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Ecosystem services of a functionally diverse riparian zone in the Amazon–Cerrado agricultural frontier

Rodolfo L. B. Nóbrega[a,1,2,*], Taciana Ziembowicz[a,1], Gilmar N. Torres[b], Alphonce C. Guzha[a,3], Ricardo S. S. Amorim[b], Domingos Cardoso[c], Mark S. Johnson[d,e], Túlio G. Santos[b], Eduardo Couto[b], Gerhard Gerold[a].

[a] Department of Physical Geography, Faculty of Geoscience and Geography, University of Goettingen, Goldschmidtstr. 5, Goettingen 37077, Germany
[b] Department of Soil and Agricultural Engineering, Faculty of Agronomy and Animal Science, Federal University of Mato Grosso (UFMT), Cuiabá 78060-900, MT, Brazil
[c] National Institute of Science and Technology in Interdisciplinary and Transdisciplinary Studies in Ecology and Evolution (INCT IN-TREE), Institute of Biology, Federal University of Bahia (UFBA), Salvador 40170-115, BA, Brazil
[d] Institute for Resources, Environment and Sustainability, University of British Columbia, Vancouver, B.C. V6T 1Z4, Canada
[e] Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, B.C. V6T 1Z4, Canada

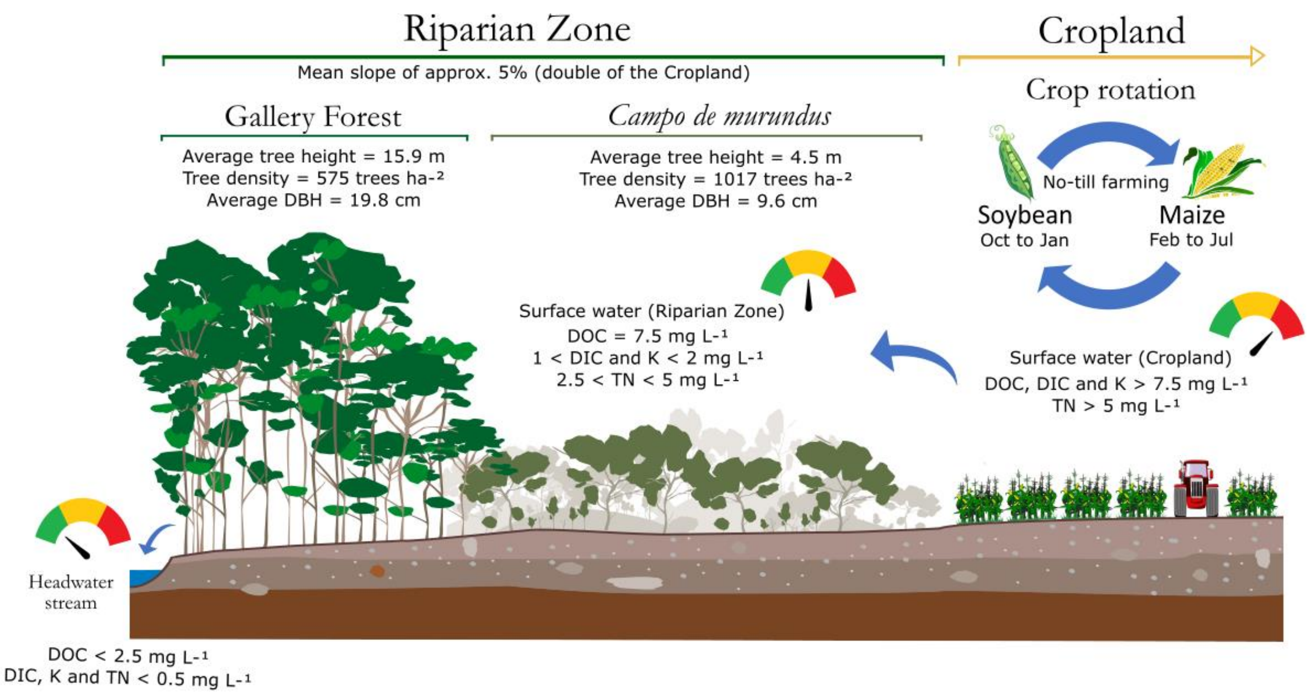
[1]These authors contributed equally to this work
[2]Present address: Department of Life Sciences, Faculty of Natural Sciences, Silwood Park Campus, Buckhurst Road, Imperial College London, Ascot SL5 7PY, United Kingdom
[3]Present address: U.S.D.A. Forest Service, International Programs, c/o African Wildlife Foundation (AWF), Ngong Road, Karen P.O. Box 310, Nairobi 00502, Kenya
[*]Corresponding author
E-mail addresses: r.nobrega@imperial.ac.uk (R. Nóbrega), taciana1984@hotmail.com (T. Ziembowicz), torresgn@ufmt.br (G. Torres), alphonce.guzha@fs-ip.us (A. Guzha), rsamorim@ufv.br (R. Amorim), cardosobot@gmail.com (D. Cardoso), mark.johnson@ubc.ca (M. Johnson), tuliogsantos@ufmt.br (T. Santos), couto@ufmt.br (E. Couto), ggerold@gwdg.de (G. Gerold).

Abstract: The ecological services provided by protected riparian zones in human-altered landscapes are widely acknowledged, yet little is known about them. In this study, we assess ecosystem properties that a protected riparian zone maintains in contrast to environmental changes in its surroundings caused by agro-industrial activities in the northwestern fringe of the Brazilian Cerrado on the Amazon–Cerrado agricultural frontier. We assessed the plant biodiversity, soil hydro-physical properties, and water quality, to understand how the underlying ecological characteristics of a riparian zone withstand the effects of its neighboring cropland area on the stream water quality. We show that the riparian zone is fundamental in providing key ecosystem regulating services, including maintenance of plant biodiversity, soil properties, and water quality. Protection of plant biodiversity in the riparian zone sustains a synergy between soil, and functionally and phylogenetically diverse plant communities by promoting higher infiltration rates, higher soil porosity, and natural soil biogeochemistry conditions, which in turn have direct implications for stream water quality. Our study reaffirms that the conservation of riparian zones is crucial to buffer the negative impacts of agricultural practices on ecosystem services. Our results provide consistent evidence to support further studies and environmental policies for riparian

environments, which are often the last fragment of natural vegetation remaining in the dominantly agricultural lands within the Cerrado and Amazon forests.

Keywords: Savanna, gallery forest, land-use change, plant biodiversity, soil, water quality.

Graphical Abstract



1. Introduction

Ecosystem services are benefits that the environment offers for human well-being, and they have become useful for promoting sustainable management of natural resources (Guzha et al., 2013). Essential ecosystem services, such as plant biodiversity, water provisioning, water quality regulation, and soil carbon storage, are commonly provided by landscapes in pristine condition (Guswa et al., 2014). When such environments are under threat by anthropogenic changes, vegetation is usually one of the first ecosystem components affected, which can cause further impacts, such as soil and water quality deterioration (Galford et al., 2010; Silva et al., 2011). The magnitude, types, and scope of these impacts are still poorly understood, especially in riparian zones (RZs) found in agro-industrial regions (Skorupa et al., 2013). These RZs, also known as riparian vegetation, riparian corridors, or gallery forests (Bianchi and Haig, 2013; Ferraz et al., 2014; Mcjannet et al., 2012; Silva et al., 2008), are often spared from deforestation in agricultural areas because they do not offer satisfactory agricultural productivity conditions due to their high slope and frequently waterlogged conditions (Tiwari et al., 2016) or because regulations require their conservation. These environmental and regulatory circumstances apply for RZs of the Brazilian Cerrado, where most of the Amazon–Cerrado agricultural frontier (AAF) deforestation has occurred (Garrett et al., 2018; Klink and Machado, 2005).

The conversion from natural land cover to crops and pastures has reduced native fire-adapted savanna-like Cerrado vegetation to approximately 50% (ca. 1 million km2) of its original land cover (Mendonça et al., 1998; Klink and Machado, 2005; Lambin et al., 2013). The Cerrado is one of the world's critical hotspots for conservation due to its high number of endemic species (Brooks et al., 2006, 2002; Loyola et al., 2009; Myers, 2003; Myers et al., 2000), and is the savanna with the greatest plant diversity in the world (Mendonça et al., 1998). The Cerrado contains different vegetation formations, ranging from grasslands to forests, including the interspersed riparian gallery forests that contain ca. 30% of Cerrado plant biodiversity (Felfili et al., 2001; Ribeiro and Walter, 2008). Most plant species in Cerrado RZs are associated with Amazonian and Atlantic rainforests and display adaptations for enduring high levels of root zone soil water (Oliveira-filho and Ratter, 1995), facilitated by their position along watercourses. Farther away from RZs, the natural landscape is occupied by other types of Cerrado vegetation that demand less water, and exhibit more open and grassy physiognomies than gallery forests (Felfili and Silva Júnior, 1992). Gallery forests have a higher leaf area index (Hoffmann et al., 2005) and biodiversity (Santiago et al., 2005; Silva-Júnior, 2005) than the other Cerrado vegetation types, with tree heights up to 40m (Felfili, 1997).

On the AAF, the Brazilian Forest Code regulates the protection of RZs, which are categorized as riparian preservation areas (Garrastazú et al., 2015; Soares-Filho et al., 2014; Stickler et al., 2013). However, Nagy et al. (2015) identified human-induced degradation in an Amazon's agricultural landscape that significantly decreased its biodiversity and regeneration capacity. Application of pesticides, herbicides, and fertilizers on agricultural lands endangers ecological functions in RZs (Gregory et al., 1991), whereas natural RZs act as buffer zones, filtering nutrients and pollutants (e.g., Addy et al., 1999; Daniels and Gilliam, 1996; Gyawali et al., 2013; Lowrance et al., 1984; Lowrance and Sheridan, 2005; Ranalli and Macalady, 2010; Randhir and Ekness, 2013; Smith et al., 2012), and reducing sediment load into streams through diminished erosion and floodplain deposition (e.g., Daniels and Gilliam, 1996; Randhir and Ekness, 2013). The width of riparian buffer zones is used as a measure of protection of

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the native RZ vegetation and it is arbitrarily established in Brazil. Since an appropriate riparian width can substantially buffer the impacts of the agricultural activities (Mander and Tournebize, 2015), Newbold et al. (1980) infer that the riparian width should depend on the ecological functions that need protection. However, research on the ecological impact of buffer width is mostly from North America and Europe (Luke et al., 2018). One of the few riparian studies in Brazil was conducted in the Atlantic Forest (Aguiar et al., 2015b), and showed that a 36-m riparian width retained 70–94% of pesticides. By contrast, the previous compulsory 30-m width for restoration of riparian buffer zones for small streams was reduced to 15 m in the revised Brazilian Forest Code of 2012. This reduction in protected riparian width threatens the maintenance of stream water quality and availability (Garrastazú et al., 2015).

The survival of many non-aquatic plants and animals depends upon the RZs of small headwater streams (Richardson et al., 2005), often the last fragment of natural vegetation remaining in cash-crop systems that dominate AAF landscapes. In Brazil, headwater streams can represent over 50% of the natural stream network length, and yet 25% of them were neglected in large-scale studies and conservation programs due to their relatively small stream size (Taniwaki et al., 2018). Understanding ecosystem properties in headwater RZs through descriptive and process-based studies of mechanisms for the ecosystem services in RZs is fundamental to support guidelines for riparian conservation (Bowler et al., 2012; Richardson et al., 2005; Weigelhofer et al., 2012). Description of ecological functioning of plant species in RZs is limited regarding the capacity of individual plant species to retain nutrients, plant biodiversity, hydro-physical and chemical soil characteristics, and stream hydrochemistry (Haridasan, 2008). Most environmental studies on Cerrado RZs have been conducted in areas surrounded by pristine savanna vegetation (e.g., Parron et al., 2011; van den Berg et al., 2012), and only a few were in areas under intense anthropogenic influence but outside the AAF (e.g., Ferraz et al., 2014).

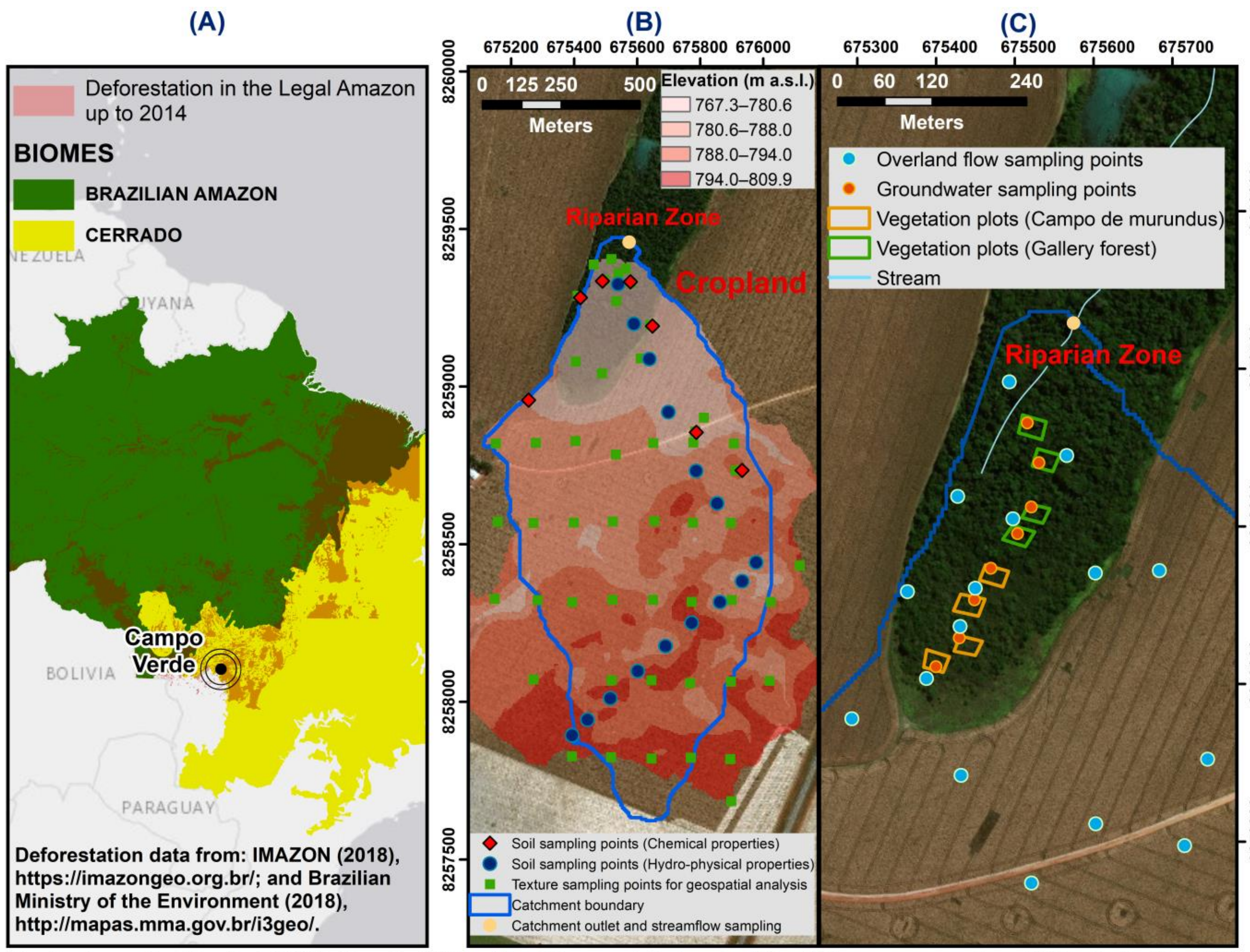
Despite the relatively small area occupied by RZs inaltered landscapes, the protection of the riparian vegetation can build natural barriers between extensively altered environments and stream networks (Sweeney et al., 2004). The sum of individual benefits provided by hundreds of RZs provides large-scale environmental protection when scaled up to the river basin level (Sweeney et al., 2004). However, the ecosystem services provided by RZs at this level remain poorly understood, especially in the tropics (Iñiguez-Armijos et al., 2016; Luke et al., 2018). RZs within the AFF have suffered degradation (Macedo et al., 2013), and large streams historically influenced by the agricultural expansion in this region have also shown upward trends in nutrient fluxes (Nóbrega et al., 2018b).

Our work aims to improve the understanding of the ecosystem services provided by the Cerrado RZs, adding to an increasing body of evidence that recognizes the importance of RZs as ecological buffer zones. By analyzing field environmental data across different landscape gradients of a typical large-scale agro-industrial system with a riparian vegetation in the AAF, we provide a detailed assessment of the associated plant biodiversity, soil hydro-physical properties, and water quality, showing the contrasting ecologies in the RZ and its surrounding cropland area.

2. Study area

This study was conducted in the municipality of Campo Verde (15.7381°S, 55.3618°W) in the Southeastern region of the Brazilian state of Mato Grosso (Fig. 1A). This region is characterized by a typical tropical savanna climate with a wet season extending from October to April, a dry season from May to September, rainfall averages ca. 1,800mm and mean monthly temperatures range from 18 to 24 °C (Meister et al., 2017; Nóbrega et al., 2017). Dominant soils in the Cerrado (e.g., Arenosols and Ferralsols, IUSS Working Group WRB, 2015) are typically highly weathered and acidic with high aluminum that requires fertilizers and lime for crop production and livestock farming (Hunke et al., 2015).

We selected a 93-ha catchment within the Rio das Mortes basin (15.743°S, 55.363°W), the main tributary of Araguaia River. Agricultural lands comprise approximately 75% of the 18,000km2 of the Rio das Mortes basin (Müller et al., 2015). Our study catchment is on the Santa Luzia farm, an agro-industrial property with ca. 2,500 ha where agriculture has been expanding since the 1980s. This catchment is composed of a cropland area and a RZ. The cropland covers 91% of the catchment area and its slope averages 2.4%. This cropland area is used for no-till mechanized rainfed agriculture and uses a crop rotation of soybean from October to January and maize from February to July. Soils in this catchment are Ferralsols (IUSS Working Group WRB, 2015), characterized by clay loam texture, and correlated with Oxisols (Soil Survey Staff, 2015) and Latossolos Vermelhos Distróficos de textura argilosa (EMBRAPA, 2006). The RZ of this catchment occupies only 9% of the catchment area and has an average slope of 4.9%. The RZ area is composed of a gallery forest and a campo de murundus Cerrado formation (Ribeiro and Walter, 2008) connected in a continuum manner and forming a mixture of typical plant species from Cerrado, and Amazon and Atlantic rainforests (Marimon et al., 2002; Oliveira-filho and Ratter, 1995). The campo de murundus is the vegetative community located on the fringe of the RZ, and it is a subtype of Cerrado vegetation characterized by plain areas intertwined with large mounds, with the former colonized by herbaceous and shrub vegetation, and presenting mostly woody savannah species (De Oliveira-Filho, 1992; Eiten, 1972; Marimon et al., 2012; Ponce and Cunha, 1993; Resende et al., 2004; Ribeiro and Walter, 2008). Within this catchment, the average width is approximately 250 m for the gallery forest and 175 m for the campo de murundus.



Service Layer Credits: Esri, HERE, Garmin, © OpenStreetMap contributors, and the GIS user community UTM projection (Zone 21L)
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Figure 1. Study area location: A) Amazon, Cerrado and the Campo Verde municipality; B) the study catchment showing terrain elevation and soil sampling points; C) a zoom in to the riparian zone surroundings where the plots were surveyed and water samples were collected.

3. Material and Methods

3.1. Vegetation survey

Surveys were conducted in the RZ for the two vegetation formations (i.e., gallery forest and campo de murundus) in March (wet season) and September (dry season) of 2014 to assess the seasonal vegetative characteristics. We delimited eight plots of approximately 20×30 m (total area of ca. 5100 m^2) spaced 35–70 m on center from each other along a 350-m path from the gallery forest area near the stream (plots 1–4) to an area of the campo de murundus formation (plots 5–8) in transition to the cropland area (Fig. 1C). To characterize the plant biodiversity within the plots, we sampled woody individuals (dead and alive) with a minimum of 15.5-cm circumference at breast height — approximately 5-cm diameter at breast high (DBH) — as well as with a minimum of 15.5-cm trunk diameter at 30cm height above ground, an adequate measurement for considering the plant biodiversity in areas of transition between the Cerrado an Amazon rainforest (e.g., Marimon et al., 2014; Ribeiro et al., 2011). We collected vegetative and fertile plant specimens that could not be identified in the field for later identification at the Tangará da Serra Herbarium of the Mato Grosso State University (UNEMAT).

3.2. Soil sampling and analyses

To select the points for soil hydro-physical and chemical sampling we regionalized soil properties by delineating sampling transects based on the surface elevation and geostatistical analysis of the clay content (Fig. 1B). To that end, we used the DEMs derived from a topographic survey for the surface elevation analysis, and collected 55 disturbed soil samples at the 0–20 cm soil depth from randomly selected points throughout the catchment and across the range of elevation to measure clay content. We interpolated the clay content values using isotropic variogram analysis and the ordinary kriging method, which exhibited a correlation coefficient of 0.92, and then we validated the interpolation by using the leave-one-out cross-validation method (Herbst et al., 2006). This procedure allowed the categorization of the surface elevation in 5 equal intervals, binning clay content into quintiles, and the delineation of transects from the catchment's crest to the stream valley passing over all elevation and clay content categories.

For hydro-physical analysis, we used the regionalization of soil properties to select 2 points in the RZ and 13 in the cropland area. At these approximately equally-spaced locations along the transects (Fig. 1B) we collected one disturbed sample and two undisturbed soil core samples (4.8 cm in diameter and 5.2 cm in height) at depth intervals of 0–10, 10–20, 20–40, and 40–60 cm for each sampling point. Disturbed soil samples were analyzed for particle size distribution, and the undisturbed samples were used to determine bulk density, saturated hydraulic conductivity (K_{sat}), total porosity, macroporosity, microporosity, and field capacity. These procedures are in line with the soil geostatistical and hydro-physical analyses conducted by Nóbrega *et al.* (2017) in headwater catchments of the *Rio das Mortes* basin.

For soil chemical analysis, we collected soil samples at 5 and 30 cm depths at four points in the RZ and three points in the cropland area (Fig. 1B). Soil chemical analysis were primarily used to understand the effects of land-use on the overland flow quality. Therefore, we collected the soil samples from areas where we detected overland flow generation, i.e., overland flow sampling points, considering the elevation and clay categories defined for the regionalization of the soil properties. We measured pH, total carbon (TC), total nitrogen (TN), calcium (Ca), potassium (K), magnesium (Mg), phosphorus (P), and sulfur (S) at the Laboratory of Landscape Ecology at the University of Goettingen, Germany. pH was measured by using the potentiometric method in a volume fraction of 1:5 suspension of soil in distilled water (inoLAB® pH Level 2, Wissenschaftlich-Technische Werkstätten GmbH). TC and TN were quantified by using the elemental analysis method (TruSpec® CHN, LECO Instrumente GmbH). The total digestion of 100–150 mg of soil was made with $HClO_4$, HF and HNO_3 in 30 mL PTFE vessels (Pressure Digestion System DAS 30, PicoTrace GmbH) and used to determine chemical concentrations by using atomic spectroscopy (ICP-OES, Optima 4300™ DV PerkinElmer).

3.3. Water sampling and analyses

An automatic water sampler (BL2000®, Hach-Lange GmbH) was installed at the outlet of the catchment, located inside of the RZ, to collect stream water samples from 20 cm below the water surface during the 2013–2014 hydrological year. The water sampling was based simultaneously on both time and water level variation to represent streamflow either during baseflow or stormflow conditions. The temporal routine was set to fill a 1-L sample bottle in 3 days by using an extraction of 200 mL from the stream at equal intervals of 14.4 h. Stormflow sampling followed a sub-hourly routine activated by water level increase, detected by a pressure bell switch (FD-01, Profimess GmbH).

Overland flow samples were collected by using fabricated overland flow detectors (OFDs) (Elsenbeer and Vertessy, 2000; Kirkby et al., 1976), consisting of a 50 mm-diameter PVC tubes with a permeable section with 5 mm holes connected at a right angle by a "tee" to a reservoir section tube with 200 mL capacity (Fig. S1 in the *Supplementary material*). The contact of the detector section with the soil diverted ponded overland flow into the reservoir tube. After field observations during rainfall events, we placed OFDs on observed flowpaths in the RZ and in the cropland area (Fig. 1C). We installed the OFDs during the wet season and collected the samples within 12 h after rainfall events. Additionally, to evaluate potential impacts of the cropland on groundwater of the RZ, samples were taken twice per month in the wet and dry season from eight wells, each located in one of the eight vegetation plots.

The water samples were protected from light following collection and transported in coolers packed with ice to the *Ecofisiologia Vegetal* Laboratory (EVL) of the Federal University of Mato Grosso (UFMT) in Cuiabá, Mato Grosso. At the laboratory, the water sample in each bottle was used to fill two aliquots of 50 mL in high-density polyethylene bottles pre-washed with deionized water. One aliquot was used for analysis of total organic carbon (TOC), dissolved organic carbon (DOC), dissolved inorganic carbon (DIC) and TN, and the other aliquot was filtered through pre-ashed glass fiber filters (0.7 µm nominal pore size, Whatman GF/F) pre-washed with 20 mL of water sample for the remaining analyses. The samples were then frozen and shipped in coolers for analysis at the Laboratory of the Department of Landscape Ecology, University of Goettingen, Germany. Quality control of this procedure was conducted by comparing the DOC of streamflow samples within 12 h after collection using a UV-Vis spectrometric device (spectro::lyser™ UV-Vis, s::can Messtechnik GmbH) with the DOC results obtained in the laboratory after final transportation and assuring that the results were not significantly different (Nóbrega *et al.*, 2018).

TOC, DOC and DIC concentrations in water were determined by using high temperature catalytic oxidation (TC-Analyzer, DIMATOC 100 (R), Dimatec GmbH). Total nitrogen (TN) concentration was quantified by using the chemiluminescence detection method (DIMA_N module (CLD), Dimatec GmbH). SO_4 concentrations were determined by using ion chromatography (761 Compact IC, Metrohm, Switzerland). Dissolved K, Ca, P, and Mg concentrations were quantified by using atomic spectroscopy (ICP-OES, Optima 4300™ DV, PerkinElmer). Before the analyses of the dissolved solutes, the water samples were filtered through membrane filters (0.45 µm nominal pore size, cellulose acetate, Sartorius Stedim Biotech GmbH). These filters were pre-washed with ultrapure water, transferred to HDPE bottles pre-washed with nitric acid solution (2.6% HNO_3), and rinsed with ultrapure water.

3.4. Statistical analyses of water and soil properties

Data on soil properties were compared using the Mann-Whitney U nonparametric test (due to their non-normal distributions) to determine whether the results from the RZ and cropland area were significantly different from each other. Soil pH was converted to H_3O for statistical comparison because of the non-linearity of these values. To compare the water quality parameters from the different hydrological pathways, we used the Kruskal–Wallis H test by ranks with the Steel–Dwass–Critchlow–Fligner

(Fligner, 1984) method for multiple comparisons. We used the language and environment R v. 3.5.1 (R Core Team, 2018) and the XLSTAT-Base v. 2018.6 software (Addinsoft, Paris, France, www.xlstat.com), with a significance threshold of 0.05. For the soil chemistry there was no significant difference at 0.05, therefore we highlighted the differences with a threshold of 0.06, which exhibited the most significant differences.

3.5. Phylogenetic diversity and community structure

To assess the among-community phylogenetic diversity and structure across the RZ, we used the open-source Phylocom 4.2 software (Webb et al., 2008) to build a community phylogeny of the plant species sampled from the eight plots in the two distinct physiognomies. The RZ species pool was then used with phylomatic function (Webb and Donoghue, 2005) and a backbone tree (version R20100701.new) based primarily on the most updated phylogenetic classification of angiosperms (APG IV, 2016). The branch lengths of the resulting community phylogeny were scaled to millions of years (Ma) using the 'bladj' (branch length adjustment) option (Webb *et al.* 2008) and the age estimates reported by Wikström et al. (2001). All polytomies within the RZ community phylogeny were randomized 999 times using the 'multi2di' function from the picante package (Kembel et al., 2010) in R v. 3.5.1 (R Core Team, 2018). We then estimated the phylogenetic diversity (PD; Faith, 1992), mean pairwise distance (MPD), and mean nearest taxon distance (MNTD; Webb *et al.*, 2002) for each plot using the picante package. The resulting boxplot graphics were made using the ggplot2 (Wickham, 2016) and the community phylogenetic tree in phytools (Revell, 2012), both packages were used in R.

4. Results

4.1. Riparian zone vegetation

The 353 individual trees sampled in the plots across the RZ revealed a floristic composition of 61 species belonging to 30 families (Table S1 in the *Supplementary material*). The most abundant botanical families of 23 found in the gallery forest were Anacardiaceae, Burseraceae, Fabaceae and Lauraceae, whereas in the *campo de murundus* the most abundant were Euphorbiaceae, Melastomataceae, and Simaroubaceae of 17 families found. The gallery forest exhibited the highest species richness with total of 126 living individuals belonging to 42 different plant species. The *campo de murundus* had 227 living individuals belonging to 28 different plant species. We were unable to identify only one individual, located in plot 3. Dead individuals represented a total of 8.7% in the gallery forest and 7.5% in the *campo de murundus*. The vegetation structure in the gallery forest mostly involved large trees, as expressed in both higher classes of DBH and height (Fig. 2A–B). The ecological and floristic distinctiveness across the RZ physiognomies were revealed by phylogenetic distance metrics (Fig. 2C–F). The most abundant plant families in the two physiognomically distinct RZ habitats are phylogenetically clustered in the orders Myrtales and Sapindales (Fig. S2 in the *Supplementary material*).

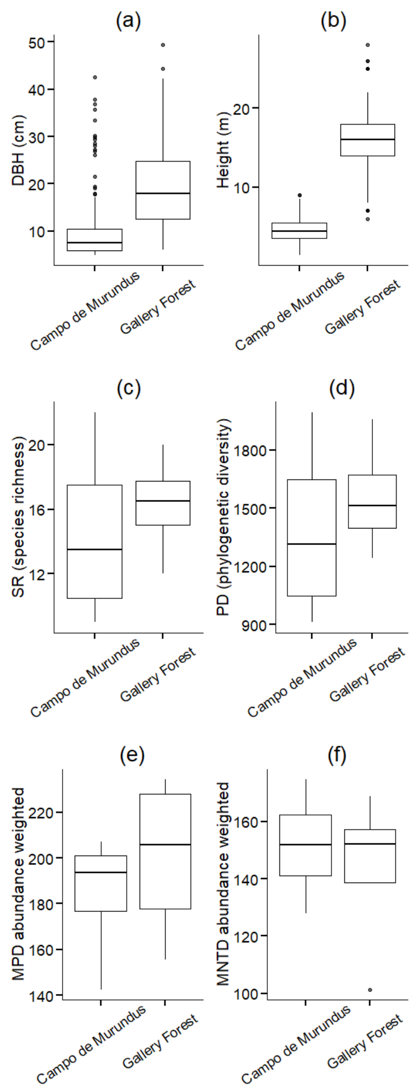

Figure 2. Boxplot of ecological and phylogenetic structure of pant communities in the *campo de murundus* (open savanna) and gallery forest across the riparian zone, showing ranges of (A) diameter at breast high (DBH); (B) plant height; (C) species richness (SR); (D) phylogenetic diversity (PD); (E) mean pairwise distance (MPD) with abundance weighted, and; (F) mean nearest neighbor distance (MNTD) with abundance weighted. Boxplots show the 25, 50, and 75% quartiles in the horizontal lines, and the vertical lines show values within the 1.5 interquartile range below the lower quartile and above the upper quartile.

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The first four plots (Plots 1–4) were located in the gallery forest and dominated (> 75% in average) with plant species that are primarily distributed in the Amazon and Atlantic rainforests, and Cerrado vegetation (Fig 3A; Oliveira-Filho and Ratter, 1995; Flora do Brasil 2020, http://floradobrasil.jbrj.gov.br). The last four plots (Plots 5–8) are in the *campo de murundus*, where we found an increasing predominance of Cerrado-related vegetation (22.9 to 28.6%) and a decrease in Amazon-related vegetation (30.5 to 25.1%) (Fig. 3B). As the plots were located further from the stream, typical Cerrado species began to predominate ($r^2 = 0.66$, $p < 0.05$).

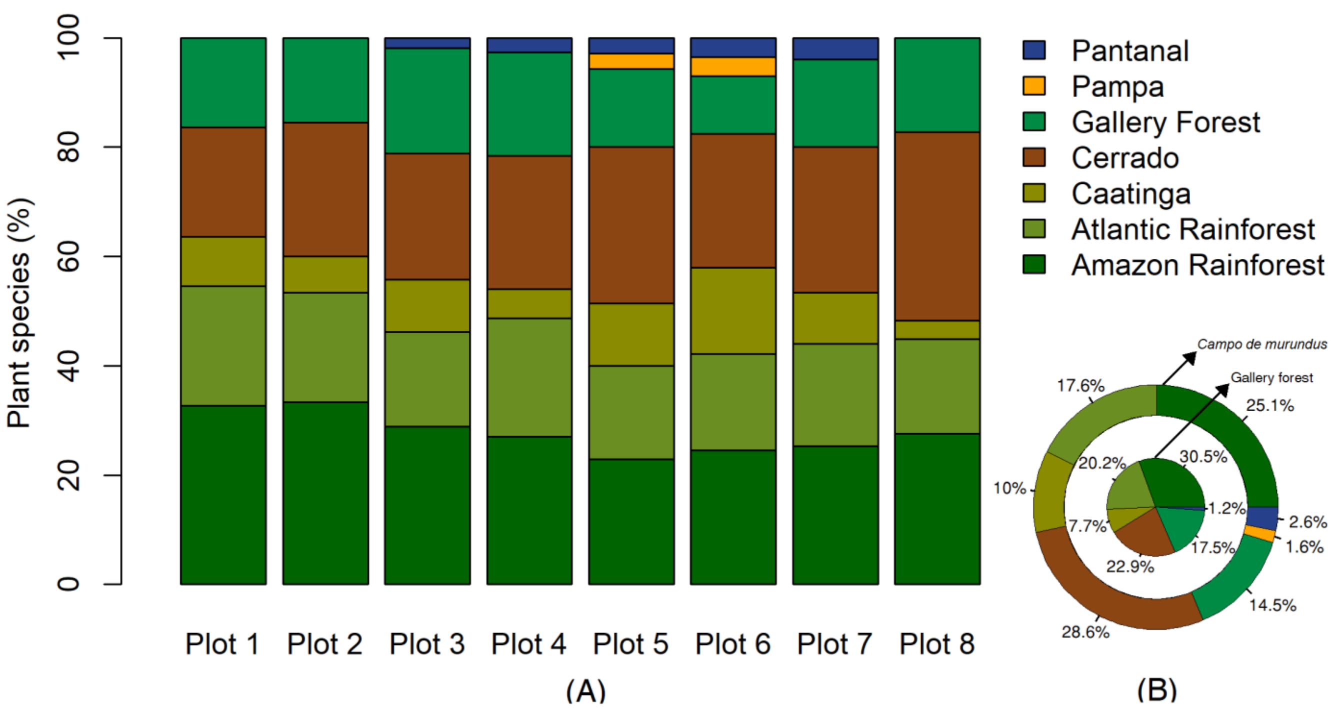

Figure 3. (A) Assembly and phytogeographic distribution of the surveyed plant species along the plots; (B) Percentage of the represented phytogeographic domains according to the two vegetation formations in RZ transect. Inner circle represents the gallery forest (plots 1–4) and outer circle represents the *campo de murundus* (plots 5–8).

4.2. Soil hydro-physical and chemical properties

Soil hydro-physical properties of both RZ and cropland show a clay-loam texture (Table 1). The cropland area had greater clay content in the topsoil compared to the RZ. Bulk density in the RZ was significantly lower than in the cropland area ($p < 0.01$). K_{sat} and field capacity did not show significant differences between these areas, but upper layer (0–10 cm) total porosity was higher in the RZ. In both areas total porosity was dominated by about 75% micropores due to high clay content (58 ± 7%, average

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of both areas). Soil acidity at the 5-cm soil depth (Table 2) was significantly higher ($p = 0.057$) in the RZ. The cropland area had higher Ca and P than the RZ at both 5 and 30-cm soil depths, and higher Mg content at 5-cm soil depth.

Table 1. Soil hydro-physical properties.

Soil depth (cm)	Location	BD ($g\ cm^{-3}$)	TP (%)	MaP (%)	MiP (%)	FC (%)	K_{sat} ($mm\ h^{-1}$)	Sand (%)	Silt (%)	Clay (%)
0–10	**Cropland**	**1.18 ± 14%[a]**	**59.1 ± 8%[a]**	**10.5 ± 40%[a]**	48.7 ± 10%[a]	39.4 ± 12%[a]	42.9 ± 154%[a]	26.5 ± 56%[a]	16.0 ± 41%[a]	57.6 ± 17%[a]
	RZ	**0.86 ± 9%[b]**	**69.1 ± 9%[b]**	**22.5 ± 3%[b]**	46.6 ± 12%[a]	40.7 ± 14%[a]	130.4 ± 68%[a]	35.4 ± 18%[a]	13.1 ± 14%[a]	51.5 ± 16%[a]
10–20	**Cropland**	**1.19 ± 11%[a]**	56.9 ± 7%[a]	13.6 ± 33%[a]	43.3 ± 13%[a]	35.9 ± 14%[a]	166.9 ± 93%[a]	25.5 ± 50%[a]	22.0 ± 37%[a]	52.5 ± 14%[a]
	RZ	**0.95 ± 10%[b]**	60.1 ± 8%[a]	15.0 ± 18%[a]	45.7 ± 17%[a]	39.9 ± 19%[a]	302.8 ± 12%[a]	29.2 ± 35%[a]	16.0 ± 5%[a]	54.8 ± 20%[a]
20–40	**Cropland**	1.16 ± 11%[a]	57.1 ± 9%[a]	16.2 ± 35%[a]	41.0 ± 10%[a]	34.2 ± 13%[a]	95.5 ± 163%[a]	25.3 ± 57%[a]	19.4 ± 29%[a]	55.4 ± 19%[a]
	RZ	0.94 ± 13%[a]	63.3 ± 11%[a]	15.6 ± 47%[a]	47.6 ± 30%[a]	41.1 ± 31%[a]	69.9 ± 83%[a]	26.0 ± 35%[a]	13.0 ± 40%[a]	61.0 ± 23%[a]
40–60	**Cropland**	**1.19 ± 9%[a]**	56.7 ± 9%[a]	11.8 ± 29%[a]	44.9 ± 9%[a]	36.7 ± 11%[a]	51.9 ± 162%[a]	19.4 ± 12%[a]	**21.4 ± 12%[a]**	59.3 ± 6%[a]
	RZ	**1.07 ± 3%[b]**	57.8 ± 1%[a]	14.8 ± 41%[a]	43.1 ± 13%[a]	37.2 ± 12%[a]	53.3 ± 55%[a]	23.8 ± 32%[a]	**9.9 ± 40%[b]**	66.4 ± 17%[a]

Results are expressed in terms of average and relative standard deviation. Significant differences ($p < 0.05$) are indicated by different letters and highlighted in bold. Comparisons were performed between Riparian Zone and Cropland at each soil property and depth.
RZ = Riparian Zone, BD = Bulk Density, TP = Total Porosity, MaP = Macroporosity, MiP = Microporosity, FC = Field Capacity, K_{sat} = Saturated Hydraulic Conductivity.

Table 2. Mean, one standard deviation and sample size (n) of soil chemical properties.

	5-cm soil depth		30-cm soil depth	
	RZ	Cropland	RZ	Cropland
pH	**3.8 ± 0.2 (4)[a]**	**5.5 ± 0.7 (3)[b]**	4.5 ± 0.3 (4)[a]	4.9 ± 0.4 (3)[a]
Total C (%)	4.69 ± 0.72 (4)[a]	3.57 ± 0.65 (3)[a]	1.99 ± 0.26 (4)[a]	1.89 ± 0.30 (3)[a]
Total N (%)	0.30 ± 0.05 (4)[a]	0.22 ± 0.05 (3)[a]	0.15 ± 0.07 (4)[a]	0.09 ± 0.01 (3)[a]
Ca ($mg\ kg^{-1}$)	**77.4 ± 44.9 (4)[a]**	**2,389.0 ± 1,781.8 (3)[b]**	**34.9 ± 11.7 (4)[a]**	**311.3 ± 22.5 (3)[b]**
K ($mg\ kg^{-1}$)	692.9 ± 129.2 (4)[a]	786.4 ± 167.2 (3)[a]	569.4 ± 100.7 (4)[a]	639.3 ± 31.6 (3)[a]
Mg ($mg\ kg^{-1}$)	**167.8 ± 40.1 (4)[a]**	**839.8 ± 617.2 (3)[b]**	129.6 ± 23.7 (4)[a]	190.7 ± 38.1 (3)[a]
P ($mg\ kg^{-1}$)	**352.4 ± 121.2 (4)[a]**	**1,244.7 ± 487.8 (3)[b]**	**187.9 ± 53.8 (4)[a]**	**430.1 ± 69.8 (3)[b]**
S ($mg\ kg^{-1}$)	372.1 ± 14.5 (4)[a]	416.6 ± 43.0 (3)[a]	208.8 ± 29.0 (4)[a]	297.7 ± 81.9 (3)[a]

Significant differences ($p = 0.057$) are indicated by different letters and highlighted in bold. Comparisons were performed between Riparian Zone and Cropland at each soil depth.

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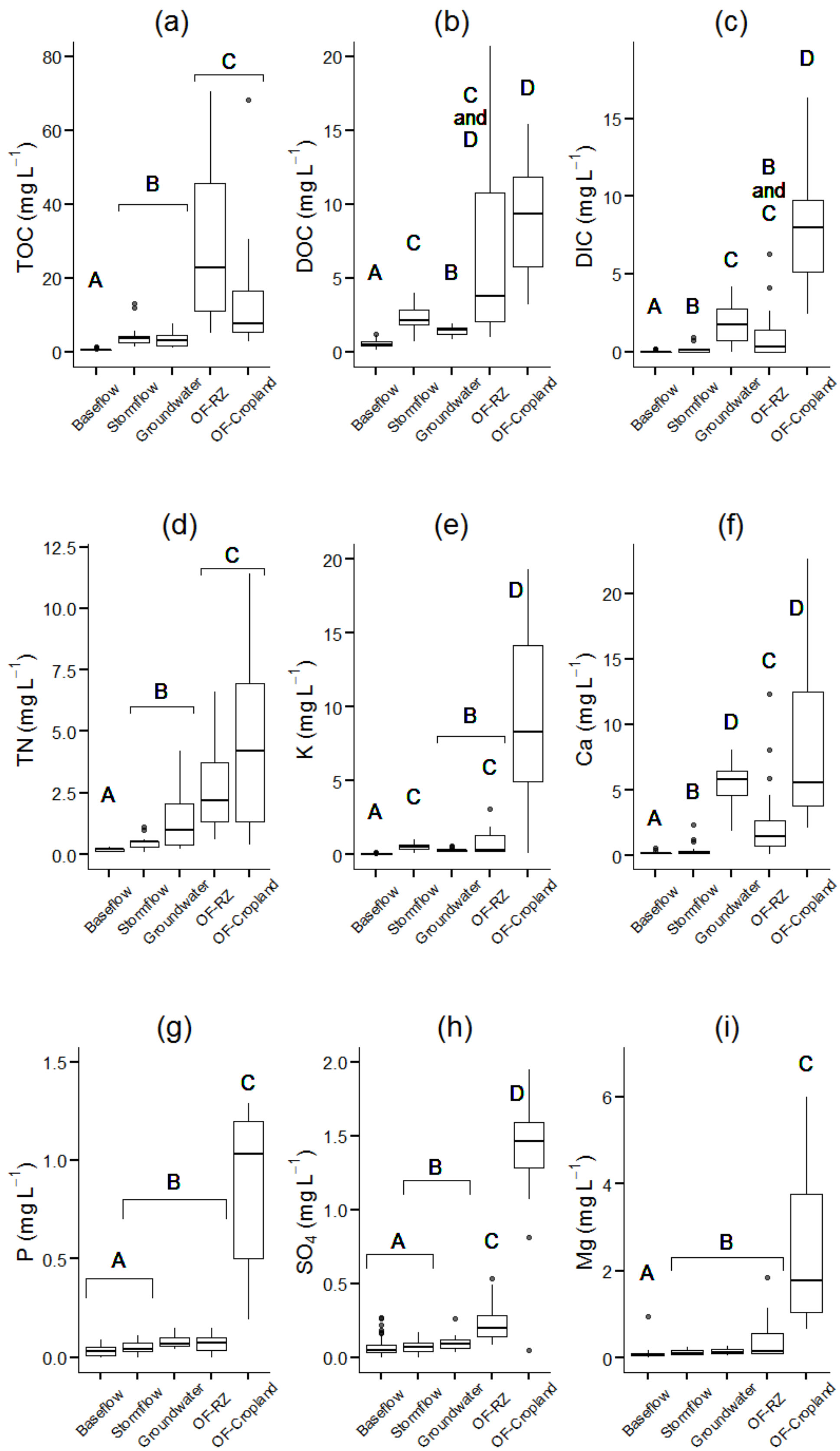

Figure 4. Boxplot of water quality results throughout the study area in different hydrological pathways. The y-axis was limited to graphically omit some outliers for a better visualization of the results in this figure. Significant differences ($p < 0.05$) are indicated by different letters. These letters follow an alphabetical order that correspond to groups with an ascendant order of mean of ranks. Boxplots show the 25, 50, and 75% quartiles in the horizontal lines, and the vertical lines show values within the 1.5 interquartile range below the lower quartile and above the upper quartile.

4.3.Water quality

The Kruskal–Wallis H test by ranks with the multiple comparison (Steel-Dwass-Critchlow-Fligner method) exhibited the water quality varying from three to five groups with similar mean values (Fig. 4). Mg was the parameter with less groups (total of three) and with the smallest variation (0–6 mg L^{-1}). The other nutrients with three groups were TOC (0.3–312.2 mg L^{-1}), TN (0.1–18.5 mg L^{-1}) and P (0–13.3 mg L^{-1}). DOC (0.1–32 mg L^{-1}), DIC (0–16.2 mg L^{-1}), K (0–32.2 mg L^{-1}), Ca (0.1–22.6 mg L^{-1}), and SO_4 (0–20.8 mg L^{-1}) exhibited the greater number groups (total of five). The descriptive statistics of each nutrient and each hydrological path are shown in the *Supplementary material* (Table S2).

Baseflow exhibited the lowest concentrations for all water quality parameters, whereas the overland flow in the cropland (hereinafter referred to as OF-Cropland) area exhibited most of the highest nutrient concentrations. Except for Ca, the differences between OF-Cropland and baseflow, stormflow and groundwater were all significant ($p < 0.01$) for all other nutrients. The overland flow in the RZ (hereinafter referred to as OF-RZ) also exhibited higher nutrient concentrations that were significantly lower ($p < 0.01$) than OF-Cropland but still higher than the other hydrological pathways, except for TOC, DOC, and TN. OF-RZ showed significant differences in TOC, TN, Ca, and SO_4 from streamflow (baseflow and stormflow). Difference between stormflow and OF-RZ were not significant for DOC, DIC, K, P, and Mg.

5. Discussion

5.1. The functionally and evolutionarily diverse plant community

Our botanical survey showed that the RZ is richly assembled by species belonging to several clades or families in the plant tree of life (Fig. S2 in the *Supplementary material*; APG IV, 2016). For example, except for *Pleroma stenocarpum* (Melastomataceae), that clearly dominates in two plots of *campo de* *murundus*, all RZ plots seem to be floristically assembled by species that are phylogenetically overdispersed. Despite the geographical proximity, the gallery forest and *campo de murundus* habitats across the RZ are somewhat phylogenetically and taxonomically different. Evolutionarily diverse plant communities are considered a key element for enhancing ecological functions by controlling light and temperature, offering shelter for biota, providing food for aquatic and terrestrial fauna, and contributing to the deposition of coarse and fine woody debris on the soil (Décamps and Naiman, 1990). This influences sediment transport directions, channeling morphology, and microhabitats inside the river, controlling the flow of water and nutrients, and maintaining the local biodiversity (Naiman et al., 1993; Weisberg et al., 2013). The composition of plant species defines the efficiency of nutrient uptake from the soil and the water (Osborne and Kovacic, 1993). Functionally diverse plant communities are known to promote greater environmental stability because their associated multiple functional traits balance abiotic instability of buffer ecosystems (Cadotte et al., 2011). For example, here we show that the RZ plant communities are sustained by important nitrogen fixing species (Sprent, 2001) such as the legume trees *Tachigali vulgaris*, *Bowdichia virgilioides*, *Hydrochorea corymbose*, and *Ormosia paraensis*. The most abundant species *Pleroma stenocarpum* belongs to a genus that is well known for its ability to colonize intensively degraded areas, thus contributing to their recovery (Lorenzo et al., 1994).

In the gallery forest, *Tapirira obtusa* was the most abundant, which is a pioneer species (Raaimakers and Lambers, 1996) that contributes to vegetation re-establishment, by attracting seed dispersers (birds) (Pereira et al., 2012). In fact, we found several dead and juvenile individuals of *Tapirira obtusa*, which indicates that a regeneration process is underway (Goodale *et al.*, 2012). Similarly to Morais *et al.* (2013), we also observed the Melastomataceae as having the greatest dominance in the *campo de murundus*. A relevant characteristic of this family is the capacity of intense regeneration in RZs, preparing the soil for the process of increasing forestation and facilitating the normal course of successional stages (Rossatto et al., 2008). The fruits of Melastomataceae generally produce great seed quantity for germinating and propagating new plants (Domingos et al., 2003; Fava and Albuquerque, 2009), which also supports the indication that this RZ is under regeneration. A common characteristic of the gallery forest and *campo de murundus* across the RZ was the predominance of pioneer species, which has important ecological roles, such as the recovery of a perturbed area or a degraded site by refilling canopy spaces inside the forest (Goodale et al., 2012).

5.2. Implications of RZ conservation on soil and water quality

The mean K_{sat} per soil depth ranged from 43 to 167 mm h^{-1} in the cropland area and 53 to 303 mm h^{-1} in the RZ. We attribute the higher variability of K_{sat} in the cropland to the use of heavy farm machinery and field operations in this area, which follow precise established routes and impact the soil heterogeneously (see the cropland field in Fig. 1C). Although modern agricultural approaches, i.e., no-till and precision farming, are often associated with low environmental impacts (Bongiovanni and Lowenberg-Deboer, 2004; Bramley et al., 2008; Jenrich, 2011), changes in soil properties as a result of modern agriculture were reported by Hamza and Anderson (2005). Farming practices such as these, particularly for soybean cultivation, enhance subsoil compaction (Hunke et al., 2015; Scheffler et al., 2011). Indeed, we observed significantly higher soil bulk density and substantially lower K_{sat} in the cropland area than in the RZ, which indicates that the conservation of the RZ maintains its soil properties and, consequently, the balance between water fluxes. These fluxes in the RZ distribute nutrients in the soil through infiltration and runoff, influencing the vegetation composition and structure (Ravi et al., 2007). For example, undisturbed soil hydro-physical conditions that promote waterlogging in the *campo de murundus* are known to reduce the Fe-oxides (Oliveira and Marquis, 2002), which play an important role in driving soil biogeochemical processes during periods of anaerobiosis (Yang and Liptzin, 2015).

Plant species in the Cerrado are evolutionarily adapted to thrive on soils with low pH and nutrient content (Ruggiero *et al.*, 2002). Soil microbiomes are environments rich in bioactive compounds and bacteria (Zhu et al., 2019). The membranes of bacteria of plant roots and other soil biota contain mechanisms, such as the water-filled transport channels, which are fundamental for root and microbial uptake (Roth et al., 2019). However, removal of plants and changes in the soil chemistry due to agricultural practices in this region disturb the natural soil conditions. We found higher pH in the topsoil of cropland than in the RZ. Our results are consistent with other studies, such as Ruggiero *et al.* (2002), that showed the soil pH less than 4.5 for three distinguished Cerrado formations, i.e., *Campo Cerrado*, Cerrado *sensu strictu* and *Cerradão*. We attribute the lower acidity of the soil in the cropland area to the calcium carbonate ($CaCO_3$) commonly applied to the topsoil to reduce soil acidity and support nutrient availability to crops. In our study area, the application of $CaCO_3$ to croplands had implication on the soil Ca content, which was significantly higher in the topsoil of the cropland area. As $CaCO_3$ reacts with water, it produces bicarbonate (HCO_3), one of the main components of DIC, and Ca and DIC concentrations in the overland flow were significantly higher in the cropland area than in the RZ. Despite this, concentration of Ca and DIC in the streamflow was low compared to the other hydrological pathways. The groundwater in the

RZ exhibited a concentration not as high as the overland flow but significantly higher than the one found in the streamflow. This suggests long-term impacts from topsoil application of $CaCO_3$. Fertilizer application may also increase the carbonate accumulation in soil profile (Guo et al., 2016; Wang et al., 2014; Zhang et al., 2015), and, as indicated by Nóbrega et al. (2018), residuals of the $CaCO_3$ applied to the soil surface can percolate the soil profile and reach the stream via groundwater. Protected RZs are crucial to maintain natural soil properties and avoid water pollution in agricultural landscapes, as the Cerrado-inhabiting plant species are adapted to these soil properties and can regenerate without nutrient additions.

Haridasan (2000) observed C content between 0.74 and 3.33% in soils located under Cerrado *sensu stricto* and *Cerradão* vegetation types, and Parron et al. (2011) showed N varying from 0.10 to 0.35% in Cerrado soils. Our results are similar to these studies. Our C and N content exhibited maximum mean values (ca. 5% for C and 0.3% for N) at the 5-cm soil depth of the RZ and minimum mean values (ca. 2% for C and 0.1% for N) at the 30-cm soil depth of the cropland area. The greater C and N contents in the topsoil of the RZ is a result of natural processes in the gallery forest and *campo de murundus*, such as litterfall and high organic matter decomposition (Parron et al., 2011), which is more intense in RZ ecosystems (Aguiar et al., 2015a). We ascribe the higher TOC concentration in the overland flow of the RZ than in the cropland area to the vegetation–soil interaction in this C-rich RZ system, which contributes with a great amount of particulate organic carbon. Conversely, DOC and TN were higher in the cropland area, which is a consequence of water-soluble fertilizer application (Chantigny, 2003; Pittaway et al., 2018; Richardson et al., 2005).

We found significantly higher P and Mg in the topsoil of the cropland area than in the RZ. This is likely due to regular fertilizer application to croplands in this region while undisturbed Cerrado soils are highly weathered and low in nutrients (Hunke et al., 2015). Other studies found nutrients, such as K, Mg or P, higher in cropland areas than in native vegetation zones without direct agricultural influence (Cruz Ruggiero et al., 2002; Haridasan, 2008; Silva et al., 2008; Tinker and Nye, 2000). However, we were able to find a downward gradient of K, P, SO_4, and Mg concentrations, which were highest in the overland flow of the cropland area, exhibiting a gradual decrease in concentration from the cropland area towards the stream (Fig. 4). On a farm in the USA, Lowrance and Sheridan (2005) also verified the capacity of RZs for retaining nutrients, i.e., NO_3, NH_4, and K. These results are also in agreement with earlier findings in the Cerrado by Parron et al. (2011), who reported reduction of N and P in water fluxes going through an RZ towards a stream.

Considering the hydrological pathways analysed, our overarching finding is that the nutrient content in overland flow from the cropland area is drastically higher than that of the streamflow. Our results indicate that a reduction or fragmentation of the RZ to the advantage of cropland expansion can increase soil bulk density and reduce its total and macro porosity. This could increase the overland flow generation, and it aligns with findings from Alvarenga *et al.* (2017), who used the Distributed Hydrology Soil Vegetation Model (Sun et al., 2015) and found that an increase in the riparian width from 30 to 100 m decreased in 6.2% the total overland flow generation in a 6.76-km² catchment in the Atlantic rainforest.

5.3. Uncertainties and research directions on RZ studies in agricultural landscapes

Our results uphold two main causes accredited to the capacity of RZs to act as buffers (Peterjohn and Correll, 1984). The first concerns the uptake of nutrients by RZ vegetation. Our findings agree with the fact that the vegetation and the soil in the RZs form a micro-environment, where the capillarity of the Cerrado's diverse RZ root plant system allows extensive contact with nutrients and their uptake by plants (Sternberg et al., 2005). The second is related to the capacity of the soils of RZs to retain or degrade nutrients and pollutants, which are delivered to roots with hyporheic flow, a component of streams and rivers that interacts with the RZ (Ward, 1989). The hyporheic zone acts as a water-purifying bioreactor that contains microbial biofilms, which in turn control biogeochemical fluxes of nutrients (Peralta-Maraver et al., 2018). However, for the ecological buffering potential of RZs, there are other variables that need to be considered in further studies, such as the residence time or the period of hydrodynamic retention in the hyporheic zone where biogeochemical processing of dissolved solutes occur (Buffington and Tonina, 2009). An ecosystem arrangement of these variables may follow spatial and temporal nestings (Peralta-Maraver *et al.*, 2018) that vary according to the different ecosystems and environmental conditions.

How pollutants and nutrients are transformed during their travel through the hyporheic zone is still unknown (Peralta-Maraver et al., 2018). Uncertainties in the efficiency of the RZs in buffering effects of croplands are also related to the fragmentation of the landscape, since small changes in vegetation cover or machinery routes in an agricultural catchment can strongly influence hydrological pathways (Leal et al., 2016). Weller and Baker (2014) used models to predict the stream nitrate concentration and annual streamflow to estimate nitrate loads and found that RZs removed 21.5% of the nitrate loads released by the croplands, which would have increased to 53.3% if the gaps in the riparian width that caused fragmentation of the riparian vegetation were restored. Although the riparian width is widely used as a measure to protect streams, this approach has been criticized for ignoring the spatial heterogeneity of biogeochemical processes and biodiversity in RZs. By using hydrologically adapted site-specific riparian widths, landowners can find more cost-efficient RZs designs (Tiwari et al., 2016).

To address these concerns, studies on ecosystem processes in RZs are necessary. As our findings show, groundwater often exhibited nutrient concentrations higher than the streamflow, i.e., baseflow and stormflow, and DIC and Ca concentrations in the groundwater were higher than overland flow in the RZ. It is important to understand how the cropland activities affect the groundwater quality spatially and temporally and how this is linked to the quality of the stream water under baseflow conditions. Another uncertainty is the portion of the active root zone of the RZ that provides for nutrient uptake significant to protect the soil and water. To that end, we show evidence that the soil–plant–atmosphere continuum needs to be addressed in an integrated manner in future research in RZs. This should consider the effects that interflow and groundwater have on the streamflow quality by using field measurements and reactive transport modelling, as well as the ecological functioning of hyporheic zones in soils and the role of root uptake systems in the groundwater quality, which are known to be complex in the Cerrado (Canadell et al., 1996).

6. Conclusions

We assessed the characteristics of the vegetation, soil, and water of a cropland-dominated catchment with a protected riparian zone in an agro-industrial area within the Amazon–Cerrado Agricultural Frontier. Our study showed that the riparian zone sustains ecosystem services by providing an intense synergy between plant biodiversity, and soil and water quality. Among our findings, we highlight the following:

- In the riparian zone, we identified a high plant biodiversity that ecologically functions by improving and recovering altered environments within the Amazon–Cerrado agricultural frontier;
- The riparian zone maintains major Cerrado soil chemical characteristics (e.g., low pH and nutrients content), which support the conservation of native plant species. We identified that natural soil hydro-physical properties, such as bulk density and porosity, were conserved in the riparian zone in contrast to its surrounding cropland area. These soil properties are important for maintaining natural water fluxes that are directly linked to buffering effects of the riparian zone;

- The maintenance of soil properties in riparian zones is directly connected to dynamics and quality of water flow to and in the stream. Overland flow in the cropland exhibited the highest nutrient concentrations, and this is attributed to the fertilization and liming practices that cause the accumulation of nutrients and carbonates in soil. Nutrient concentrations decreased as the surface water advanced towards the stream, signifying the buffering properties of the riparian zone ecosystem.

Data statement

The data of this study is available from the Open Science Framework at https://osf.io/v8wzh/ (DOI 10.17605/OSF.IO/V8WZH).

Author contributions

Conceptualization: RN, TZ; Data curation and formal analysis: RN, TZ, GT, RA, DC; Funding acquisition: RA, GG; Investigation: RN, TZ, GT, TS, AG, RA; Methodology: RN, TZ, AG, RA, MJ, GG; Project administration: RN, RA, GG; Resources: RA, EC, GG; Supervision: RN, RA, EC, GG; Validation: RN, RA, DC; Visualization: RN, DC; Writing original draft: RN, TZ; Writing review & editing: RN, TZ, AG, RA, DC, MJ, GG.

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Supplementary material

The following information is provided to the article

Ecosystem services in the Amazon–Cerrado agricultural frontier: separating the wheat from the chaff in a functionally diverse riparian zone

by

Rodolfo L. B. Nóbrega*, Taciana Ziembowicz, Gilmar N. Torres, Alphonce C. Guzha, Ricardo S. S. Amorim, Domingos Cardoso, Mark S. Johnson, Túlio Santos, Eduardo Couto, Gerhard Gerold.

* Corresponding author: r.nobrega@imperial.ac.uk

Supporting Information Summary: 6 Pages including cover page, 2 figures and 2 tables.

Figure S1. A) one example of surface runoff pathway from the cropland into the riparian zone; B and C) overland flow detectors in the gallery forest and *campo de murundus*, respectively, and; D and E) overland flow detectors few minutes after a rainstorm in the border between the cropland and the riparian zone and in the gallery forest, respectively.

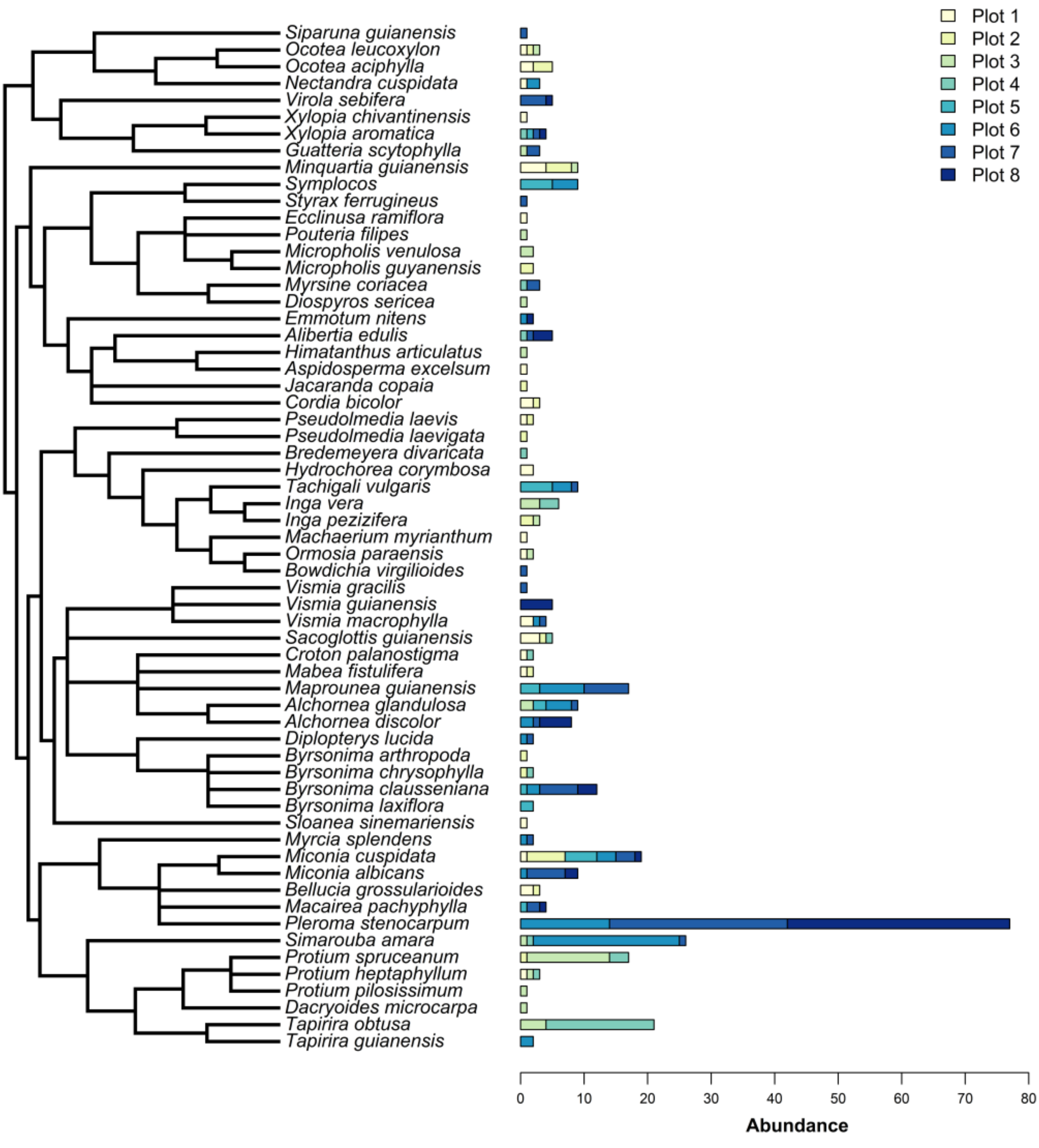

Figure S2. Community phylogeny and species abundance for angiosperm species pool sampled in the plots of the gallery forest and *campo de murundus* across the Riparian Zone.

Table S1. Plant survey results with the list of plant species and families and their respective occurrence in each surveyed plot.

Family	Plant species	Gallery forest				*Campo de murundus*			
		Plot 1	Plot 2	Plot 3	Plot 4	Plot 5	Plot 6	Plot 7	Plot 8
Anacardiaceae	*Tapirira guianensis*	-	-	-	-	-	2	-	-
	Tapirira obtusa	-	-	4	17	-	-	-	-
Annonaceae	*Guatteria scytophylla*	-	-	1	-	-	-	2	-
	Xylopia aromatica	-	-	-	1	1	-	1	1
	Xylopia cf. *chivantinensis*	1	-	-	-	-	-	-	-
Apocynaceae	*Aspidosperma* cf. *excelsum*	1	-	-	-	-	-	-	-
	Himatanthus articulatus	-	-	1	-	-	-	-	-
Aquifoliaceae	*Symplocos*	-	-	-	-	5	4	-	-
Bignoniaceae	*Jacaranda copaia*	-	1	-	-	-	-	-	-
Boraginaceae	*Cordia bicolor*	2	1	-	-	-	-	-	-
Burseraceae	*Dacryodes microcarpa*	-	-	1	-	-	-	-	-
	Protium cf. *heptaphyllum*	1	-	1	1	-	-	-	-
	Protium pilosissimum	-	-	1	-	-	-	-	-
	Protium spruceanum	-	1	13	3	-	-	-	-
Ebenaceae	*Diospyros sericea*	-	-	1	-	-	-	-	-
Elaeocarpaceae	*Sloanea sinemariensis*	1	-	-	-	-	-	-	-
Euphorbiaceae	*Alchornea glandulosa*	-	-	2	-	2	4	1	-
	Alchornea discolor	-	-	-	-	-	2	1	5
	Croton cf. *palanostigma*	1	-	-	1	-	-	-	-
	Mabea fistulifera	1	1	-	-	-	-	-	-
	Maprounea guianensis	-	-	-	-	3	7	7	-
Fabaceae	*Bowdichia virgilioides*	-	-	-	-	-	-	1	-
	Hydrochorea corymbosa	2	-	-	-	-	-	-	-
	Inga pezizifera	-	2	1	-	-	-	-	-
	Inga vera	-	-	3	3	-	-	-	-
	Machaerium myrianthum	1	-	-	-	-	-	-	-
	Ormosia paraensis	1	-	1	-	-	-	-	-
	Tachigali vulgaris	-	-	-	-	5	3	1	-
Humiriaceae	*Sacoglottis guianensis*	3	1	-	1	-	-	-	-
Hypericaceae	*Vismia guianensis*	-	-	-	-	-	-	-	5
Icacinaceae	*Emmotum nitens*	-	-	-	-	-	1	-	1
Lauraceae	*Nectandra cuspidata*	1	-	-	-	-	2	-	-
	Ocotea aciphylla	2	3	-	-	-	-	-	-
	Ocotea leucoxylon	1	1	1	-	-	-	-	-

Family	Plant species	Gallery forest				*Campo de murundus*			
		Plot 1	Plot 2	Plot 3	Plot 4	Plot 5	Plot 6	Plot 7	Plot 8
Malpighiaceae	*Byrsonima arthropoda*	-	1	-	-	-	-	-	-
	Byrsonima chrysophylla	-	1	-	1	-	-	-	-
	Byrsonima clausseniana	-	-	-	-	1	2	6	3
	Byrsonima laxiflora	-	-	-	-	2	-	-	-
	Diplopterys cf. *lucida*	-	-	-	-	-	1	1	-
Melastomataceae	*Bellucia grossularioides*	2	1	-	-	-	-	-	-
	Macairea cf. *pachyphylla*	-	-	-	-	1	-	2	1
	Miconia albicans	-	-	-	-	-	1	6	2
	Miconia cuspidata	1	6	-	-	5	3	3	1
	Pleroma stenocarpum	-	-	-	-		14	28	35
Moraceae	*Pseudolmedia* cf. *laevigata*	-	1	-	-	-	-	-	-
	Pseudolmedia laevis	1	1	-	-	-	-	-	-
Myristicaceae	*Vismia macrophylla*	2	-	-	-	-	1	1	-
	Vismia gracilis	-	-	-	-	-	-	1	-
	Virola sebifera	-	-	-	-	-	-	4	1
Myrtaceae	*Myrcia splendens*	-	-	-	-	-	1	1	-
Olacaceae	*Minquartia guianensis*	4	4	1	-	-	-	-	-
Polygalaceae	*Bredemeyera divaricata*	-	-	-	1	-	-	-	-
Primulaceae	*Myrsine coriacea*	-	-	-	1	-	-	2	-
Rubiaceae	*Alibertia edulis*	-	-	-	1	-	-	1	3
Sapotaceae	*Ecclinusa* cf. *ramiflora*	1	-	-	-	-	-	-	-
	Micropholis guyanensis	-	2	-	-	-	-	-	-
	Micropholis venulosa	-	-	2	-	-	-	-	-
	Pouteria cf. *filipes*	-	-	1	-	-	-	-	-
Simaroubaceae	*Simarouba amara*	-	-	1	1	-	23	1	-
Siparunaceae	*Siparuna guianensis*	-	-	-	-	-	-	1	-
Styracaceae	*Styrax ferrugineus*	-	-	-	-	-	-	1	-
Dead	-	1	4	3	3	4	4	5	4
Not Identified	-	-	-	1	-	-	-	-	-

Table S2. Descriptive statistics of the water quality parameters.

Water quality parameter (mg L^{-1})	Flow type	n	Min.	Max.	Freq. of min.	Freq. of max.	1st Quartile	Median	3rd Quartile	Mean	Variance (n-1)	Standard deviation (n-1)	Variation coefficient	Skewness (Pearson)	Kurtosis (Pearson)	Standard error of the mean
TOC	Baseflow	50	0.3	1.4	1	1	0.4	0.5	0.6	0.5	0.1	0.2	0.4	1.5	2.7	0.0
	Stormflow	21	1.2	13.1	1	1	2.5	3.5	4.2	4.2	8.9	3.0	0.7	2.0	3.4	0.7
	Groundwater	24	1.0	7.6	1	1	1.6	3.0	4.5	3.1	3.2	1.8	0.6	0.7	-0.3	0.4
	OF-RZ	22	5.1	312.2	1	1	11.0	22.7	45.5	48.4	5,832.8	76.4	1.5	2.7	6.0	16.3
	OF-Cropland	18	2.9	92.2	1	1	5.5	7.7	16.4	17.8	586.5	24.2	1.3	2.2	3.8	5.7
DOC	Baseflow	50	0.1	1.2	1	1	0.4	0.5	0.7	0.6	0.1	0.2	0.4	0.6	-0.3	0.0
	Stormflow	23	0.7	4.0	1	1	1.8	2.1	2.9	2.3	0.8	0.9	0.4	0.3	-0.7	0.2
	Groundwater	24	0.8	1.9	1	1	1.2	1.4	1.7	1.4	0.1	0.3	0.2	-0.1	-1.0	0.1
	OF-RZ	22	1.0	32.0	1	1	2.0	3.8	10.8	7.5	65.8	8.1	1.1	1.6	1.9	1.7
	OF-Cropland	19	3.2	15.4	1	1	5.7	9.3	11.8	9.2	14.3	3.8	0.4	0.0	-1.1	0.9
DIC	Baseflow	50	0.0	0.2	43	1	0.0	0.0	0.0	0.0	0.0	0.1	2.6	2.6	5.4	0.0
	Stormflow	23	0.0	0.9	8	1	0.0	0.1	0.2	0.1	0.0	0.2	1.5	2.5	5.4	0.0
	Groundwater	24	0.0	4.2	2	1	0.7	1.7	2.8	1.8	1.7	1.3	0.7	0.3	-1.1	0.3
	OF-RZ	22	0.0	6.3	7	1	0.0	0.3	1.4	1.0	2.5	1.6	1.6	2.1	4.0	0.3
	OF-Cropland	19	2.4	16.3	1	1	5.1	8.0	9.8	8.2	14.0	3.7	0.4	0.6	-0.4	0.9
TN	Baseflow	50	0.1	0.3	6	1	0.1	0.2	0.2	0.2	0.0	0.0	0.2	-0.2	1.0	0.0
	Stormflow	21	0.1	1.1	1	1	0.3	0.5	0.5	0.5	0.1	0.2	0.5	1.2	1.4	0.1
	Groundwater	24	0.2	4.2	3	1	0.4	1.0	2.1	1.4	1.4	1.2	0.9	1.0	0.0	0.2
	OF-RZ	22	0.6	18.5	1	1	1.3	2.2	3.7	3.7	19.6	4.4	1.2	2.4	4.8	0.9
	OF-Cropland	19	0.4	18.2	2	1	1.3	4.2	7.0	5.1	22.1	4.7	0.9	1.3	1.2	1.1
K	Baseflow	50	0.0	0.1	1	1	0.0	0.0	0.1	0.0	0.0	0.0	0.5	1.9	4.2	0.0
	Stormflow	22	0.1	1.0	1	1	0.4	0.5	0.6	0.5	0.1	0.3	0.5	0.3	-0.7	0.1
	Groundwater	24	0.1	0.6	1	1	0.2	0.3	0.3	0.3	0.0	0.1	0.4	0.9	0.3	0.0
	OF-RZ	22	0.1	25.2	1	1	0.2	0.3	1.3	1.8	27.8	5.3	2.8	4.2	16.3	1.1
	OF-Cropland	19	0.1	32.2	1	1	4.9	8.3	14.1	10.6	56.0	7.5	0.7	1.2	1.6	1.7
Ca	Baseflow	50	0.1	0.6	1	1	0.1	0.2	0.2	0.2	0.0	0.1	0.5	2.7	9.6	0.0
	Stormflow	22	0.1	2.4	1	1	0.2	0.2	0.3	0.4	0.3	0.5	1.2	2.8	7.6	0.1
	Groundwater	24	1.9	8.0	1	1	4.6	5.8	6.5	5.3	3.4	1.8	0.3	-0.5	-0.7	0.4
	OF-RZ	22	0.1	12.4	1	1	0.7	1.4	2.7	2.5	8.8	3.0	1.2	2.1	4.0	0.6
	OF-Cropland	19	2.1	22.6	1	1	3.8	5.6	12.5	8.3	33.9	5.8	0.7	1.0	-0.1	1.3
P	Baseflow	39	0.0	0.1	3	1	0.0	0.0	0.1	0.0	0.0	0.0	0.8	0.7	-0.6	0.0
	Stormflow	22	0.0	0.1	1	1	0.0	0.0	0.1	0.0	0.0	0.0	0.6	0.5	-0.4	0.0
	Groundwater	8	0.0	0.1	1	1	0.1	0.1	0.1	0.1	0.0	0.0	0.4	0.8	-0.6	0.0
	OF-RZ	22	0.0	4.9	1	1	0.0	0.1	0.1	0.3	1.1	1.0	3.5	4.4	17.0	0.2
	OF-Cropland	19	0.2	13.3	1	1	0.5	1.0	1.2	1.9	9.6	3.1	1.6	2.9	7.8	0.7
SO_4	Baseflow	48	0.0	0.3	3	1	0.0	0.0	0.1	0.1	0.0	0.1	0.9	1.7	2.2	0.0
	Stormflow	23	0.0	0.2	1	1	0.0	0.1	0.1	0.1	0.0	0.0	0.6	0.5	-0.6	0.0
	Groundwater	24	0.0	0.3	1	1	0.1	0.1	0.1	0.1	0.0	0.0	0.5	1.5	3.1	0.0
	OF-RZ	22	0.1	15.9	1	1	0.1	0.2	0.3	0.9	11.2	3.3	3.5	4.4	17.0	0.7
	OF-Cropland	19	0.0	20.8	1	1	1.3	1.5	1.6	2.6	20.4	4.5	1.7	3.7	12.5	1.0
Mg	Baseflow	50	0.0	1.0	1	1	0.1	0.1	0.1	0.1	0.0	0.1	1.3	6.0	37.4	0.0
	Stormflow	22	0.1	0.3	1	1	0.1	0.1	0.2	0.1	0.0	0.1	0.4	0.8	-0.3	0.0
	Groundwater	24	0.1	0.3	2	1	0.1	0.1	0.2	0.1	0.0	0.1	0.4	0.5	-0.7	0.0
	OF-RZ	22	0.1	1.9	3	1	0.1	0.1	0.6	0.4	0.2	0.5	1.1	1.7	2.6	0.1
	OF-Cropland	19	0.7	6.0	1	1	1.0	1.8	3.8	2.4	2.7	1.6	0.7	0.8	-0.6	0.4