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Influence of riparian vegetation and forest structure on the water quality of rural low-order streams in SE Brazil

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ABSTRACT

Land use changes have resulted in large deforestation of rural landscapes, thus influencing transport of water and materials along the watersheds. Riparian zones have strong effects on stream water quality, but most studies evaluated the effects of riparian vegetation (forested vs. deforested), although riparian forests may greatly differ in structure. Here we evaluated the effects of riparian vegetation characteristics (RV) and riparian forest structure (RFS) on stream water quality in a tropical rural landscape in SE Brazil. We sampled 15 low-order streams along a gradient in riparian degradation, from completely deforested streams to those with well-developed riparian forests. In each stream we established a 100 m reach and evaluated RV (trees, grasses, vines, bamboo, canopy closure, and riparian forest width), RFS (tree density and height, vertical canopy structure, mean basal area and diameter at breast height), and stream habitat and water quality (mean water depth, fine sediment cover (FSC), electric conductivity (EC), dissolved oxygen (DO), ammonium, nitrate, total *N*, dissolved, particulate, and total *P*). We used Principal Components Analyses to reduce dimensionality of RV and RFS variables, and evaluated the separate effects of RV and RFS on water quality variables using conditional autoregressive models. We found effects of both RV and RFS on FSC, EC, DO and ammonium concentrations, and effects of only RFS on total and dissolved *P* concentrations. These results suggest that although RV variables are good predictors of the buffering role of riparian zones, the structure of the riparian forest can influence stream water quality variables. Thus, heterogeneity in riparian forest structure due to forest degradation or restoration should be considered when evaluating buffering effects of riparian zones.

1. Introduction

Human activities have severely changed landscapes in rural zones, mainly through the conversion of large areas for planting and pasture. These changes at the watershed scale included deforestation of riparian areas, impacting watercourses through sedimentation and degradation of water quality (chemical, physical, and biological characteristics) and loss of biological diversity (Quinn et al., 1997; Allan, 2004). Deforestation of riparian zones can have disproportional effects on water quality because they are the interface between terrestrial and aquatic ecosystems, influencing flows of energy and materials between both (Naiman et al., 2005; Fausch et al., 2010); as such, they are considered critical transition zones between both ecosystems (Ewel et al., 2001). Riparian zones have several functions such as reducing surface runoff and bank erosion, retaining sediments, processing nutrients, altering biological conditions by providing shade and moderating temperatures, increasing both riparian and in-stream habitat complexity and food availability and, at a larger scale, providing corridors for the movement of biota, increasing biodiversity at the landscape scale and contributing to the maintenance of water quality (Naiman et al., 2005; Lees and Peres, 2008; Merritt et al., 2010; Miserendino et al., 2011).

Most studies evaluating the effects of riparian zones as buffers have contrasted distinct vegetation types (e.g., forests vs. forbs and grasses) or streams with and without forests, finding strong effects of riparian vegetation on water quality (Tabacchi et al., 1998; Stewart et al., 2001; Roberts et al., 2012). However, riparian forests may vary in structure due to differences in soil and abiotic conditions, time since last disturbance (differing successional stages), previous land use differences, and current landscape composition in the adjacent areas (Hermy and Verheyen, 2007; Dosskey et al., 2010; Hagen et al., 2010). Thus, riparian forests of differing structure may not have the same effect in improving the quality of watercourses. In fact, riparian forests are not homogeneous, and their effects as buffers could be variable (Hoffman et al., 2009; Dosskey et al., 2010).

Forest stands in distinct successional stages can have very different characteristics, with strong reduction in stem density and

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increase in basal area in a few decades following harvest (Naiman et al., 2005). Osborne and Kovacic (1993) suggested that nutrient removal efficiency of forest buffer strips could be influenced by several factors, such as forest successional stage, but very few studies have evaluated this hypothesis (Boggs and Weaver, 1994; Nislow and Lowe, 2006). Riparian forests within a catchment can differ in several forest characteristics, including stand age and height, basal area, forest stratification, and so on, depending on prevailing land uses at local scales (Tabacchi et al., 2000; Naiman et al., 2005). Mature forests can also present variation in structure, through a mosaic of closed and open canopies that allows understory vegetation communities, influencing buffer efficiency (Castelle et al., 1994; Tabacchi et al., 2000; Merritt et al., 2010). In catchment forests, differences in forest density along topographic gradients can influence catchment runoff ratios, since sparser canopies of upslope vegetation can increase the water subsidy to downslope vegetation in exceeding quantities (Hwang et al., 2009), whereas forest canopies can influence hydrological regimes depending both on the timescales considered and on phenological patterns due to leafless periods (Post and Jones, 2001). Differences in forest structure can influence runoff responses and partitioning of rainfall into throughfall, stemflow, and interception, due to local-scale effects of vegetation resulting from tree characteristics such as crown size, canopy gaps, leaf shape and orientation, branch angle, flow path obstructions and bark type (Crockford and Richardson, 2000).

Although effects of riparian vegetation (proportion of forest and grasses, forest width, and above-stream canopy cover) on stream water quality have been widely reported, less is known about whether differences in riparian forest structure (such as tree density and vertical canopy structure, mean dbh, stand height, and total basal area) also influences water quality parameters. Forest structure and riparian vegetation may have their effects confounded, because larger trees with larger basal areas can be related with higher proportion and width of forests in the riparian zones. In this study, we evaluated if riparian vegetation (RV) and riparian forest structure (RFS) influenced stream habitat and water quality variables in a rural landscape in central São Paulo State, SE Brazil. Then, we compared the relative importance of RV vs. RFS on these variables to evaluate if forest structure could explain additional variation not related with riparian vegetation.

2. Methods

2.1. Study area

This study was carried out in rural streams draining to the lower Jacaré–Pepira River and Jacaré–Guaçu River watersheds. Both watersheds are located in the central region of São Paulo State, southeastern Brazil, and belong to the Tietê River watershed, as part of the Tietê–Jacaré Water Resources Management Unit (UGRHI-13) in São Paulo State. The Jacaré–Pepira River watershed is located between the coordinates 21°55′ and 22°30′ S, 47°55′ and 48°55′ W, whereas the Jacaré–Guaçu River watershed is located between the coordinates 21°37′ and 22°22′ S, 47°43′ and 48°57′ W. Land use in the UGRHI-13 is mainly divided in sugarcane plantations, orange, pasture, and *Pinus* and *Eucalyptus* plantations, with only 11.3% of remaining native vegetation. About 60% of the water is used for irrigation and other agricultural uses (Tundisi et al., 2008). The climate in the region is tropical wet and dry (Aw) according to Köppeńs classification, with mean monthly temperatures varying between 19.3 and 25.4 °C and mean annual rainfall of 1260 mm, concentrated between October and March (Miranda et al., 2012). Sampling was carried out during the dry season, in September 2009.

2.2. Sampling

Fifteen low-order streams were selected for the study, representing a gradient in riparian zone cover, eight in the Jacaré–Guaçu watershed and seven in the Jacaré–Pepira watershed (Fig. 1). For each stream, a 100 m reach was established along the channel and three 10×10 m plots were randomly marked. Within each plot, all trees with diameter at breast height (dbh – measured at 1.3 m height) larger than 5.0 cm were recorded, and total height measured with a laser hypsometer; dbh was obtained by first measuring circumference with a graduated tape and then converting these values to diameter. These data were used to obtain the riparian forest structure (RFS) variables per stream: tree density and basal area per hectare, mean tree height, mean vertical canopy structure (VCS – coefficient of variation of tree heights), and mean dbh. Riparian vegetation (RV) characteristics were cover by trees, grasses, vines and bamboos, which were visually estimated for each plot using the following cover categories: 0–25%, 25–50%, 50–75% and 75–100%; riparian forest width, measured with a tape to the nearest cm; and light availability (in percentage) along the channel, which was determined using a Solar Pathfinder, following Harris et al. (2005).

To evaluate water quality, the following variables were determined with a multiprobe YSI 556 at each sampling point: electric conductivity (EC), pH, and dissolved oxygen concentrations (DO). Each stream was sampled once during the studied period. Two samples of surface stream water were also obtained from each reach, frozen, and later analyzed in the laboratory for nitrogen and phosphorus concentrations. Water samples were analyzed for nitrate-*N*, ammonium-*N*, total *N* (TN) (Koroleff, 1976; Mackereth et al., 1978); total phosphorus (TP) was determined following Strickland and Parsons (1960), whereas dissolved phosphorus (DP) was determined after passing through a 0.45 μm membrane filter. Particulate phosphorus (PP) was obtained by the difference between TP and DP. Stream habitat quality was evaluated by determining sedimentation and mean water depth. Fine sediments were quantified by estimating the proportion of the stream bed covered by fine sediments using the following categories: 0–25%, 25–50%, 50–75% and 75–100%. Mean water depth was determined at three randomly allocated transects within the reach; each transect had 10 equidistant points where depth was determined, and mean depths for each transect were calculated. A single average value for each reach was calculated from the transect means.

2.3. Data analyses

To reduce the dimensionality of independent variables, we analyzed RV and RFS separately by Principal Component Analyses (PCA). Variable distributions did not differ significantly from normal distributions (Kolmogorov–Smirnov test, $P > 0.05$), and they were all standardized for zero mean and unity variance to account for different measurement units. The first two axes of each PCA were used as independent variables in spatial regression models to evaluate separately the effects of RV and RFS on stream habitat and water quality variables. In this analysis, we evaluated if the same associations between stream habitat and water quality variables were found considering the different aspects of the independent variables, RV or RFS. We used spatial regression models because Peterson et al. (2006) found strong effects of spatial autocorrelation on stream water chemistry. Several regression models were developed to account for spatial autocorrelation, and in a recent review Beale et al. (2010) found that generalized least squares (GLS) models and Bayesian methods performed well in simulation experiments. Thus, we used conditional autoregressive models (CAR) to model spatial autocorrelation in the residuals using a GLS framework; in CAR models, the value in a particular location

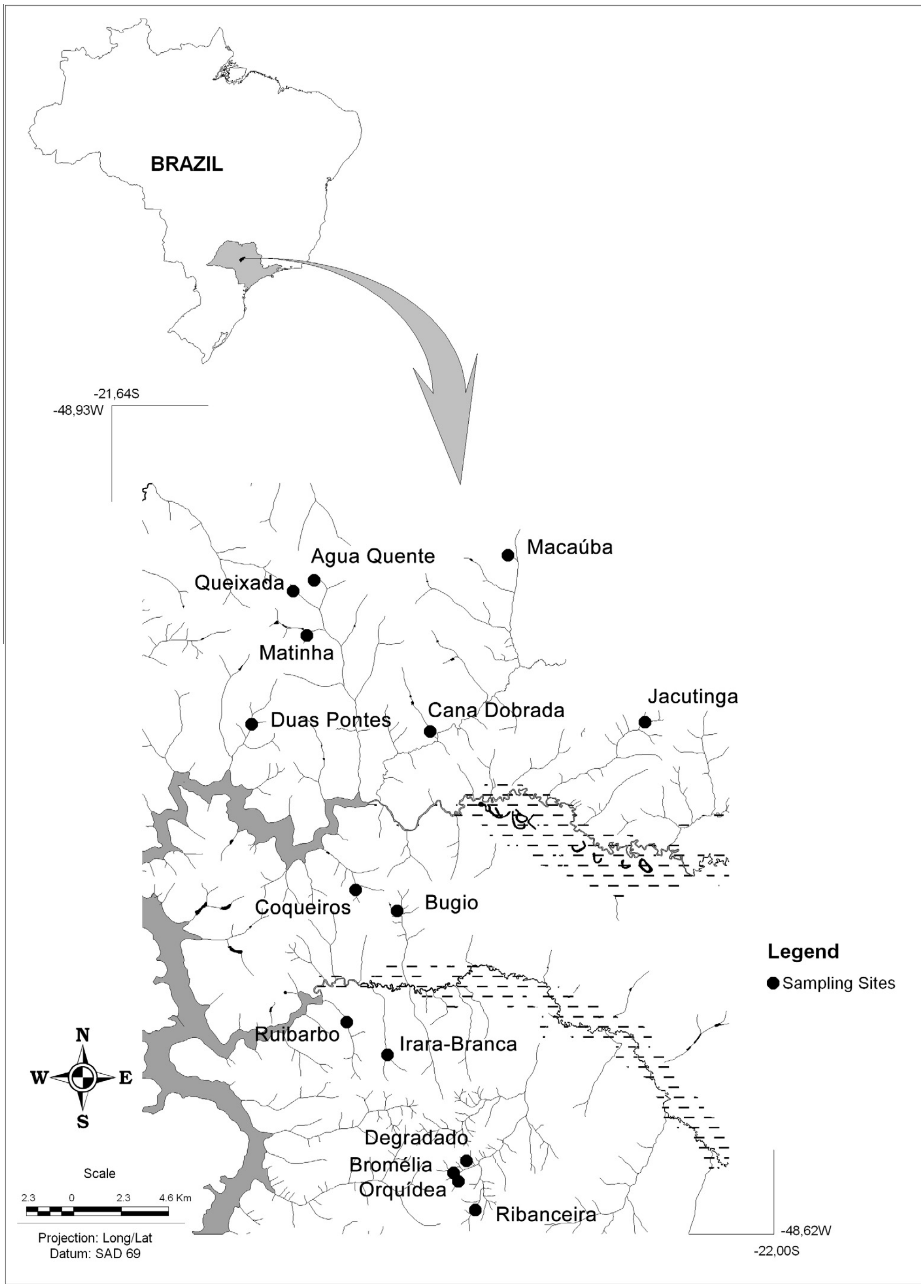

Fig. 1. Location of the studied streams in Central São Paulo State, SE Brazil.

is conditional upon the neighbor values, and the weight matrix for the variance–covariance matrix is symmetric (Fortin and Dale, 2005). For each stream variable, we ran CAR models separately for RV and RFS using the software SAM v. 4.0 (Rangel et al., 2010).

Although riparian vegetation and forest structure evaluate distinct aspects of the riparian zone, both RV and RFS can be correlated, and their effects can be confounded. To test for correlation, we calculated the Pearson correlation coefficient between pairs of PCA axes for both RV and RFS variables. We also analyzed if RFS variables could explain additional variation not explained by RV variables, to separate out the effects of both riparian vegetation and forest structure on stream habitat and water quality variables. For each stream variable, we obtained the residuals from the spatial regression models using RV variables. These residuals are the variation not explained by RV variables or by spatial variation. The residuals of each stream variable were considered dependent variables and analyzed with linear regression models, using the first two axes of the PCA on RFS variables as independent variables. The significance value considered in all analyses was $P < 0.05$.

3. Results

The studied streams varied greatly in the composition of the riparian zone: three streams had no riparian forest at all, whereas the remaining presented a gradient in riparian forest structure, from degraded forests to older, well structured forests up to 50 m wide (Table 1). Within riparian forests ($n = 12$), the range of forest structure variables showed a wide variation, as well as the variables of stream habitat and water quality (Table 1). The first two axes in PCA explained 81.8% of the variation in riparian vegetation (eigenvectors, axis 1 = 3.639, axis 2 = 1.270). The first axis (hereafter referred to as RV1) explained 60.7% of the variation, representing a gradient of streams with riparian forests to those with lower tree cover, which were dominated by grasses in the riparian zone, and thus higher incidence of solar radiation (Fig. 2A and C). The second axis (RV2) explained 21.2% of the variation, a gradient from higher bamboo cover but no native trees to more open streams with higher solar radiation input (Fig. 2A and C). RV axes were significantly related with ammonium, EC, DO, fine sediments, and mean water depth (Table 2). Ammonium concentration was positively related with decreased forest width and cover, and also with bamboo cover, a pattern detected due to one stream with high bamboo occurrence (Matinha). The same patterns were recorded for water electric conductivity, with 59% of the variance explained by the model (Table 2). Dissolved oxygen was significantly related to RV2, with lower values in bamboo-dominated streams (Table 2). Finally, fine sediment cover was more pronounced in streams with lower tree cover and narrower forests ($r^2 = 0.67$), indicating more degraded in-stream habitats. These degraded streams tended to be deeper, although the relationship was weak ($P = 0.052$, $r^2 = 0.27$; Table 2).

In the second PCA, the first two axes explained 89.1% of the variation in forest structure variables (eigenvectors, axis 1 = 3.621, axis 2 = 0.833). The first axis (hereafter referred to as RFS1) explained 72.4% of the variation and represented a gradient of increased tree heights, mean dbh, forest stratification, and mean basal area, whereas the second axis (RFS2) explained 16.7% of the variation, mainly separating streams with high tree density but lower values of mean dbh (Fig. 2B and D). RFS axes also explained variation in ammonium, EC, DO, and fine sediments, as the RV axes did (Table 2). RFS1 was negatively related with ammonium levels, whereas EC and fine sediments decreased with both axes, with higher values in streams with smaller trees, lower basal area, stratification and tree density, with 48–59% of the variance explained by the models (Table 2). We found a significant relationship between TP and PP concentrations and both RFS axes, with higher concentrations in streams with larger trees, forest stratification and lower tree density. Particulate P and DO concentrations were negatively related with RFS2, with higher values in streams with lower tree densities and larger trees (Table 2).

We found a significant correlation between RV1 and RFS1 ($r = -0.824$, $P < 0.001$), but no significant correlation between RV1 and RFS2 ($r = -0.202$), RV2 and RFS1 ($r = -0.042$), RV2 and RFS2 ($r = 0.132$). The residual variation of TP, DP, and DO not explained by riparian vegetation and spatial variation was significantly related to RFS axes (Table 2). TP and DP were negatively related with RFS2, whereas DO was positively related with RFS1.

Table 1
Mean, median, and range of measured variables describing riparian vegetation (RV), riparian forest structure (RFS), and stream habitat and water quality.

Variables	Mean	Median	Range
Riparian zone structure (n = 15)			
Forest width (m)	17.1	16.0	0–50.0
Light availability (%)	40.3	26.6	8.7–97.2
Grass cover (%)	54.0	25.0	25.0–100.0
Tree cover (%)	58.9	58.3	25.0–91.7
Vine cover (%)	38.3	25.0	25.0–91.7
Bamboo cover (%)	27.5	25.0	25.0–62.5
Forest structure (n = 12)			
Tree density (ind/ha)	1361.1	1166.7	66.7–4233.3
Basal area (m^2/ha)	26.7	21.9	0.2–85.8
Diameter at breast height (cm)	13.7	12.6	6.1–29.4
Tree height (m)	7.1	7.0	3.1–11.2
Vertical canopy structure	0.39	0.35	0.19–0.79
Water and stream quality (n = 15)			
Ammonium-*N* ($\mu g\ L^{-1}$)	18.5	15.9	3.2–50.8
Nitrate-*N* ($\mu g\ L^{-1}$)	164.5	166.9	6.5–598.1
Total *N* ($\mu g\ L^{-1}$)	1045.7	977.4	775.6–1904.7
Dissolved *P* ($\mu g\ L^{-1}$)	20.0	15.7	11.2–65.7
Particulate *P* ($\mu g\ L^{-1}$)	20.3	17.2	3.7–49.3
Total *P* ($\mu g\ L^{-1}$)	40.3	34.3	14.9–94.0
Dissolved oxygen ($mg\ L^{-1}$)	6.1	6.0	3.6–9.1
Electric conductivity ($mS\ cm^{-1}$)	0.053	0.043	0.013–0.103
Fine sediment cover (FSC) (%)	50.0	50.0	0–87.5
Mean water depth (cm)	14.3	13.8	5.2–25.3

4. Discussion

Riparian zones can influence stream conditions, and their effect as buffers may depend on riparian composition. We found that along a gradient in forest cover, both riparian vegetation (RV1) and variables associated with tree size (RFS1) were correlated, and their effect on stream habitat and water quality variables was mainly by a separation of streams with the riparian zone dominated by grasses or forests. Streams with lower riparian forest cover and higher cover of grasses presented more fine sediments and higher values of ammonium and EC. Stream draining pasture areas can present dominance of ammonium relative to nitrate due to lower nitrification rates, ammonium runoff or other agricultural sources of ammonia emissions (Chaves et al., 2009), but significant differences are not always found between forested and deforested rural streams (Neill et al., 2001), since this result depends on the demand for ammonium within the stream (Peterson et al., 2001). Other studies also showed that reduction in riparian forest cover results in increases in ammonium concentrations and suspended sediments within the streams (Jones et al., 2001). However, Peterjohn and Correll (1984) found significant reduction of dissolved ammonium over 19 and 50 m distances of a forest buffer, and Schoonover et al. (2005) found that 10 m wide forest riparian buffer zones reduced ammonium surface runoff concentrations by 73%.

The second axis of riparian vegetation was related to ammonium, EC, and DO concentrations, and was strongly influenced by a stream with the highest ammonium concentrations which had mainly bamboos in its margin, resulting in a shaded stream but without a riparian forest. The concentrations recorded ($42.9\ \mu g\ L^{-1}$) were two times higher than the stream with the second highest concentration ($20.6\ \mu g\ L^{-1}$); EC values were also the highest recorded, but were not so different from the values recorded in the other studied streams. The relationship of RV2 and variation in canopy cover resulted both from (1) streams with very narrow riparian forests (less than 5 m), resulting in high incidence of solar radiation, and (2) heterogeneous distribution of the riparian forest, with some parts wider and some narrower along the stream, probably increasing variance in the buffering effects. The results were average ammonium concentrations (about $19\ \mu g\ L^{-1}$) and higher DO concentrations ($>8.0\ mg\ L^{-1}$), which were not typical of streams with narrow riparian forests.

Riparian forest structure was also related with stream habitat and water quality variables, so that the presence of a riparian forest may not be sufficient to act as buffer, but differences in forest degradation or successional states can be as important as the presence of a riparian forest. The three-dimensional spatial distribution of the vegetation, together with specific traits regarding plant metabolism, resource allocation and growth rates influence both hydrological and nutrient cycles, thus influencing stream water quality and quantity (Tabacchi et al., 2000; Dosskey et al., 2010; Roberts

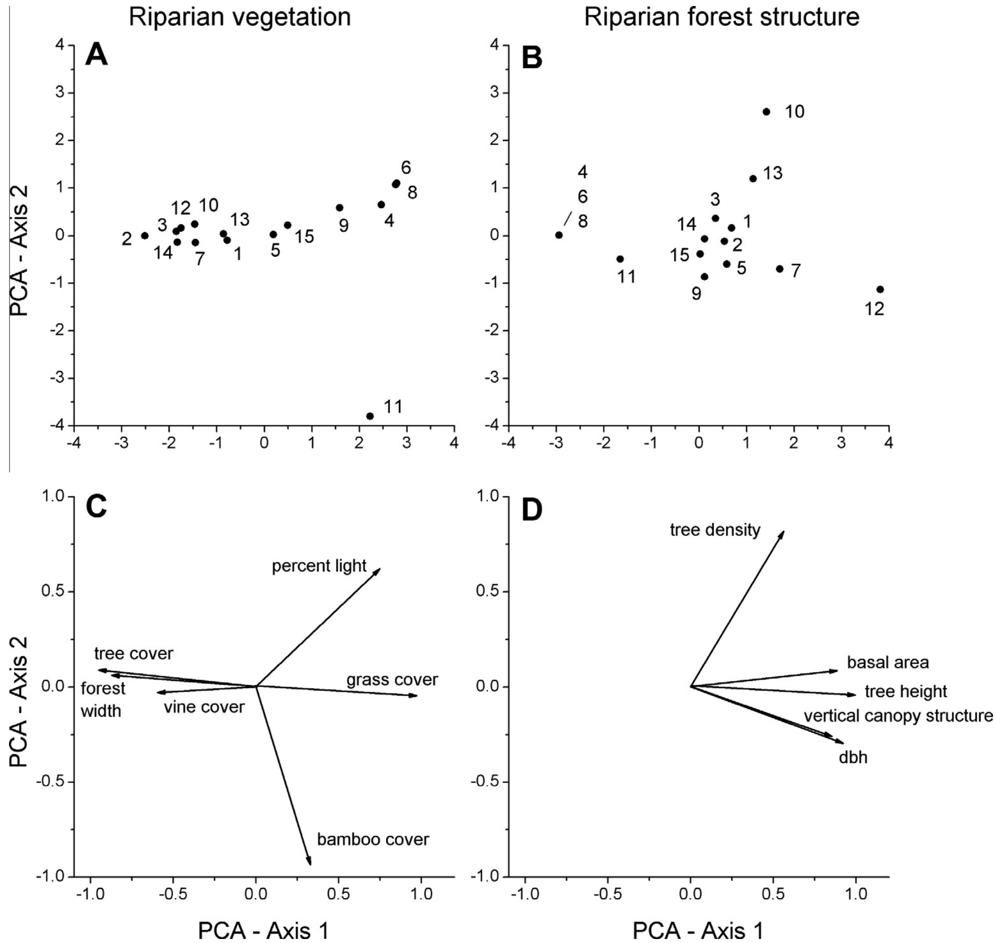

Fig. 2. Results of Principal Component Analysis for riparian vegetation (A and C) and riparian forest structure variables (B and D). Upper panels show sampling site ordinations, lower panels show the correlation biplots for the variables. Key for stream names: Água Quente (1), Bromélia (2), Bugio (3), Cana-dobrada (4), Coqueiro (5), Degradado (6), Duas Pontes (7), Irara-branca (8), Jacutinga (9), Macaúba (10), Matinha (11), Orquídea (12), Queixada (13), Ribanceira (14), and Ruibarbo (15).

Table 2
Coefficients of conditional autoregressive models evaluating the effects of riparian vegetation (RV) and riparian forest structure (RFS) descriptors on stream habitat and water quality, and results of linear regression models evaluating the effects of RFS on the residuals of conditional autoregressive models for riparian vegetation.

	Riparian vegetation			Riparian forest structure			Riparian forest structure (residuals)		
	Axis 1	Axis 2	r^2	Axis 1	Axis 2	r^2	Axis 1	Axis 2	r^2
Ammonium	4.06**	−4.65**	0.59	−4.42*	−1.80	0.42	−1.23	1.22	0.08
Nitrate	21.35	−2.00	0.15	−13.75	−6.31	0.10	−11.15	7.63	0.03
Nitrite	0.21	−0.21	0.15	−0.30	−0.12	0.19	−0.24	0.09	0.08
Total *N*	3.76	−14.7	0.08	8.16	−85.44	0.15	−18.59	−84.58	0.09
Total *P*	−1.22	3.12	0.10	5.21*	−14.35**	0.50	3.51	−14.82*	0.47
Dissolved *P*	−1.53	1.31	0.12	3.77*	−6.21*	0.49	2.49	−7.17*	0.40
Particulate *P*	0.31	1.82	0.10	1.44	−8.14*	0.32	1.02	−7.66	0.29
DO	0.29	1.01**	0.49	0.13	−0.93*	0.41	0.45*	−0.53	0.40
EC	0.008*	−0.012**	0.59	−0.007*	−0.016*	0.48	<.001	−0.009	0.12
FSC	0.47***	0.23	0.67	−0.34**	−0.62**	0.59	0.044	−0.45	0.22
Mean water depth	1.31	1.35	0.27	−1.38	1.03	0.28	−0.44	−0.14	0.03

* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.

et al., 2012). In our study, RFS2 influenced stream habitat and water quality variables, so that streams with riparian forests characterized by higher densities of small trees were associated with lower values of EC, DO, fine sediments and phosphorus concentrations. Higher densities of small trees increase surface roughness, thereby increasing the interception of overland flow, and reducing the amount of particulate matter that reaches the stream (Welle and Woodward, 1986; Dosskey et al., 2010). These differences in the transport of particulate matter can be related to the buffering effect of the overland flow.

Only forest structure variables explained variation in phosphorus concentrations and, when effects of riparian vegetation and spatial variation were removed, we found higher concentrations of TP and DP in streams with mature and structured forests, with higher stratification and presence of larger trees, but no effects of forest structure variables on PP. As reviewed by Hoffman et al. (2009), riparian buffers strips are more effective in retaining PP than DP, either with grass or tree-dominated zones. However, dissolved reactive phosphorus (DRP) retention was more variable, with some studies finding net release of DRP in *P*-saturated buffer zones (Hoffman et al., 2009). Retention increases during plant growth periods and when stands are in early successional stages, but declines to zero when maximum sizes are attained, for a variety of plant species and growth forms (Roberts et al., 2012). At this stage, remobilization of P can occur, resulting in net release of *P* from mature stands (Hoffman et al., 2009). Therefore, less dense stands with larger trees, probably reaching their maximum sizes, should retain less *P* than stands with dense and smaller trees.

Thus, differences in forest structure influences stream habitat and water quality, either through differences in species or functional group composition, plant age and successional stages, or to the interaction between these factors. Several studies found that riparian forest structure and functional group composition can change along successional paths and this variation could influence the transport of water and nutrients. For example, different succession models resulting from distinct strategies of riparian forest restoration can lead to changes in the structure and composition of riparian forests along the Sacramento River, in California, especially on the understory component (McClain et al., 2010). In coastal rain forests of North America, stem density can decrease from about 26,000 to 500 stems/ha during the first 20 to 40 years, with corresponding increases of the basal area, although with high spatial variability (Balian and Naiman, 2005). These changes along succession paths can result in large nutrient accumulation in plants (Boggs and Weaver, 1994), so that harvesting of riparian vegetation or logging of forests could remove large amounts of nutrients from the system (Likens et al., 1970; Kelly et al., 2007).

Riparian zones have strong effects on stream water quality, and their management as buffers to reduce stream degradation is now accepted worldwide, mainly by conserving or restoring riparian forests (Naiman et al., 2005). Our results suggest that even when riparian forests are present, they may be in different states of regeneration or degradation due to local-scale activities, and may present differences in forest structure that can influence stream habitat and water quality in rural landscapes. However, since the present study is observational and restricted to two watersheds in the tropical region, studies carried out in other systems can improve the models found here.

5. Conclusions

In the present study, variables associated both with riparian vegetation and riparian forest structure were related to habitat and water quality of low-order streams in rural landscapes. Both types of variables explained variation in electrical conductivity, fine sediment cover, dissolved oxygen and ammonium concentrations. However, when using methods to separate out the effects of riparian vegetation and riparian forest structure, we found that in-stream phosphorus concentrations were related only to riparian forest structure variables. Therefore, riparian forests with differing structure can influence their buffering effect, at least in the rural landscapes studied. Most streams studied had only forest remnants in their headwaters, so at the landscape level remnants with differing forest composition either due to stand age or disturbance history will probably differ in their effect as buffers, and these differences can be as large as those from changes in riparian vegetation. Therefore, management of watersheds for the maintenance of water quality could benefit from forest management practices that promote riparian forest heterogeneity (areas of varying successional stages) to capture the range in forest structure that will affect stream habitat and water quality over and above simple forest cover alone.

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References

Allan, J.D., 2004. Landscapes and riverscapes: the influence of land-use on river ecosystems. Annu. Rev. Ecol. Evol. Syst. 35, 257–284.
Balian, E.V., Naiman, R.J., 2005. Abundance and production of riparian trees in the lowland floodplain of the Queets River, Washington. Ecosystems 8, 841–861.
Beale, C.M., Lennon, J.J., Yearsley, J.M., Brewer, M.J., Elston, D.A., 2010. Regression analysis of spatial data. Ecol. Lett. 13, 246–264.
Boggs, K., Weaver, T., 1994. Changes in vegetation and nutrient pools during riparian succession. Wetlands 14, 98–109.
Castelle, A.J., Johnson, A.W., Conolly, C., 1994. Wetland and stream buffer size requirements – a review. J. Environ. Qual. 23, 878–882.
Chaves, J., Neill, C., Germer, S., Gouveia Neto, S., Krusche, A.V., Castellanos Bonilla, A., Elsenbeer, H., 2009. Nitrogen transformations in flowpaths leading from soils to streams in Amazon forest and pasture. Ecosystems 12, 961–972.
Crockford, R.H., Richardson, D.P., 2000. Partitioning of rainfall into throughfall, stemflow and interception: effect of forest type, ground cover and climate. Hydrol. Process. 14, 2903–2920.
Dosskey, M.G., Vidon, P., Gurwick, N.P., Allan, C.J., Duval, T.P., Lowrance, R., 2010. The role of riparian vegetation in protecting and improving chemical water quality in streams. J. Am. Water Resource As. 48, 261–277.
Ewel, K.C., Cressa, C., Kneib, R.T., Lakes, P.S., Levin, L.A., Palmer, M.A., Snelgrove, P., Wall, D.H., 2001. Managing critical transition zones. Ecosystems 4, 452–460.
Fausch, K.D., Baxter, C.V., Murakami, M., 2010. Multiple stressors in north temperate streams: lessons from linked forest–stream ecosystems in northern Japan. Freshwater Biol. 55, 120–134.
Fortin, M.J., Dale, M., 2005. Spatial Analysis: a Guide for Ecologists. Cambridge University Press, Cambridge.
Hagen, E.M., McTammany, M.E., Webster, J.R., Benfield, E.F., 2010. Shifts in allochthonous input and autochthonous production in streams along an agricultural land-use gradient. Hydrobiologia 655, 61–77.
Harris, R.R., Kocher, S.D., Gerstein, J.M., Olson, C., 2005. Monitoring the Effectiveness of Riparian Vegetation Restoration. University of California, Center for Forestry, Berkeley.
Hermy, M., Verheyen, K., 2007. Legacies of the past in the present-day forest biodiversity: a review of past land-use effects on forest plant species composition and diversity. Ecol. Res. 22, 361–371.
Hoffman, C.C., Kjaergaard, C., Uusi-Kämppä, J., Hansen, H.C.B., Kronvang, B., 2009. Phosphorus retention in riparian buffers: review of their efficiency. J. Environ. Qual. 38, 1942–1955.
Hwang, T., Band, L., Hales, T.C., 2009. Ecosystem processes at the watershed scale: extending optimality theory from plot to catchment. Water Resour. Res. 45, W11425. http://dx.doi.org/10.1029/2009WR007775.
Jones, K.B., Neale, A.C., Nash, M.S., Van Remortel, R.D., Wickham, J.D., Riitters, K.H., O'Neill, R.V., 2001. Predicting nutrient and sediment loadings to streams from landscape metrics: a multiple watershed study from the United States Mid-Atlantic Region. Landscape Ecol. 61, 301–312.
Kelly, J.M., Kovar, J.L., Sokolowsky, R., Moorman, T.B., 2007. Phosphorus uptake during four years by different vegetative cover types in a riparian buffer. Nutr. Cycl. Agroecosys. 78, 239–251.
Koroleff, F., 1976. Determination of Nutrients. In: Grasshoff, K. (Ed.), Methods of Sea Water Analysis. Verlag Chemie, Weinhein, pp. 117–181.
Lees, A.C., Peres, C.A., 2008. Conservation value of remnant riparian forest corridors of varying quality for Amazonian birds and mammals. Conserv. Biol. 22, 439–449.
Likens, G.E., Bormann, F.H., Johnson, N.M., Fisher, D.W., Pierce, R.S., 1970. Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook Watershed-Ecosystem. Ecol. Monogr. 40, 23–47.
Mackereth, F.J.H., Heron, J., Talling, J.F., 1978. Water Analysis: Some Revised Methods for Limnologists. Titus Wilson & Son Ltd., Kendall.
McClain, C.D., Holl, K.D., Wood, D.M., 2010. Successional models as guides for restoration of riparian forest understory. Restor. Ecol. 19, 280–289.
Merritt, D.M., Scott, M.L., Poff, N.L., Auble, G.T., Lytle, D.A., 2010. Theory, methods and tools for determining environmental flows for riparian vegetation: riparian vegetation-flow response guilds. Freshwater Biol. 55, 206–225.
Miranda, M.J., Pinto, H.S., Zullo Júnior, J., Fagundes, R.M., Fonsechi, D.B., Calve, L.,Pellegrino, G.Q., 2012. Clima dos municípios paulistas. CEPAGRI/UNICAMP. Available from: <http://www.cpa.unicamp.br/outras-informacoes/clima-dos-municipios-paulistas.html> (accessed 08.11.12).

Miserendino, M.L., Casaux, R., Archangelsky, M., Di Prinzio, C.Y., Brand, C., Kutschker, A.M., 2011. Assessing land-use effects on water quality, in-stream habitat, riparian ecosystems and biodiversity in Patagonian northwest streams. Sci. Total Environ. 409, 612–624.
Naiman, R.J., Décamps, H., McClain, M.E., 2005. Riparia: Ecology, Conservation, and Management of Streamside Communities. Elsevier, Amsterdam.
Neill, C., Deegan, L.A., Thomas, S.M., Cerri, C.C., 2001. Deforestation for pasture alters nitrogen and phosphorus in small Amazonian streams. Ecol. Appl. 11, 1817–1828.
Nislow, K.H., Lowe, W.H., 2006. Influence of logging history and riparian forest characteristics on macroinvertebrates and brook trout. Freshwater Biol. 51, 388–397.
Osborne, L.L., Kovacic, D.A., 1993. Riparian vegetated buffer strips in water-quality restoration and stream management. Freshwater Biol. 29, 243–258.
Peterjohn, W.T., Correll, D.T., 1984. Nutrient dynamics in an agricultural watershed: observations on the role of a riparian forest. Ecology 65, 1466–1475.
Peterson, B.J., Wollheim, W.M., Mulholland, P.J., Webster, J.R., Meyer, J.L., Tank, J.L., Marti, E., Bowden, W.B., Valett, H.M., Hershey, A.E., McDowell, W.H., Dodds, W.K., Hamilton, S.K., Gregory, S., Morrall, D.D., 2001. Control of nitrogen export from watersheds by headwater streams. Science 292, 86–90.
Peterson, E.E., Merton, A.A., Theobald, D.M., Urquhart, N.S., 2006. Patterns of spatial autocorrelation in stream water chemistry. Environ. Monit. Assess. 121, 571–596.
Post, D.A., Jones, J.A., 2001. Hydrologic regimes of forested, mountainous, headwater basins in New Hampshire, North Carolina, Oregon, and Puerto Rico. Adv. Water Res. 24, 1195–2010.
Quinn, J.M., Cooper, A.B., Davies-Colley, R.J., Rutherford, J.C., Williamson, R.B., 1997. Land use effects on habitat, water quality, periphyton and benthic invertebrates in Waikato, New Zealand. New Zeal. J. Mar. Fresh. 31, 579–597.
Rangel, T.F., Diniz-Filho, A.F., Bini, L.M., 2010. SAM: a comprehensive application for Spatial Analysis in Macroecology. Ecography 33, 46–50.
Roberts, W.M., Stutter, M.I., Haygarth, P.M., 2012. Phosphorus retention and remobilization in vegetated buffer strips: a review. J. Environ. Qual. 41, 389–399.
Schoonover, J.E., Williard, K.W.J., Zaczek, J.J., Mangun, J.C., Carver, A.D., 2005. Nutrient attenuation in agricultural surface runoff by riparian buffer zones in Southern Illinois. USA. Agroforest. Syst. 64, 169–180.
Stewart, J.S., Wang, L., Lyons, J., Horwatich, J.A., Bannerman, R., 2001. Influences of watershed, riparian-corridor, and reach-scale characteristics on aquatic biota in agricultural watersheds. J. Am. Water Resource As. 37, 1475–1487.
Strickland, J.D.H., Parsons, T.R., 1960. A manual of seawater analysis. Bull. Fish. Res. Bd Can. 125, 1–185.
Tabacchi, E., Correll, D.L., Hauer, R., Pinay, G., Planty-Tabacchi, A.M., Wissmar, R.C., 1998. Development, maintenance and role of riparian vegetation in the river landscape. Freshwater Biol. 40, 497–516.
Tabacchi, E., Lambs, L., Guilloy, H., Planty-Tabacchi, A.M., Muller, E., Décamps, H., 2000. Impacts of riparian vegetation on hydrological processes. Hydrol. Process. 14, 2959–2976.
Tundisi, J.G., Matsumura-Tundisi, T., Pareschi, D.C., Luzia, A.P., Von Haeling, P.H., Frollini, E.H., 2008. A bacia hidrográfica do Tietê/Jacaré: estudo de caso em pesquisa e gerenciamento. Estudos Avançados 22, 159–172.
Welle, P.I., Woodward, D., 1986. Time of concentration. Hydrology Technical Note No. N4, USDA, Soil Conservation Service, Pennsylvania.