams; we did not observe the presence of macroscopic periphyton these streams. In altered streams, 23 aquatic herbaceous species were identified, versus only four in the pristine streams. Results showed that riparian deforestation contributes to increased autochthonous primary production, which is also influenced by different hydrological periods, with algae and aquatic herbaceous plants responding differently to dry and rainy periods. The responses of these primary producers confirm their role as important bioindicators of change in the environmental integrity of southern Amazonian streams.

Keywords: Riparian deforestation, bioindicators, algal biomass, herbaceous aquatic plants, discharge variations.

1. Introduction

In headwaters, most of the energy enters the system via organic matter from the litter of terrestrial vegetation (mainly leaves) (Wantzen et al., 2008). In these environments, heterotrophic metabolism predominates (Cummins, 1975), with an allochthonous primary production that accounts for 90% of the input of organic matter to streams (Vannote et al., 1980). The riparian forest provides the organic material on which the food web depend (Wallace et al., 1997), and thus influences the functional structure of stream ecosystems (Gregory et al., 1991), but it also limits the autochthonous primary production by shading (Davies et al., 2008), thus preventing significant growth of planktonic algae, periphyton, or aquatic plants (Begon et al., 2007). Thus, autochthonous primary productivity declines when the canopy above the stream intercepts the entry of sunlight (Hill et al., 2001).

On the other hand, the partial or total removal of riparian forest may increase or change the primary production in streams (Davies et al., 2008). Among the effects of increased light input into streams are changes in functional groups, with palatable unicellular algae being replaced by filamentous green algae, which require a lot of light (Bunn et al., 1999); moreover the abundance of aquatic herbaceous plants in streams may also increase (Fletcher et al., 2000), together with the productivity of periphyton (Neill et al., 2001). While light is a limiting factor for primary production in stream ecosystems, nutrients play an important secondary role, and must be present for biosynthesis to take place (Hill et al., 1995). Nutrient limitation may have a significant influence on aquatic primary production in situations where light is not the limiting factor (Davies et al., 2008).

If openings in the canopy occur or forests are replaced by pasture, the amount of light entering the Amazon headwater streams will increase and may modify the primary productivity in these streams (Neill et al., 2001; Thomas et al., 2004). Thus, these changes in the riparian forest can lead to the loss or reduction of the environmental integrity of streams, and the primary aquatic producers (i.e., algae and aquatic herbaceous plants) may be good indicators for measuring these changes (Karr, 1991; Karr and Chu, 2000). These organisms respond quickly to conditions that are favorable to their development, whether it be an increase in insolation, or the availability of nutrients or substrate (Bleich et al., 2009; Calijuri et al., 2008; Camargo et al., 2003; Cardinale et al., 2002; Castro et al., 2008; Rodrigues et al., 2005; Wetzel, 2001).

Cardinale et al. (2005) suggest that changes in the productivity and diversity of streams can have a big impact on organisms sensitive to disturbances. Therefore, to understand the effects of changes in the riparian zone on the integrity of Amazonian streams, one must also know the responses of the autochthonous primary producers. However, there are no comprehensive studies done in Amazonian headwater streams, e. g. Neill et al., 2001 and Thomas et al., 2004, even though region has suffered important changes regarding land use (Soares-Filho et al., 2006; Trancoso et al., 2009). As deforestation is the main environmental impact in the huge network of rivers of various orders that cut across the Southern Brazilian Amazonia, and the degradation in water bodies has been continuously increasing, we proposed use a novel bioindicator of change in the environmental integrity of southern Amazonian streams, 'autochthonous primary production'. The hypothesis is that autochthonous primary production increases in altered streams and varies among hydrological periods. Altered and pristine streams classifications were based in the habitat integrity index, where altered streams presented median value of 0.52 and pristine streams, 0.98 (Bleich et al., 2014 in press). And to test this hypothesis, we quantified the autochthonous primary production of a set of headwater streams with and without riparian deforestation, and its variation among hydrological periods. We determined the impact of the removal of riparian forest cover on autochthonous primary production in order to provide elements for environmental impacts assessment and the monitoring of these water bodies.

2. Materials and Methods

2.1 Study Area

This study was conducted in 2010 and 2011 in streams in the southern Brazilian Amazon (9°30'28 " – 10°17'07" S; 55°59'59 " – 56°44'37" W), between 238 and 296 m above sea level in the Baixo Teles Pires River sub-basin, Alto Tapajós River, in the northern region of the state of Mato Grosso (Figure 1). The watershed of the Teles Pires river traverses the land area of the Cerrado, followed by the Amazon–Cerrado transition area, and reaches the Amazon area in the northern region of the state of Mato Grosso, Brazil. In this geographical region, rainfall shows two well-defined seasons throughout the year, with June, July, and August being the driest months (SEPLAN, 2000).

2.2 Sampling Design

We assessed the presence of macroscopic periphytic algae, the free algal biomass in the water column, and the richness and cover of aquatic herbaceous plants in 10 sites selected based on their spatial location (Figure 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 sampling site consisted of a 50 m stretch of a chosen stream. We sampled stretches during three periods between July 2010 and May 2011: dry period (July and August 2010; mean rainfall = 5 mm), beginning of the rainy period (i.e., rain/begin; November and December 2010; mean rainfall = 363 mm), and end of the rainy period (i.e., rain/end; April and May 2011; mean rainfall = 158 mm).

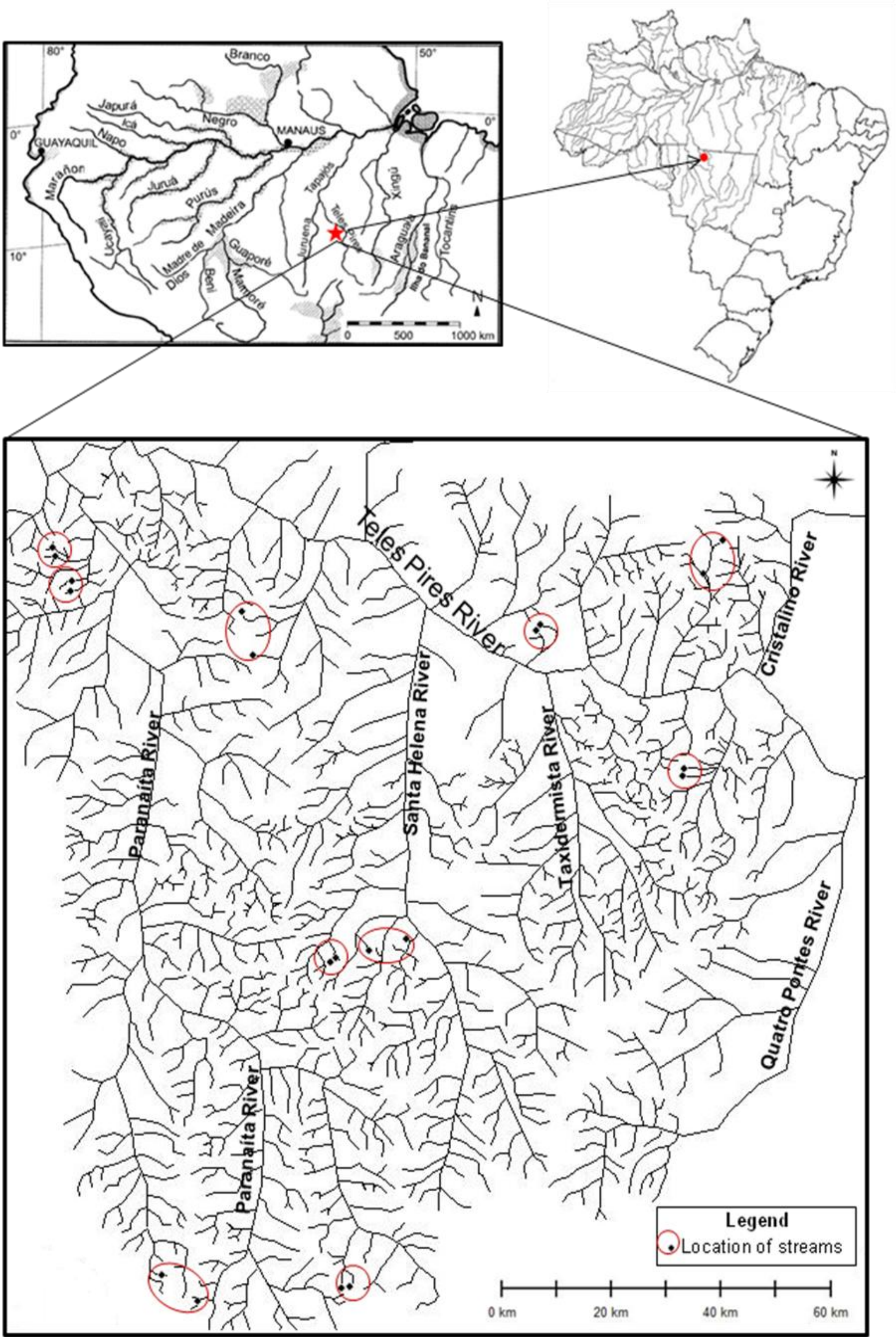

Figure 1. Location of 10 study sites (red circle), at each site one pristine stream and an altered stream, along the southern boundary of the Brazilian Amazon.

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 (ESRI, 2006). 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).

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

The presence of macroscopic periphytic algae was determined by surveying a 50 m stretch of the stream. The free algal biomass in the water column (mg/L) was determined by extracting chlorophyll *a*, for which three water samples were collected from each stream, then packed in bottles protected from light by aluminum foil and kept refrigerated until filtering and early extraction (which occurred within 12 hours of collection). For water filtration (2000 mL), we used fiberglass filters (52 mm GF/C Whatman) that was previously calcined in a muffle furnace at 450 °C for 4h. Chlorophyll *a* was extracted with 90% ethanol heated to 78 °C and a concentration reading was conducted according to Nush (1980) and using a spectrophotometer (Quimis, Q798U2M model).

The richness and cover of aquatic herbaceous plants were evaluated by identifying species over a stretch of 50 m following the course of the stream and 1 m wide on each bank. Fertile specimens were collected, recorded, and incorporated into the Herbarium of the National Institute for Amazonian Research (Instituto Nacional de Pesquisas da Amazônia, INPA, collector ME Bleich 247406-247505). Taxonomic identification was performed at the INPA herbarium and species scientific names and families were updated according to the Angiosperm Phylogeny Group III system (APG III 2009); these species names and their authors were confirmed using the Tropicos (2013) database from the Missouri Botanical Garden, USA. The coverage of aquatic herbaceous plants was measured as the percentage of coverage for a given length of stretch evaluated: 0% (no aquatic herbaceous plants), 0.1 to 2% in up to 1 m of stretch evaluated, 2.1 to 20% in up to 10 m of stretch, 21–50% in up to 25 m of stretch, 51–70% in up to 35 m, and 71–100% in up to 50 m of stretch. Classification of the lifeforms of aquatic herbaceous species was conducted according to Cook (1996).

Canopy openness (CO) was estimated with three equidistant digital photographs of the canopy per stretch (50 m) 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) (ESRI, 2006). CO (%) was calculated as the mean of the proportion of white pixels from the total amount of pixels per image (Bunn et al., 1999; Mendonça et al., 2005).

2.3 Data Analyses

We evaluated streams' autochthonous primary production by analyzing the minimum, maximum, median, and coefficient of variation (%CV = standard deviation/mean*100) values across the three hydrological periods. The differences in autochthonous primary production between pristine and altered streams were compared using a nonparametric multivariate analysis of variance (NPMANOVA) with 999 permutations (Adonis function, Vegan package) using the Gower distance function (Gowdis function, FD package) (Anderson, 2001; Oksanen et al., 2011); variables were also analyzed individually with a Wilcoxon paired test (wilcox.test function, Stats package). The differences for each variable across hydrological periods were tested with a Kruskal-Wallis test (kruskal.test function, Stats package, followed by the kruskalmc function in the pgirmess package). To test the association between the canopy openness and algal biomass, the richness and cover of aquatic herbaceous plants in each hydrological period, we performed a Sperman correlation (rs) using corr.test function from Psych package. The analyses were performed using the R language (R Development Core Team, 2011).

3. Results

The autochthonous primary production in headwater streams was altered by the removal of riparian forest cover (NPMANOVA, $F_{(1,59)} = 43.93$; $R^2 = 0.43$; $p = 0.001$). There was a difference between pristine and altered streams in 1) the amount of algal biomass during the dry period (Wilcoxon, $p < 0.01$) and during the rain/begin period (Wilcoxon, $p < 0.04$), 2) in the presence of macroscopic periphyton during all three hydrologic periods tested (Wilcoxon, $p < 0.02$), 3) in the richness of aquatic herbaceous plants during the rain/end period (Wilcoxon, $p < 0.02$), and 4) in the cover of aquatic herbaceous plants during the rain/begin and rain/end periods (Wilcoxon, $p < 0.03$). The canopy openness is significantly correlated to: algal biomass in dry and rain/begin periods; and richness and coverage of aquatic herbaceous plants in rain/begin and rain/end periods (Table 4). Canopy presented 17.10% of annual median openness above watercourses of the pristine streams and 56.2% of canopy/vegetation cover in altered streams (Figure 2).

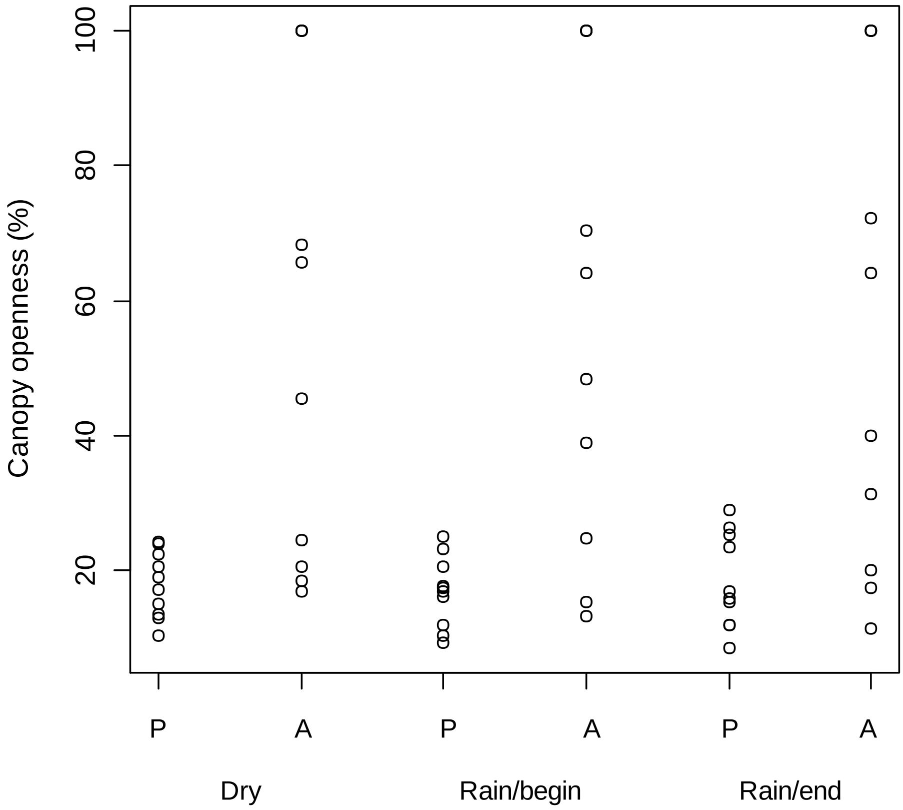

Figure 2. Variation range of canopy openness of the pristine (P) and altered (A) streams across hydrological periods (Dry; Rain/begin; Rain/end) in Southern Brazilian Amazonia.

In pristine streams, we did not observe the presence of macroscopic periphyton, but we did record free algal biomass in the water column (median = 0.08 mg/L) (Table 2). On the other hand, in 83% of altered streams, we recorded the presence of macroscopic periphyton, and the median concentration of algal biomass was 0.14 mg/L, with the highest concentration recorded during the dry season (0.25 mg/L) (Table 2). This concentration was four times higher than during rain/begin and twice that of the rain/end period. However, in altered streams, the difference in algal biomass differed significantly only between the dry and rain/begin periods (Kruskal-

Wallis, $p < 0.05$), while in pristine streams, variations in hydrological periods did not contribute significantly to increasing or reducing the free algae in the water column (Table 2).

Table 2. Autochthonous primary production in pristine and altered streams among hydrological periods in the southern Brazilian Amazon.

Hydrological periods		**Algal biomass (µg/L)**		**Aquatic herbaceous plants**			
				Richness		**Coverage (%)**	
		Streams		**Streams**		**Streams**	
		Pristine	**Altered**	**Pristine**	**Altered**	**Pristine**	**Altered**
Dry	**Min.**	0.00	0.02	0.00	0.00	0.00	0.00
	Max.	0.23	0.59	1.00	6.00	2.00	50.00
	Med.	0.08	0.25	0.00	0.50	1.00	1.00
	CV	70.52	59.57	129.10	156.15	105.41	180.45
Rain/begin	**Min.**	0.00	0.02	0.00	0.00	0.00	0.00
	Max.	0.22	0.31	1.00	6.00	2.00	70.00
	Med.	0.06	0.06	0.00	1.00	1.00	5.00
	CV	92.66	88.99	129.10	122.19	105.41	180.87
Rain/end	**Min.**	0.00	0.00	0.00	0.00	0.00	0.00
	Max.	0.20	0.34	2.00	10.00	5.00	100.00
	Med.	0.09	0.12	0.50	2.50	2.00	9.00
	CV	76.18	77.92	117.61	87.40	105.41	157.41
All hydrological periods	**Min.**	0.00	0.00	0.00	0.00	0.00	0.00
	Max.	0.23	0.59	2.00	10.00	5.00	100.00
	Med.	0.08	0.14	0.00	1.50	2.00	5.00
	CV	78.53	80.78	125.94	122.03	105.78	168.49

Min. = Minimum value; Max. = Maximum value; Med= Median value; VC= Variation coefficient

Among altered streams, 20% did not contain aquatic herbaceous plants, while 40% had a large amount of these plants, reaching 100% coverage (Table 2). On the other hand, in 40% of pristine streams, there were no aquatic herbaceous plants during any of the hydrological periods, and in the remaining pristine streams, we recorded at most two species in each stream, which occupied less than 2% of the analyzed stretch. We recorded 25 species of aquatic herbaceous plants, 23 in altered streams and four species in pristine streams (Table 3), and the emergent life form was predominant among the recorded aquatic herbaceous plants. Among the aquatic herbaceous plants, the *Bognera recondita* and *Rhynchospora cephalotes* were observed exclusively in pristine streams, while *Calyptrocarya glomerulata* and *Ceratopteris pteridoides* were recorded in both pristine and altered streams. The *Calyptrocarya glomerulata* was recorded in all hydrological periods, and had the highest frequency among the 10 pristine streams (Table 3).

We recorded an increase in the richness and cover of aquatic herbaceous plants in streams during the rain/end period. Among altered streams, 12 species were recorded for all hydrological periods analyzed. The most frequent species in altered streams were *Calyptrocarya glomerulata*, *Cyperus luzulae*, *Fimbristylis dichotoma*, *Fuirena umbellata*, and *Scirpus umbellatus* (Table 2), with the Cyperaceae family making up 54.2% of identified species. Although there are variations in the richness and cover of aquatic herbaceous plants between hydrological periods, these differences were not significant in the altered streams (Kruskal-Wallis, $p > 0.05$) as in the pristine streams (Kruskal-Wallis, $p > 0.05$).

Table 3. Frequency of occurrence (%) of aquatic herbaceous plant species in pristine and altered streams among hydrological periods (Dry period = D; Rain/begin period = RB; Rain/end period = RE) in the southern Brazilian Amazon.

Family	**Species**	**Streams**					
		Altered			**Pristine**		
		D	**RB**	**RE**	**D**	**RB**	**RE**
Araceae	*Bognera recondita* (Madison) Mayo & Nicolson	0	0	0	0	0	10
Cyperaceae	*Calyptrocarya glomerulata* (Brongn.) Urb.	20	30	40	40	30	40
	Cyperus diffusus Vahl	10	10	10	0	0	0
	Cyperus luzulae (L.) Rottb. e.g. Retz.	10	10	50	0	0	0
	Cyperus odoratus L.	0	10	20	0	0	0
	Eleocharis acutangula (Roxb.) Schult.	10	10	20	0	0	0
	Eleocharis interstincta (Vahl) Roem. & Schult.	10	10	10	0	0	0
	Eleocharis minima Kunth	10	10	10	0	0	0
	Eleocharis nigrescens (Nees) Kunth	10	10	10	0	0	0
	Fimbristylis dichotoma (L.) Vahl	0	10	50	0	0	0
	Fimbristylis miliacea (L.) Vahl	0	20	10	0	0	0
	Fuirena umbellata Rottb.	10	10	50	0	0	0
	Rhynchospora cephalotes (L.) Vahl	0	0	0	0	0	10
	Scirpus umbellatus (Rottb.) Kuntze	10	10	40	0	0	0
	Scleria macrophylla J. Presl & C. Presl	10	10	10	0	0	0
Melastomataceae	*Aciotis acuminifolia* (Mart. ex DC.) Triana	0	0	20	0	0	0
	Rhynchanthera dichotoma (Desr.) DC.	0	0	10	0	0	0
Onagraceae	*Ludwigia affinis* (DC.) H. Hara	0	0	10	0	0	0
	Ludwigia decurrens Walter	0	0	10	0	0	0
	Ludwigia octovalvis (Jacq.) P.H. Raven	0	0	20	0	0	0
Poaceae	*Ichnanthus axillaris* (Nees) Hitchc. & Chase	0	0	10	0	0	0
	Panicum pilosum Sw.	0	0	10	0	0	0
	Steinchisma laxum (Sw.) Zuloaga	0	0	10	0	0	0
Pteridaceae	*Ceratopteris pteridoides* (Hook.) Hieron.	20	10	10	0	10	0
Xyridaceae	*Xyris jupicai* Rich.	10	10	10	0	0	0

Table 4. Spearman correlation (rs) among canopy openness and autochthonous primary production in the hydrological periods (Dry period = D; Rain/begin period = RB; Rain/end period = RE) in southern Brazilian Amazon.

Variables		**Hydrological periods**	**Spearman Correlation**	**P-value**
Algal biomass		D	0.65	0.00
Algal biomass		RB	0.45	0.05
Algal biomass		RE	-0.15	0.53
Aquatic herbaceous plants	Coverage	D	0.28	0.23
	Coverage	RB	0.70	0.00
	Coverage	RE	0.77	0.00
	Richness	D	0.36	0.12
	Richness	RB	0.51	0.02
	Richness	RE	0.71	0.00

4. Discussion

Our study supports the claim that autochthonous primary production can be used as indicators of altered environmental integrity tropical streams, because when there is clearing of the riparian forest, there is greater insolation in the streams, which contributes to an increase in free algal biomass, macroscopic periphyton, and aquatic herbaceous plants in stream of the southern Amazon. The modified of autochthonous primary production in headwater streams is extremely worrying considering the advance of Brazilian Amazon degradation, especially by deforestation occurring along Southern and Eastern borders (Rosa et al., 2013).

Autochthonous primary production was influenced not only by riparian zone conditions, but also by rainfall favoring the growth of riparian vegetation and decrease the algal biomass. Rainfall can provide shade for the streams and scour algae during the beginning of the rainy season (Lamberti and Steinman, 1997). Algal biomass increased by 68% during the dry period and 25% during the rain/begin period in streams with altered riparian forest cover. Likewise, in headwater streams in the United States, higher riparian canopy openness led to an increase in algal biomass (Elliot et al., 2004) of up to 60% (Bilby and Bisson, 1992) and in the abundance of aquatic herbaceous plants (Fletcher et al., 2000).

In southern Amazonian, deforestation of the riparian forest also led to the loss of variability in headwater stream habitat structure across hydrological periods (Bleich et al., 2014 in press), which results from differences in precipitation, and are very important in the Amazon, as it influences structural and functional aspects of aquatic ecosystems (Espirito-Santo et al., 2008; Germer et al., 2010; Junk and Piedade, 2005; Rueda-Delgado et al., 2006). In Madagascar streams, changes in the type of algal species and a reduction in their number were recorded when comparing forest streams to streams with an open canopy and greater light, suggesting that algal diversity is affected by tropical deforestation (Bixby et al., 2009). Furthermore, Finlay (2011) studied 200 streams and rivers and detected that primary and secondary production increased by 600% in altered versus pristine streams, and that autotrophic production predominated in altered streams.

The increased autochthonous primary production in altered streams, that are poor in nutrients in the southern Amazon (Bleich et al., 2014), reflects the greater insolation in these environments, which were previously shaded by riparian forest (Fletcher et al., 2000). However, the lower amount of algae during flooding in the southern Amazon reflects the possibility that rains scour these organisms. According to Thomas et al. (2004), the low concentrations of chlorophyll *a* during the rainy season in Amazonian streams suggest that the effects of land use were suppressed by the dilution caused by increased water flow in streams. Moreover, these hydrological alterations can determine seasonal patterns of resource consumption in tropical streams (Frauendorf et al., 2013).

The variation in rainfall between hydrological periods also affected aquatic herbaceous plants in altered streams in southern Amazon, where water loss is possibly greater due to the direct exposure to sun and wind. The humidity from streams and rain seems to determine the colonization success of aquatic herbaceous plants in streams altered by deforestation. These streams displayed an increase in the richness and abundance of aquatic herbaceous plants during the rain/end period, when humidity (as opposed to rain) is ideal for these plants' development.

In pristine streams, on the other hand, the variation between hydrological periods did not affect primary production, which consisted of small algal biomass as well as four species of aquatic herbaceous plants, of which only *Calyptrocarya glomerulata* was recorded in the riparian zone of streams from the Ducke reserve in Central Amazonia (Drucker et al., 2008). The significant presence of the *Cyperaceae* family recorded in this study was also identified for Central Amazonia (Junk and Piedade, 1993), in the Araguaia River basin (Oliveira et al., 2011), and in northeastern Brazil (Moura-Junior et al., 2013).

The way in which cattle ranching is conducted in southern Amazonia leaves streams vulnerable, alters the availability of resources (mainly light), and provides a new niche in the riparian zone; this niche is occupied by aquatic herbaceous plants such as the *Eleocharis acutangula*, *Fuirena umbellata*, and *Rhynchanthera dichotoma*, which take over the banks of some streams. Moreover, the fact that most species of aquatic herbaceous plants were emergent species indicates that stream habitat conditions—especially in terms of water depth and velocity (Fletcher et al., 2000)—allow this life form to successfully occupy wetland margins. In a few cases (e.g., *E. interstincta* and *R. dichotoma*), these organisms occupy a small area in the channel of the stream.

Bunn et al. (1999) suggest that the growth of aquatic herbaceous plants in streams can alter the channel's morphology, promote habitat loss, and alter water quality. As a result, stream productivity may be altered, generating a large impact on aquatic ecosystems (Cardinale et al., 2005). On the other hand, aquatic herbaceous plants can also provide new habitats and niches (Piedade and Junk, 2000; Piedade et al., 2010) that can affect other communities, especially fauna that respond to greater coverage of aquatic herbaceous plants, like macroinvertebrates (Lopes et al., 2011) and fish (Sánchez-Botero et al., 2008).

Although lower humidity during the dry season limits the growth of aquatic herbaceous plants, the lack of rainfall-induced turbulence contributes to increased algal biomass in altered streams, where there is greater light input. Similar results were reported in Rondônia, where streams with pasture in the riparian zone had higher chlorophyll *a* concentrations during the dry season than forest streams (Thomas et al., 2004); this also resulted in higher amounts of periphyton, indicating that changes in insolation can cause changes in algal production (Neill et al., 2001).

In forest headwater streams, allochthonous primary producers provide the largest initial contribution to the food chain, thus determining the structure of the aquatic community (Vannote et al., 1980). However, in the headwater streams with changes in riparian forest cover, there was an increase in the contribution of autochthonous primary producers compared to that seen in forested streams. Despite evidence that the carbon from algae plays an important role in the trophic chain (Forsberg et al., 1993; March and Pringle, 2003; Thorp and Delong, 2002), especially for invertebrates and fish (Lewis et al., 2001), the extra energy that enters the streams is not necessarily incorporated into secondary production (Davies et al., 2008), given that only a few species of collector insects (especially Ephemeroptera) benefit from the increased primary production (Benstead and Pringle, 2004). Many aquatic insects of the Plecoptera, Trichoptera, and Diptera orders depend on carbon derived from terrestrial organic matter (Benstead and Pringle, 2004).

These changes at the base of the food chain of headwater streams can affect the functional structure of the ecosystem, since increased light entry is expected in higher-order rivers (Vannote et al., 1980). Nevertheless, the effects of these changes in the Amazon are still poorly understood. It has been reported that the presence of grazing in riparian zones (Nessimian et al., 2008), anthropogenic siltation of streams (Couceiro et al., 2011), and Amazon riparian deforestation for road construction (Monteiro Jr. et al., 2013) modify the composition and density of macroinvertebrates. Deforestation-induced alterations in communities of aquatic invertebrates in streams have also been recorded in the tropical rainforest of Madagascar (Benstead et al., 2003). These alterations reflect organisms' capacity to adjust to changes in terrestrial detritus and algae production, given that functional groups have been shown to change in altered streams, with a predominance of generalist collectors (Benstead et al., 2003). These changes in ecosystem productivity lead to the loss of biological integrity (Karr and Chu, 2000), since the streams can no longer support and maintain a balanced, integrated, and adapted community of organisms whose functional organization is comparable to that of a pristine habitat (Couceiro et al., 2011; Karr and Dudley, 1981; Nessimian et al., 2008).

5. Conclusions

The increase in autochthonous primary production in altered streams confirms the importance of algae (however small the biomass) and aquatic herbaceous plants as bioindicators for the assessment of alterations to the integrity of streams in the southern Amazon. The following are indicators of altered streams in the southern Amazon: *Cyperus luzulae*, *Fimbristylis dichotoma*, *Fuirena umbellata*, and *Scirpus umbellatus*. These organisms may be considered good bioindicators because they are sensitive to environmental changes (Karr, 1991) and are important in the functional organization of the community (Bunn and Davies, 2000).

The hydrological periods also need to be considered when assessing the integrity of Amazonian streams, considering that algae and aquatic herbaceous plants respond differently to dry and rainy seasons. Since this study shows the effect of deforestation on the autochthonous primary production of headwater streams, the information about pristine streams can be used to identify changes in headwater streams in this region of the Amazon.

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SÍNTESE

Em sua vastidão a Amazônia detém condições particularmente heterogêneas, seja na estrutura da floresta (Quesada *et al*., 2012; Schietti *et al*., 2013; ter Steege *et al*., 2013) ou nas tipologias de águas (Sioli, 1984; Junk e Piedade, 2005, Junk *et al*., 2011), que estão associadas a uma complexa combinação de fatores edáficos, fisiográficos e climáticos. Os resultados deste estudo mostram que essa heterogeneidade na estrutura do habitat aquático de igarapés de cabeceira também se estende à mesma tipologia de água, no caso, as água claras no Alto Rio Tapajós; por sua vez, essa estrutura de habitat também é influenciada pelos períodos hidrológicos de seca, início do período chuvoso e final do período chuvoso do sul da Amazônia. Estudos em igarapés da Amazônia Central (Espírito-Santo *et al*., 2008) e na região sudoeste da bacia Amazônica (Neill *et al*., 2001; Biggs *et al*., 2004) corroboram a influência do regime de chuvas em igarapés Amazônicos, assim como já registrado nos grandes rios da Amazônia (Junk e Piedade 2005; Bustillo *et al*., 2011; Junk *et al*., 2011).

A partir dos resultados obtidos nos igarapés íntegros, os quais podem ser considerados como referência, é possível identificar alterações na integridade de igarapés antropizados. Embora exista heterogeneidade espacial e temporal nos riachos íntegros (Ward, 1989; Ward, 1998), quando a floresta ripária é destruída ocorrem alterações na estrutura do habitat que levam à redução de sua integridade, conforme comprovado por meio do Índice de Integridade do Habitat para os igarapés estudados. Além disso, os riachos alterados perderam a variabilidade na estrutura do habitat entre os períodos hidrológicos. A homogeneização das condições do habitat, bem como a perda de sua qualidade, reflete a estreita relação dos igarapés com sua zona ripária (Hynes, 1975), que em igarapés de cabeceira é ainda mais importante dada a contribuição de material orgânico alóctone proveniente da floresta circundante (Vannote *et al*., 1980; Ward, 1989).

As alterações da cobertura florestal na zona ripária dos igarapés de cabeceira também modificaram aspectos funcionais, como a produtividade primária autóctone e a disponibilidade de material orgânico alóctone que foi reduzida ou passou a não estar mais disponível em 20% dos igarapés avaliados. O aumento da abertura do dossel ripário contribuiu para o aumento da produção primária autóctone, tendo os igarapés alterados apresentado maiores valores de biomassa algal, maior presença de perifíton, e maior riqueza e abundância de herbáceas aquáticas. Esta alteração na base da cadeia trófica pode comprometer a estrutura funcional desses igarapés de cabeceira, bem como a estrutura dos rios à jusante. De acordo com a teoria do *continuum* do rio (Vannote *et al*., 1980), os igarapés são responsáveis pelo transporte de material orgânico proveniente da floresta ripária, e somente em rios de maior ordem, onde naturalmente aumenta a entrada de luz decorrente do aumento da largura do canal, é esperada uma maior contribuição de algas e plantas aquáticas.

Os igarapés estudados são estreitos, com largura inferior a 1,30 m. A legislação brasileira prevê a conservação de 15 m de floresta ripária para estes riachos, pois já há atividade consolidada na zona ripária. Entretanto, nos igarapés alterados estudados foram detectados os efeitos da ausência de cobertura florestal sobre a estrutura do habitat e produtores primários, mesmo havendo manchas de capoeira na zona tampão de 50m de largura, o que podem contribuir para a redução da entrada de luz. A comparação destes igarapés com os igarapés íntegros, protegidos pela floresta, indica a necessidade de proteção dos igarapés de cabeceira por uma faixa maior que 50m de largura de floresta. Embora a legislação brasileira (Brasil, Lei nº 12.727/2012) defina os limites para proteção dos corpos de água, estes limites não parecem ser suficientes visto que são desconsideradas as exigências conjuntas das espécies associadas a estes ambientes. Aos olhos dos governantes há uma preocupação maior em considerar o tamanho das propriedades, a quantidade de terra que um proprietário adquiriu, ao invés da necessidade dos ecossistemas quando é definida a largura da zona ripária a ser protegida (Brasil, Lei nº 12.727/2012).

São fortes as pressões sobre os igarapés de cabeceira, principalmente na periferia da Bacia Amazônica, onde além da alta densidade destes corpos de água há também elevadas taxas de desmatamento (e.g. Trancoso *et al*., 2009; Rosa *et al*., 2013), com a utilização das zona ripárias para a pecuária ou agricultura (Hayhoe *et al*., 2011). Por exemplo, na microbacia do Rio Taxidermista I, em Alta Floresta/MT, a paisagem foi dominada pela pecuária e predominam pequenos fragmentos de floresta desconectados da zona ripária (Bleich e Silva, 2013). Em face disso, tornase ainda maior o desafio de reabilitar a estrutura funcional de ecossistemas lóticos, e de proteger a integridade ainda existente (Ward, 1998). Nesse sentido, os dados fornecidos por este estudo para os igarapés íntegros poderão subsidiar o monitoramento de ações para a restauração de centenas de igarapés atualmente degradados na borda sul da bacia Amazônica.

A partir da comparação pareada entre os riachos íntegros e alterados estudados emergiram bons indicadores, bastante sensíveis às alterações ambientais impostas (Karr, 1991). Esses indicadores, que foram a abertura do dossel, a temperatura da água, concentração de oxigênio dissolvido na água, nutrientes, a disponibilidade de material orgânico no substrato bentônico, algas, herbáceas aquáticas, e o Índice de Integridade do Habitat poderão ser utilizados na identificação de impactos ambientais em outros riachos de cabeceira da bacia Amazônica. A identificação de indicadores que possam ser gerados com rapidez e baixos custos é de fundamental importância, pois pode facilitar o monitoramento e as ações de reabilitação de riachos degradados no sul da Amazônia e de outras áreas da região. Estas ferramentas podem ser de grande relevância, principalmente para os órgãos fiscalizadores, que dispõe de poucos recursos para este trabalho fundamental.

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Apêndice A

PG-ECO-INPA

INPA
INSTITUTO NACIONAL DE PESQUISAS DA AMAZÔNIA

GOVERNO FEDERAL
BRASIL
PAÍS RICO É PAÍS SEM POBREZA

AULA DE QUALIFICAÇÃO

PARECER

Aluno(a): MONICA ELISA BLEICH
Curso: ECOLOGIA
Nível: DOUTORADO
Orientador(a): MARIA TERESA FERNÁNDEZ PIEDADE

Título

"Efeitos de alterações na zona ripária sobre a integridade de igarapés amazônicos no baixo Rio Teles Pires, norte do Mato Grosso"

BANCA JULGADORA

TITULARES:
Albertina Pimentel Lima (INPA)
Ana Maria Pes (INPA)
Bruce Rider Forsberg (INPA)
Jansen Alfredo Sampaio Zuanon (INPA)
Sheyla Couceiro (Uni Nilton Lins)

SUPLENTES:
Rita de Cássia Guimarães Mesquita (INPA)
William Ernest Magnusson (INPA)

	PARECER		ASSINATURA
Albertina Pimentel Lima (INPA)	(X) Aprovado	( ) Reprovado	
Ana Maria Pes (INPA)	(X) Aprovado	( ) Reprovado	
Bruce Rider Forsberg (INPA)	(X) Aprovado	( ) Reprovado	
Jansen Alfredo Sampaio Zuanon (INPA)	(X) Aprovado	( ) Reprovado	
Sheyla Couceiro (Uni Nilton Lins)	(X) Aprovado	( ) Reprovado	
Rita de Cássia Guimarães Mesquita (INPA)	( ) Aprovado	( ) Reprovado	
William Ernest Magnusson (INPA)	( ) Aprovado	( ) Reprovado	

Manaus(AM), 08 de fevereiro de 2012

OBS: A banca recomenda que a aluna explicite melhor a hipótese central e os objetivos específicos do projeto, de forma a direcionar objetivamente o trabalho para as publicações esperadas como resultado da tese.

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Apêndice B

INPA
INSTITUTO NACIONAL DE PESQUISAS DA AMAZÔNIA

PG-ECO-INPA

Ministério da Ciência, Tecnologia e Inovação

BRASIL

ATA DA DEFESA PÚBLICA DA TESE DE DOUTORADO DO PROGRAMA DE PÓS-GRADUAÇÃO EM ECOLOGIA DO INSTITUTO NACIONAL DE PESQUISAS DA AMAZÔNIA

Aos 11 dias do mês de fevereiro do ano de 2015, às 09:00 horas, na Sala de Seminário da Biblioteca do INPA,Campus I/Aleixo, reuniu-se a Comissão Examinadora de Defesa Pública, composta pelos seguintes membros: o(a) Prof(a). Dr(a). **Cláudia Pereira de Deus**, do Instituto Nacional de Pesquisas da Amazonia - INPA, o(a) Prof(a). Dr(a). **Bruce Walker Nelson** - INPA, o(a) Prof(a). Dr(a). **Joana D' Arc de Paula,** da Universidade Nilton Lins, o(a) Prof(a). Dr(a). **Jefferson Cruz,** da Universidade Federal do Amazonas - INPA,e o(a) Prof(a). Dr(a). **Renato Tavares Martins,** Instituto Nacional de Pesquisas da Amazonia - INPA, tendo como suplentes o(a) Prof(a). Dr(a). Jansen Alfredo Sampaio Zuanon, do Instituto Nacional de Pesquisas da Amazonia - INPA, e o(a) Prof(a). Dr(a). Albertina Pimentel Lima, do Instituto Nacional de Pesquisas da Amazônia - INPA, sob a presidência do(a) primeiro(a), a fim de proceder a argüição pública do trabalho de **TESE DE DOUTORADO** de **MONICA ELISA BLEICH**, intitulado **"EFEITOS DE ALTERAÇÃO NA ZONA RIPÁRIA SOBRE A INTEGRIDADE DE IGARAPÉS AMAZONICOS NOBAIXO RIO TELES PIRES,NORTE DE MATO GROSSO"**, orientado pelo(a) Prof(a). Dr(a). Maria Teresa Fernandez Piedade, do Instituto Nacional de Pesquisas da Amazônia - INPA.

Após a exposição, o(a) discente foi argüido(a) oralmente pelos membros da Comissão Examinadora, tendo recebido o conceito final:

[X] APROVADO(A) [ ] REPROVADO(A)

[X] POR UNANIMIDADE [ ] POR MAIORIA

Nada mais havendo, foi lavrada a presente ata, que, após lida e aprovada, foi assinada pelos membros da Comissão Examinadora.

Prof(a).Dr(a). **Cláudia Pereira de Deus** ____________________

Prof(a).Dr(a). **Bruce Walker** ____________________

Prof(a).Dr(a). **Joana D' Arc de Paula** ____________________

Prof(a).Dr(a). **Jefferson Cruz** ____________________

Prof(a).Dr(a). **Renato Tavares Martins** ____________________

____
Coordenação PPG-ECO/INPA