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PRIMARY RESEARCH PAPER

Can the structure of a riparian forest remnant influence stream water quality? A tropical case study

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Abstract In rural areas, riparian forest remnants can be very important for the maintenance and improvement of stream water quality. We evaluated if a forest remnant influenced stream water quality, and if these results were influenced by forest structure. We sampled reaches from 140 m upstream of the remnant edge until 600 m within the forest remnant. Electric conductivity (EC) and ammonium concentrations decreased as the stream flowed through the remnant, whereas dissolved oxygen, total phosphorus (P), total dissolved P, organic P, and silicate concentrations increased along the remnant. Variation in forest structure was due to a gradient in forest stratification versus tree height and diameter at breast height, and a gradient in tree density versus basal area. More stratified parts of the forest, with smaller trees, resulted in lower EC values and concentrations of total nitrogen and nitrite, whereas higher density of trees resulted in lower levels of total and dissolved P, creating heterogeneity at very local scales. The overall mean influence of this riparian forest remnant improved stream water quality, suggesting that forest remnants have local effects that can be important when managing stream water quality at larger spatial scales.

Keywords Riparian vegetation · Land use · Rural landscapes · Forest fragments

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Introduction

Rural landscapes have been dramatically changed, mainly through deforestation for agriculture and pasture (Allan, 2004). For example, in São Paulo state, SE Brazil, only about 13% of the original forest persists, mainly in the form of fragments (Rodrigues & Bononi, 2008). Forest fragments include remnants of riparian forests, which were left uncut or have been managed to restore parts of the riparian zones. Changes in the riparian zones, from continuous forests to forest remnants, are important for water quality, since riparian zones are an important connection between terrestrial and aquatic systems and between processes that occur at different spatial scales (Tran et al., 2010). Both the distribution of regional land use patterns and forest fragments influence catchment hydrology and the flow of nutrients to streams

(Shandas & Alberti, 2009). Also, riparian forests and their uses are of particular importance to local water quality. Riparian forest remnants are known to change physical and chemical characteristics of the water, and influence stream biodiversity patterns and habitat quality (Storey & Cowley, 1997; Scarsbrook & Halliday, 1999).

Riparian forested reaches can improve stream water quality as it passes through the forest remnant, but the distance necessary for an improvement of water quality depends on the characteristic evaluated. For example, Storey & Cowley (1997) found increases in dissolved oxygen (DO) concentrations after the stream entered 300 m into the remnant. Harding et al. (2006) sampled locations within continuous forest catchments, and locations in three forest fragment catchments: two were in agricultural land and the other was in the center of the forest fragment. No differences in water and habitat characteristics were found, suggesting that other factors could influence these results, including riparian forest structure, remnant location within the watershed, and distance from other forest remnants. Studies carried out along streams in Zimbabwe (Chakona et al., 2009) and Australia (Arnaiz et al., 2011) found no effects of forest fragments on water quality, although differences in benthic macroinvertebrate communities were recorded. Suga & Tanaka (2013) worked in the same system studied here, and found changes in macroinvertebrate communities as the stream flowed through the forest fragment.

The effects of riparian forest remnants on stream water quality are variable, and remnant sizes may be not enough to explain responses in water variables. Differences in riparian forest structure can influence both surface and subsurface water movement, so that variation in stand age and composition, tree size, and density, and vertical canopy stratification can vary in their efficiency to retain nutrients and buffer streams from nutrient loads and sediments (Hoffman et al., 2009; Souza et al., 2013). For example, nutrient absorption by the vegetation can directly influence the nutrient pools that flow through the riparian zones, and these effects can vary with vegetation age (Dosskey et al., 2010). Younger vegetation presents higher nutrient absorption than mature forests (Ericsson, 1994), so that streams flowing through mature forests could receive higher nutrient input (Hoffman et al., 2009). Also, differences in forest structure (canopy stratification, tree size and densities and accumulation of plant detritus) throughout stand development can influence overland roughness and thus influence overland flow, water infiltration and sediment deposition in the riparian zone (Parsons et al., 1996; Jin et al., 2000).

Here, we evaluated if a riparian forest remnant and the structure of the forest remnant influenced the physical and chemical characteristics of a tropical rural stream in SE Brazil. We tested the following hypotheses, (1) the forest remnant would change water characteristics as the stream flowed through the remnant, (2) local differences in forest structure within the forest remnant would alter water characteristics.

Materials and methods

Study area

We carried out this study in the Vassununga State Park (VSP), municipality of Santa Rita do Passa Quatro, located between the coordinates 21°20′ and 21°55′S, and 47°32′ and 47°40′W. The VSP is located in the Mogi-Guaçu river watershed, in Northeastern São Paulo State, SE Brazil. The main vegetation types in the park are tropical savannah (Cerrado), seasonal semideciduous forest, riparian forest, and wetlands; the vegetation types are not distributed continually within the park, since the VSP is subdivided in six main units, inserted in a matrix predominantly used for perennial cultures, sugar cane, and pasture (Korman, 2003). We studied the unit named Capetinga Oeste, which contains a large forest remnant with an area of 327.83 ha. The studied stream was the Córrego da Gruta, whose source is located hundreds of meters upstream of the remnant, within a plantation of sugar cane, then runs about 1 km throughout the remnant, and leaves the unit, running through agricultural land until it reaches the Mogi-Guaçu River (Fig. 1). The maximum distance upstream of the remnant where there was water flowing was at the point—140 m, since locations upstream of this point were dry (Fig. 1). Stream width of flow varied between 16 and 130 cm (mean = 48.6 cm), mean flow depth was 14.7 (maximum = 27.5 cm), and bankfull depth varied between a few centimeters to about 2 m (Hanai, unpublished data).

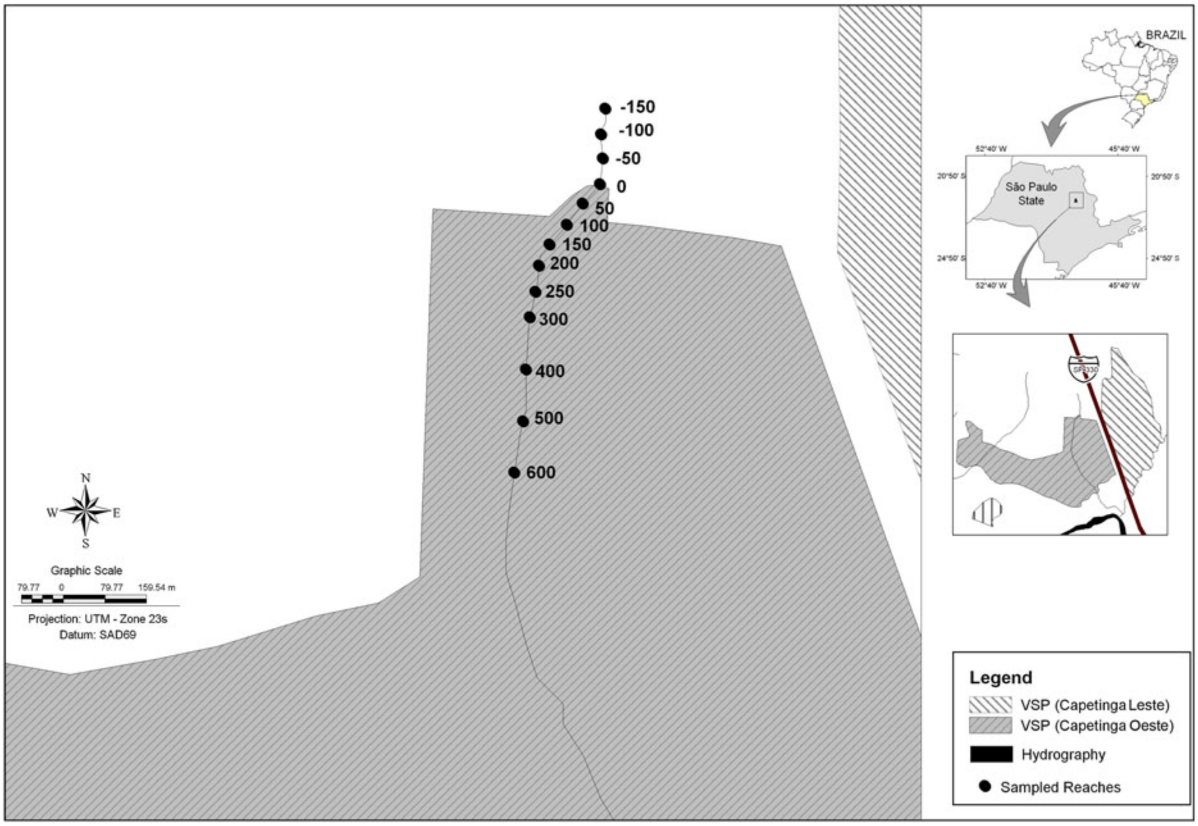


Fig. 1 Location of the studied stream and forest remnant (Capetinga Oeste) in São Paulo State and sampling design to evaluate the effects of distance from the forest remnant edge and forest structure on stream water quality. *Negative values* indicate distances (m) of deforested reaches upstream of the forest remnant edge, and *positive values* indicate distances within the forest remnant. The remainder of the watershed was mainly covered with sugar cane plantation

The climate of this region is Cwa according to Koppen (Setzer, 1966), with mean monthly temperatures between 17.6°C in July and 23.5°C in February, and mean annual rainfall of 1,478 mm, concentrated during the summer months (Pivello & Varanda, 2005). The VSP is located in the contact zone between the Basaltic Cuesta, with altitudes between 700 and 780 m, and the Peripheral Depression (Mogi Guaçu Zone), which has altitudes between 540 and 650 m. The soil is dystrophic red latosol, red latosol, and red–yellow latosol, with the occurrence of quartzite sands ("neossolos") and gleysols nearby the watercourses (Pivello & Varanda, 2005).

Sampling

We collected samples from within the sugar cane plantation, 100 m (point −100) before the edge of the forest remnant (point 0), until 600 m into the forest interior (Fig. 1). We sampled water and forest characteristics every 50 m, from the points −100 to 300, and every 100 m until the point 600. Thus, we sampled two reaches outside the forest remnant (−100 and −50 m), one at the forest remnant edge (point 0), and nine reaches within the remnant (50, 100, 150, 200, 250, 300, 400, 500, 600 m), totaling 12 reaches sampled.

To evaluate the physical and chemical characteristics of the stream water, we sampled in the dry season, in August 2011. At each point, we measured electric conductivity (conductance; EC) and pH with a multiparameter Horiba U-10 water quality meter, whereas DO and temperature were determined with a YSI-55 portable meter. To determine nutrient concentrations, two samples of stream water were also obtained from each reach. Each water sample was collected from the middle of the water column into a previously acid-washed plastic bottle, frozen, and later analyzed in the laboratory. We determined nitrate concentrations using the cadmium reduction method (Mackereth et al., 1978) and ammonium concentrations based on the phenate method (Koroleff, 1976), whereas nitrite concentrations were determined by colorimetric methods (Golterman et al., 1978). Total nitrogen (TN) and total phosphorus (TP) concentrations were determined by the persulfate method (Valderrama, 1981). Total dissolved phosphorus (TDP) was obtained by digesting samples with the persulfate method and then determining concentrations by the ascorbic acid method (Strickland & Parsons, 1960). Total reactive phosphorus (TRP) was directly estimated by the ascorbic acid method; organic phosphorus concentrations were obtained by the difference between TP and TRP (Strickland & Parsons, 1960). Finally, silicate concentrations were determined by the molybdate method (Golterman et al., 1978).

Forest structure was determined along each 50 m reach by randomly sampling four 10 × 10 m plots positioned immediately adjacent to the stream, totaling 36 plots; samples of forest structure from the 300-m point and beyond were obtained from the intervals 350–400, 450–500, and 550–600 m. Thus, the area available for sampling was 50 m length of the reach × 10 m (width of each plot) × 2 margins, totaling 1,000 m^2, and 40% of the riparian forest was sampled in each reach. Two plots were established in each margin, and the position of each plot was sorted along the reach, so that plots in the same margin did not overlap. Within each plot, all trees with diameter at breast height (DBH) $\geq$3.0 cm were marked; circumference at breast height was measured with a measuring tape, and total tree height was determined with a laser digital hypsometer. The following variables were obtained from each plot: tree density, mean DBH, mean canopy height, total basal area, and vertical canopy structure (forest stratification), which was estimated as the coefficient of variation of tree heights within each plot. Tree density was the number of trees per 0.01 ha and total basal area was estimated by the sum of basal areas of all trees within the plot.

Data analysis

To evaluate if the forest structure varied along the remnant, we used a principal components analysis (PCA), using the mean values of the vegetation variable per sampled reach. We did not use sampling points upstream of the remnant because there were no trees, so forest variables scored zero values. The values were checked for normality, and mean tree height and DBH were transformed to natural logarithms; all variables were then normalized for zero mean and unity variance before the PCA analysis.

We tested for correlation between the PCA axes and distance along the remnant using the Spearman correlation coefficient. Since no correlation was observed ($P > 0.05$; see "Results" section) the effects of distance and forest structure were separately analyzed. To evaluate the effect of accumulated distance on water characteristics, we used a non-linear model as suggested by Lim et al. (1998) and Harding et al. (2006) for the effects of riparian buffering. The following first-order exponential model was fitted: $y = y_0 + Ae^{-x/t}$, where A and t are constants and x is the distance along the longitudinal stream gradient, from 100 m before the edge to 600 m into the forest remnant. The model was fitted by iteration using the Levenberg–Marquardt algorithm as implemented in the software OriginPro 8.0, following Seber & Wild (2003).

The effects of forest structure were evaluated using the residuals of the exponential model fitted above as dependent variables in a linear regression model. Each PCA axis was used as an independent variable, to evaluate if there was residual information that could be explained by the forest structure. The significance level considered in this study was $P < 0.05$.

Results

Nutrient concentrations within the stream were generally low, although they presented a wide variation (Table 1): maximum values were 2 × larger than minimum values (for TDP) but could be 27 × larger than minimum values (nitrite). Temperature variation was less than 1°C (Table 1), whereas DO concentrations varied greatly, with maximum values 2 × larger than minimum values (Table 1). EC and pH presented a lower variation; pH values were lower than 6.0 in the points outside the remnant (−100, −50, and in the edge).

Although parameters were variable, the accumulated distance along the forest remnant did not significantly explain the variation in pH, nitrite,

Table 1 Range of riparian forest structure and water characteristics measured at Córrego da Gruta, SE Brazil

Variable	Range
Forest structure	
Tree density (ind ha^{-1})	181.3–531.3
Mean DBH (cm)	8.33–15.16
Mean canopy height (m)	3.79–8.31
Total basal area (m^2 ha^{-1})	5.5–11.8
Forest stratification	0.11–0.32
Water characteristics	
pH	5.50–6.51
Electric conductivity (mS cm^{-1})	0.05–0.07
Temperature (°C)	19.7–20.6
Dissolved oxygen (mg L^{-1})	3.94–8.24
Total N (μg L^{-1})	73.39–169.93
Ammonium (μg L^{-1})	4.99–16.26
Nitrite (μg L^{-1})	0.02–0.47
Nitrate (μg L^{-1})	2.77–33.46
Total P (μg L^{-1})	14.11–67.29
Total dissolved P (μg L^{-1})	12.79–25.62
Inorganic P (μg L^{-1})	7.39–18.23
Organic P (μg L^{-1})	1.93–14.72
Silicate (mg L^{-1})	7.17–13.70

nitrate, and TRP. On the other hand, EC and ammonium concentrations decreased as the stream passed through the remnant (Fig. 2). Ammonium concentrations outside the remnant dropped 35% from 11.2 to 7.3 μg L^{-1} just before entering the remnant.

DO concentrations increased rapidly as the stream entered the remnant, and remained approximately constant along the stream; the first-order exponential model showed an excellent fit, explaining 99% of the variation (Fig. 2). Other nutrient concentrations increased significantly as the stream passed through the remnant, including TP, TDP, organic P, and silicate (Fig. 2). The model also showed a good fit, with R^2 values ranging between 0.36 (TP) and 0.73 (silicate).

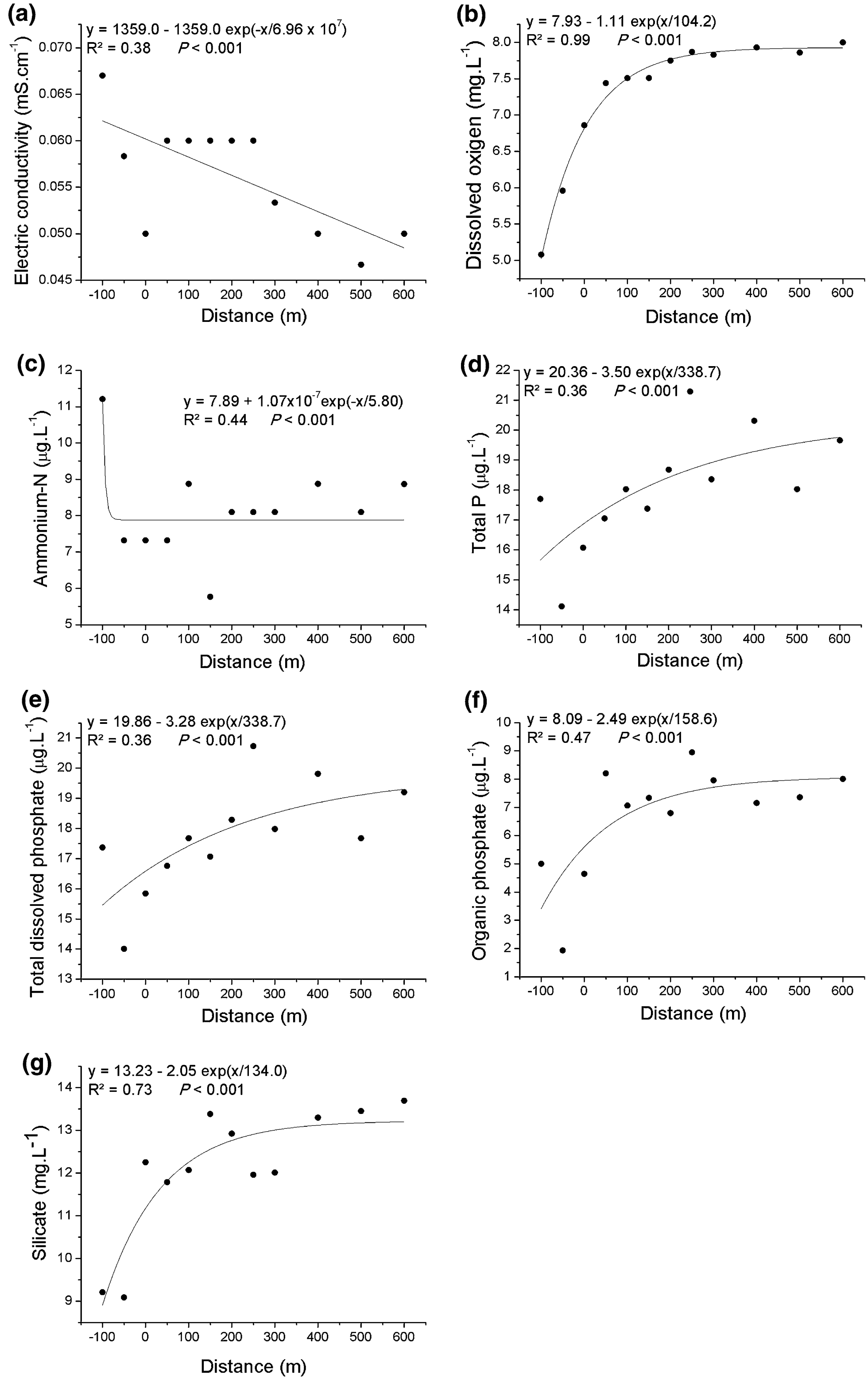
The structure of the riparian forest remnant varied in the sampled reaches (Table 1). Tree density and forest stratification presented the largest variation, with maximum values 3 × larger than minimum ones. On the other hand, mean DBH, tree height, and total basal area showed less variation, with maximum values 2 × larger than minimum ones (Table 1). The first two axes of the PCA explained 79.1% of the variation in forest structure data (Table 2). The first axis explained 45.0% of the variation, and represented a gradient from more stratified forests and smaller trees, to less stratified forests but with taller trees, with larger DBH values. The second axis explained 34.1% of the variation in forest structure, and was a gradient from reaches with higher density of trees but lower basal area, to reaches with higher basal area but lower tree density (Table 2).

We found no significant correlation of the first ($r = -0.42$) and second ($r = 0.38$) axes of the PCA on forest structure variables and the distance along the forest remnant. In fact, there was some heterogeneity in forest structure along the remnant; higher tree density and lower basal areas characterized the reaches 0–50, 50–100, 100–150, 150–200, and 400–500 m (Fig. 3). However, reaches 200–250 and 500–600 m presented lower tree densities and higher basal area; further, lower tree density in the 200–250 m reach resulted from the presence of a large clearing in one of the stream margins, dominated mainly by the shrub *Urtica dioica* L. with heights between 1.5 and 3.0 m. The reaches 250–300 and 300–400 m presented trees with smaller heights and DBH, but more stratified forests, whereas in the reaches 0–50, 150–200, 200–250, and 500–600 m taller trees with higher DBH values were observed, although with less forest stratification (Fig. 3).

The heterogeneity in forest structure explained the residual variation in some of the stream water characteristics. There was a significant relationship between EC and concentrations of TN and nitrite in relation to PCA axis 1. Thus, in areas with larger trees but less stratified forests, values of EC, as well as TN and nitrite concentrations were higher (Fig. 4). On the other hand, both TP and TDP tended to increase with increases in PCA axis 2 ($P = 0.087$); thus, areas with lower tree density and higher basal areas tended to present higher values of both TP and TDP concentrations (Fig. 4).

Discussion

Forest remnants are common in rural landscapes, but their role in ameliorating stream water quality has been poorly explored, and patterns are not clear. Our results suggest that forest remnants have positive


(a)
y = 1359.0 - 1359.0 exp(-x/6.96 x 10^7)
R² = 0.38 P < 0.001
Electric conductivity (mS.cm^-1)
Distance (m)
(b)
y = 7.93 - 1.11 exp(x/104.2)
R² = 0.99 P < 0.001
Dissolved oxigen (mg.L^-1)
Distance (m)
(c)
y = 7.89 + 1.07x10^-7exp(-x/5.80)
R² = 0.44 P < 0.001
Ammonium-N (μg.L^-1)
Distance (m)
(d)
y = 20.36 - 3.50 exp(x/338.7)
R² = 0.36 P < 0.001
Total P (μg.L^-1)
Distance (m)
(e)
y = 19.86 - 3.28 exp(x/338.7)
R² = 0.36 P < 0.001
Total dissolved phosphate (μg.L^-1)
Distance (m)
(f)
y = 8.09 - 2.49 exp(x/158.6)
R² = 0.47 P < 0.001
Organic phosphate (μg.L^-1)
Distance (m)
(g)
y = 13.23 - 2.05 exp(x/134.0)
R² = 0.73 P < 0.001
Silicate (mg.L^-1)
Distance (m)

◂**Fig. 2** Fitted exponential models relating stream water characteristics and accumulated distance along the studied riparian forest remnant. The zero values indicate the edge of the forest remnant, so that *negative values* indicate distances upstream of the remnant border, and *positive values* to the right indicate studied reaches within the forest remnant. **a** electrical conductivity, **b** dissolved oxygen, **c** ammonium, **d** total phosphorus, **e** total dissolved phosphate, **f** organic phosphate, **g** silicate

Table 2 Results of principal components analysis comparing the riparian forest structure in the studied forest remnant

Variable	Axis 1	Axis 2
Tree height	0.623	−0.014
Diameter at breast height	0.583	0.242
Tree density	0.392	−0.604
Total basal area	0.094	0.753
Forest stratification	−0.332	−0.099
Eigenvalues	2.251	1.703
Percentage explained	45.02	34.06
Cumulative percentage explained	45.02	79.08

effects on stream quality, but we found different effects on water characteristics not only due to the presence of forest remnants, but also in relation to riparian forest structure. Riparian forests are not homogeneous, and forest remnants can differ in quality, age, and composition, so different remnants and even small-scale heterogeneity within remnants can influence their role as buffers, as suggested by Harding et al. (2006). To our knowledge, this is the first study that evaluated combined effects of accumulated distance within a forest remnant and riparian forest structure on within-stream conditions.

The Capetinga Oeste unit is inserted within a matrix of sugar cane plantations, where management includes application of both organic and inorganic fertilizers, and chemical pesticides (Corbi et al., 2006). The organic fertilizers are rich in phosphorous (P)—which is gradually released by mineralization and soil microorganisms—and in nitrogen (N), which can be leached to the forest soil and to the stream. The buffering effect of riparian forests is well known (Naiman et al., 2005), and these forests can be important pools of P retention. However, some studies showed that the retention of DP was lower and, in some cases, riparian zones increased the delivery of P to surface waters, possibly due to increased remobilization of particulate P retained within the riparian zone that ends up being delivered as DP to the stream (Roberts et al., 2012). The increase in P concentrations with distance along the studied remnant also suggests that riparian zones can in some cases increase DP delivery to the streams, and this pattern could be related with the structure of the riparian forest (see below).

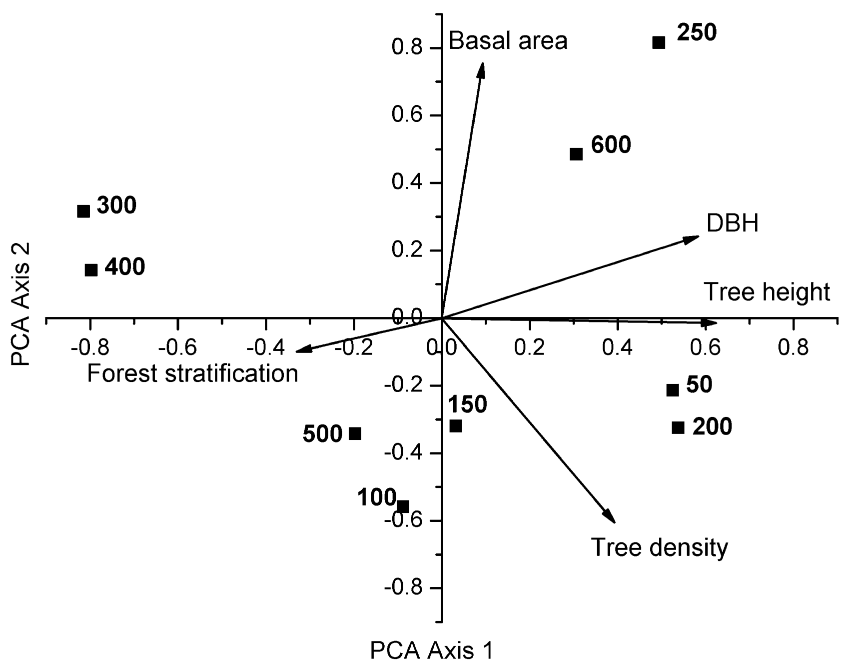


Fig. 3 PCA results showing the ordination of the studied reaches from the edge to the interior of the forest remnant, and the forest structure variables. *Symbol values* represent the distances in relation to the edge of the remnant

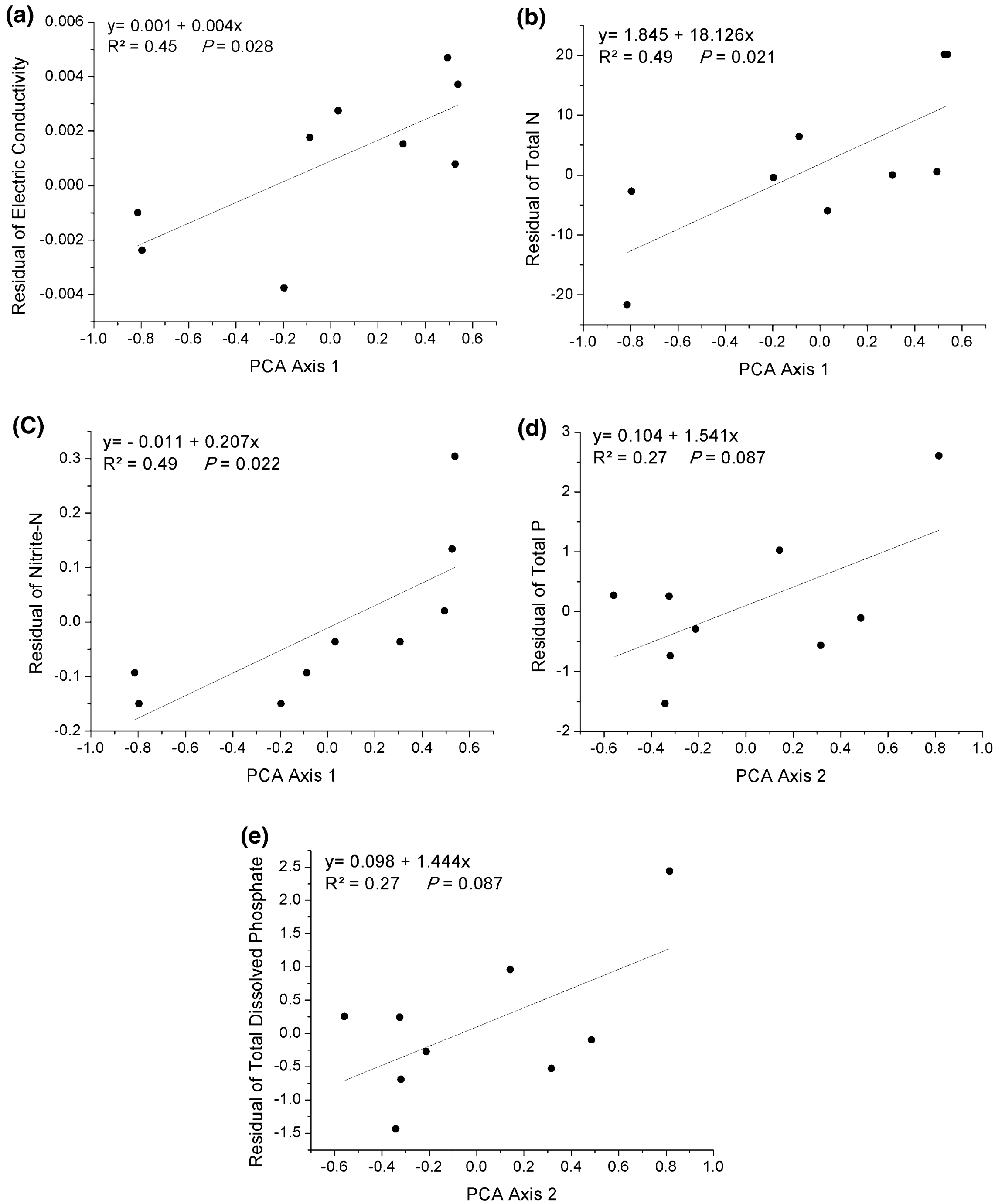


Fig. 4 Relationship between residuals of the fitted exponential models in relation to the structure of the riparian forest studied (PCA axes 1 or 2). **a** electrical conductivity, **b** total nitrogen, **c** nitrite, **d** total phosphorus, **e** total dissolved phosphate

The forest remnant influenced some water characteristics, with lower EC and higher DO concentrations within the forest. These results are in agreement with Storey & Cowley (1997) who found positive effects of forest remnants on DO concentrations in pastoral streams and Scarsbrook & Halliday (1999) who found lowered EC on forest remnants in one of the watersheds studied. However, Harding et al. (2006), Chakona et al. (2009), and Arnaiz et al. (2011) found no effects of forest remnants on these variables. Souza et al. (2013) studied 15 streams along a gradient of forest cover and found lower values of EC and higher DO concentrations in streams with greater forest cover. Our results were similar to this pattern, with variation in these parameters within a single stream as it flowed through a forest remnant, strengthening the hypothesis that forest remnants can locally improve stream water quality. Within the forest remnant, there were increasing amounts of large woody debris (LWD), increasing water turbulence and thus increasing DO concentrations due to exchanges with the atmosphere. Paula et al. (2011) showed that the supply of LWD to the stream channel increases with riparian forest cover and age, thus increasing the frequency and size of LWD pools.

We also found increasing concentrations of silicates in stream water with accumulated distance within the forest remnant. Silicates are considered essential nutrients for the growth of some phytoplankton organisms like diatoms. Although the other studies on the effects of forest remnants on stream water quality did not evaluate silicate concentrations, we expected that the presence of the forest would have a positive effect by increasing the biogenic silica pools to the stream. Biogenic silica pools as phytoliths in forest soils can be significant, and Derry et al. (2005) found that most silica delivered to Hawaiian stream water had passed through the biogenic pool. In a recent review, Keller et al. (2012) concluded that agriculture depleted the phytoliths pool due to the exportation of straw, so increasing forest cover could replenish these biogenic pools, thus increasing silicate concentrations in stream water.

The effects of accumulated distance along the forest remnant were not correlated with the structure of the riparian forest, and the riparian forest presented small-scale variations possibly due to local disturbances. Riparian forest structure was not homogeneous in the forest remnant, and the PCA identified two main gradients of variation: a gradient in forest stratification versus tree height and DBH, and a gradient in tree density versus basal area. The gradient in stratification versus tree height and DBH influenced EC and N concentrations. First, more stratified parts of the forest could be related with the rainfall redistribution through damping, directing, and retention of water drops by tree canopies (Nadkarni & Sumera, 2004). Also, Dietz et al. (2006) found that higher canopy roughness due to increased vertical distribution of foliage and other canopy components increases canopy water storage. These effects could reduce the overland flow of water, increasing rainfall infiltration to the soil, thus resulting in higher nutrient retention and lower EC of the stream water. A second effect of the forest structure gradient is related to the growth phase of the plants. Plant growth demands more nutrients but, as the vegetation matures, biomass accumulation both above and below ground tends to slow (Vitousek & Reiners, 1975; Boggs & Weaver, 1994; Kelly et al., 2007). This lowered growth rate can contribute to decreased demand for nutrients. Thus, in reaches with younger trees, plant growth can lead to higher assimilation of nitrogen than in reaches dominated by larger trees, resulting in lower N concentrations in the stream water of these reaches.

The other gradient in forest structure identified in our study, tree density versus basal area, presented a trend in influencing P concentrations in the stream. The buffering effect of riparian forests can be related with basal area, which is an indicator of forest woody biomass within each plot. Higher woody biomass can or cannot be related with forest age, since a few large trees can have the same basal area than many smaller trees. We found a trend for higher P concentrations in areas with lower density but higher total basal area, thus tree density seems more important to retain P than higher woody biomass within plots. The presence of more trees can reduce overland flow speed and increase the interception of particulate material, thereby reducing the input of nutrients to the stream (Dosskey et al., 2010). Also, the physical retention of P by riparian buffer strips is important to reduce P delivery to the streams, and higher basal area can be related with larger and denser root systems that increase the permeability and porosity of the soil, thereby increasing overland infiltration (Roberts et al., 2012). Further, Souza et al. (2013) studied 15 streams along a gradient of forest cover and found that a gradient in tree size versus density influenced P concentrations in the streams, with lower concentrations in streams with higher tree density in the riparian forest due to increased P uptake.

This study showed that forest remnants can improve water characteristics, thus helping to mitigate non-point effects of agricultural activities in rural landscapes. The effects also depended on the local structure of the riparian forest, so that differences in forest structure influenced variables such as EC and nutrient concentrations. Thus, there is a large potential for more studies to understand how riparian forests of differing structure influence nutrient concentrations, and also to understand how characteristics of the remnants such as width, composition, age, and integrity influence their buffering efficiency. We suggest that the presence of forest remnants may improve water quality and contribute to nutrient inputs to low-order streams, since these streams depend on allochthonous energy and nutrient sources to maintain aquatic communities (Naiman et al., 2005). Further, our results—even studying a single stream—suggest that the structure of these forest remnants can significantly influence these relationships. For example, secondary-growth forests contribute to reduce stream nutrient concentrations due to higher absorption rates and higher infiltration of overland flow due to increased tree densities, whereas old-growth forests contribute with allochthonous resources, so that the organic matter is retained longer within the stream due to LWD (Valett et al., 2002; Warren et al., 2009). Therefore, even though land use at the landscape level can overcome riparian effects (Stewart et al., 2001), forest remnants have local effects that can be important when managing stream water quality at larger spatial scales.

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