Journal of Environmental Management 286 (2021) 112132

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: http://www.elsevier.com/locate/jenvman

Riparian buffer length is more influential than width on river water quality: A case study in southern Costa Rica

Brumberg Hilary [a,b,*], Beirne Chris [c], Broadbent Eben North [d], Almeyda Zambrano Angelica Maria [d], Almeyda Zambrano Sandra Lucia [d], Quispe Gil Carlos Alberto [d], Lopez Gutierrez Beatriz [d], Eplee Rachael [e], Whitworth Andrew [a,f]

[a] Osa Conservation, Puerto Jiménez, Golfito, Puntarenas, Costa Rica
[b] Princeton in Latin America, Princeton University, Louis A. Simpson International Building, Princeton, NJ, 08544, USA
[c] Department of Forest Resources Management, University of British Columbia, Vancouver, Canada
[d] Spatial Ecology and Conservation (SPEC) Lab, University of Florida, Gainesville, FL, 32611, USA
[e] Columbia University, School of International and Public Affairs, 420 West 118th Street, New York, NY, 10027, USA
[f] Institute of Biodiversity, Animal Health and Comparative Medicine, College of Medical, Veterinary and Life Sciences, University of Glasgow, Glasgow, Scotland, UK

A R T I C L E I N F O

Keywords:
Riparian buffer
Water quality
Watershed management
River conservation
Land use planning
Neotropics

A B S T R A C T

Riparian zones are one of the most productive ecosystems in the world, but are at risk due to agricultural expansion and climate change. To maximize return on conservation investment in mixed-use landscapes, it is important to identify the minimum intact riparian forest buffer sizes to conserve riparian ecosystem services. The minimum riparian forest buffer width necessary to maintain tropical river water quality remains unclear, and there is little analysis of effective riparian buffer lengths. Also, in studies on the effect of land use on river water quality globally, there is little standardization in the area where land use is analyzed. Here, these challenges were addressed in the Osa Peninsula in southwestern Costa Rica. Water quality parameters and social variables were sampled at 194 locations across the region. For each sample, land use was calculated in nine different riparian buffer sizes and at the sampling location. Riparian forest cover had a positive effect on water quality parameters, while agricultural cover had a negative effect. The longer the length of the buffer considered, the greater the relative support for influencing water quality (1000 m > 500 m > 100 m). All buffer widths yielded similar support within each length class. These results indicate that length of riparian forest buffers, not width, drives their ability to conserve water quality. While wide and long riparian forests are ideal to maximize the protection of river water quality and other ecosystem services, in landscapes where that is impractical, the 15-m-wide riparian forest buffers that are supported by Costa Rican legislation could improve water quality, providing that they are at least 500 m long. The results also indicate the importance of methodological standardization in studies that monitor land use effects on water quality. The authors propose that studies in similar regions analyze land use in riparian zones 15-m-wide by 1000 m upstream. Conserving and restoring narrow, long riparian forest buffers could provide a rapid, economical management approach to balance agricultural production and water quality protection.

1. Introduction

Riparian zones are one of the most productive ecosystems in the world, but are also among the most threatened (Capon et al., 2013; Tockner and Stanford, 2002). Pressures on rivers and riparian zones are expected to increase in the coming decades due to human population growth, land use change, and climate change; heightening the importance of strategic riparian management (Capon et al., 2013; Martínez-Fernández et al., 2018; Mello et al., 2017). Riparian forests are ecologically important because they harbor a higher richness of plants and wildlife compared to non-riparian forests, moderate fluctuations in water temperature, and can serve as altitudinal climate-adaptive biological corridors (Luke et al., 2018; Mello et al., 2017). These forests also protect river water quality and aquatic wildlife by serving as buffer

* Corresponding author. Osa Conservation, Puerto Jiménez, Golfito, Puntarenas, Costa Rica.
E-mail address: hbrumberg@wesleyan.edu (B. Hilary).

https://doi.org/10.1016/j.jenvman.2021.112132
Received 29 April 2020; Received in revised form 23 December 2020; Accepted 3 February 2021
Available online 20 February 2021

zones from degradative anthropogenic practices, including erosion from deforestation and harmful agricultural and industrial pollutants (Aguiar et al., 2015; Luke et al., 2018). High water quality is critical to support sensitive freshwater aquatic wildlife and downstream marine ecosystems, as well as the local communities that depend on rivers for drinking water and recreation.

The pressures on riparian zones are heightened in the tropics, a region which hosts the majority of the world's most threatened ecosystems (Bradshaw et al., 2009). Tropical forests comprise the most diverse terrestrial biome on Earth; consequently, tropical riparian forests and rivers harbor more biodiversity than their temperate counterparts (Boulton et al., 2008; Bradshaw et al., 2009). However, the vast majority of tropical countries are characterized as developing economies and rely heavily on agriculture and natural resource extraction (Sachs, 2001; Tockner and Stanford, 2002). Over the last century, migration to remote regions for economic opportunity has concentrated farming communities near critical waterways, exacerbating deforestation and exposing freshwater systems to exploitation and contamination. Moreover, many rural communities in less developed regions of the tropics depend on river resources for drinking, cooking, bathing, and agriculture, especially indigenous groups (Laurance, 1999; Rhoades, 2016). Despite their critical importance, tropical riparian forests and tropical rivers remain understudied in comparison to their temperate counterparts (Luke et al., 2018).

One potential solution that balances riparian forest functioning with human land use needs is to focus riparian forest conservation on the minimum effective buffer zone sizes needed to protect forest ecosystem functioning. However, while there are many scientific studies on minimum riparian zone widths, there is little consensus. Various reviews and meta-analyses have compared studies in mostly temperate ecosystems and suggest different buffer sizes, with widths ranging from five to 500 m (Lee et al., 2004; Lind et al., 2019; Luke et al., 2018). The lack of consensus on the minimum recommended riparian zone widths could be attributed to variability between regions, sampling methodologies, socio-economic factors, or the specific riparian function that is being measured (e.g. water quality, terrestrial wildlife, aquatic wildlife, bank stabilization, leaflitter input, etc.). Even among studies focusing on a single riparian function in a region, there is a great deal of variability (Luke et al., 2018). For example, literature addressing riparian buffer sizes to protect river water quality parameters in the Neotropics suggest minimum widths ranging from 5 to 90 m, and even entire exclusive contribution areas (Appendix A).

Literature that analyzes minimum riparian buffer sizes to conserve river water quality has focused on buffer width and largely ignored assessments of buffer length (Stanford et al., 2019). A short patch of riparian forest, no matter how wide, is unlikely to reverse the contamination from large stretches of degradation upstream. Thus, it is important to determine the minimum upstream length that riparian buffers that should be conserved in order to protect water quality in mixed-use landscapes. In one of the few studies on this topic, Stanford et al. (2019) showed that the length of riparian corridors affected benthic macroinvertebrate communities and river physiochemistry in northern California. They suggested that conserving and restoring long yet narrow riparian corridors may be a cost-efficient and rapid approach to reduce aquatic stressors given land use constraints.

There is little research on riparian buffer length in the Neotropics, and even less consensus on effective lengths to protect water quality (Luke et al., 2018; Stanford et al., 2019). Of the 10 papers identified in the literature review on Neotropical riparian buffer size impact on water quality (listed in Appendix A), only three studies analyzed various lengths, with conflicting results de Jesús-Crespo and Ramírez (2011) recommend a minimum length of 1000 m, Iñiguez-Armijos et al. (2014) recommend continuous riparian buffers for the entire stream length, while de Oliveira et al. (2016) recommend continuous riparian buffers for the entire contribution area. Three papers analyzed a single buffer length: 400 m in Moraes et al. (2014); entire catchment in Monteiro et al. (2016); exclusive contribution area in Maillard and Santos (2008). Four studies analyzed buffer widths but did not specify lengths (Braun et al., 2018; Little et al., 2015; Lorion and Kennedy, 2009; Valle et al., 2013).

Another reason for the lack of consensus regarding minimum recommended buffer sizes likely relates to a lack of standardization in the methodology used to determine the effects of riparian land use on river water quality. For example, some studies analyzing water quality consider the land use directly adjacent to the sampling point (ex. Quinn et al., 1997; Ngoye and Machiwa 2004). Other studies consider land use in riparian buffers of various widths and distances upstream, portions of basins, or the entire basin (ex. Li et al., 2008; Kibena et al., 2014). The land use proximity analyzed could influence the strength of its effect on water quality. For example, Tran et al. (2010) Statefound no significant correlation between water quality indicators and land cover type at the watershed zone of influence but did find a correlation at the 200-m proximity in their study in New York. The different proximities in which land use is considered also creates difficulties in effectively comparing results between studies.

Policy can be a valuable tool to protect rivers and riparian forests. However, in tropical countries, these policies are often absent or vague, making them hard to enforce. Existing policies are often not based on scientific evidence from the specific region (Luke et al., 2018; Meli et al., 2019). These gaps could be due to the lack of research in the region to provide data for evidence-based policies. This study was carried out in Costa Rica, whose Forestry Law No. 7575 of 1996 created the pioneering Payment for Ecosystem Services program in Latin America and established riparian buffers as protected areas. By these laws, it is illegal to deforest 15 m on either side of rivers in rural areas, yet this is not instated in is not instatem many areas. There is no mention of a minimum length requirement, and questions remain as to whether 15 m is sufficiently wide to protect water quality. Moreover, enforcement is limited, leaving remnant riparian forest patches of all sizes throughout the country (Lorion and Kennedy, 2009). Riparian buffer protection is especially important in Costa Rica, because the country has one of the highest intensities of pesticide use in the world, and only four percent of its total water waste is managed, causing runoff sewage water, chemicals, toxic materials, and heavy metals to enter waterways (Soto, 2013; Willis, 2016).

This study was carried out in the Osa Peninsula, which is in one of the most biodiversity rich yet socioeconomically disadvantaged regions of Costa Rica (Ministerio de Planificación Nacional y Política Económica, 2017). The local economy relies mainly on tourism and primary industries, including cattle ranching and oil palm plantations. Furthermore, rural communities depend on freshwater from its abundant rivers and streams as their principal source for household water needs. This study aims to tackle 4 main questions: 1) What is the most efficient riparian buffer width to conserve water quality given landscape constraints inherent to agricultural areas? 2) Does the length of riparian buffers affect their ability to conserve water quality? 3) Does the sampling methodology affect the results of analysis of land use impacts on river water quality, and what is the most effective proximity of land use to the sampling point to analyze? 4) Does the recently implemented Osa Biological Corridor protect stream reaches with high water quality? Finally, the authors discuss how these results can be applied in context to inform management decisions globally, including policy for protecting riparian buffers of appropriate sizes and guiding riparian restoration to improve water quality.

2. Materials and methods

2.1. Study area

This study was carried out in the Osa Peninsula on the south Pacific slope of Costa Rica. This area covers approximately 4200 km^2, representing 8.6% of the entire Costa Rican land territory. The region includes

Corcovado National Park, Piedras Blancas National Parks, the International Ramsar Site Térraba-Sierpe National Wetlands, Alto Laguna indigenous reserve, several wildlife refuges, and a mosaic of privately-owned protected areas forming the Golfo Dulce Forest Reserve. The Golfo Dulce Forest Reserve and the recently implemented Osa Biological Corridor connect and buffer the national parks. Agriculture in the region is dominated by grassland, oil palm, plantations, rice, and bananas.

Mean annual temperatures range from 24.5 °C to 26.5 °C, and rainfall ranges from 3000 to 7000 mm (Taylor et al., 2015). Rainfall intensifies from August to early December and diminishes from late December to April. Temperature, rainfall, and relative humidity variations from lower to higher elevations have enabled the development of different zones comprising lowland tropical humid forest, pluvial pre-montane forest, lowland pluvial montane forest, and one of the largest mangrove forests on the Central American Pacific coast. Climatological and geographical conditions within the region have given rise to large aquifers and multiple watershed basins and micro-basins.

2.2. Field data collection and water chemistry analysis

River physiochemistry was analyzed at 194 points across 41 watersheds in the region (Fig. 1). The number of samples collected per watershed was scaled based on the size of the watershed, such that the largest watersheds in the region had the most samples (>10 points each). The sites were stratified across the entire study region using high-resolution satellite imagery from Google Earth to identify portions of the streams that varied widely in land use and were accessible by a team using a 4 × 4 vehicle.

At all 194 points, a Hanna HI9828 Multiparameter was used to analyze water temperature, DO, ORP, DO%, conductivity, specific conductivity, salinity, sigma t, and pH, from May 15 to June 11, 2014. A subset of sites was selected for analysis of nitrite (n = 125), ammonia (n = 99), and phosphate (n = 71). This subset was also stratified to be spatially distributed across the study area, to encompass a wide variety of land cover. At these sites, nitrite (Hanna high range nitrite colorimeter and Hanna saltwater aquarium ultra-low range nitrite colorimeter), ammonium (Hanna high range ammonia colorimeter), phosphate (Hanna high range phosphate colorimeter and Hanna low range phosphate colorimeter), and phosphorous (Hanna high range phosphorus colorimeter) were analyzed.

2.3. Land use classification & spatial analysis

High-resolution maps (5 × 5 meters) of land cover classification in the Osa Peninsula were created using 46 individual RapidEye satellite images in stacks of 5–9 to remove clouds from the study regions (Broadbent et al., 2012), and the land classifications were ground-truthed in the field (http://inogo.stanford.edu). The validation error matrix of the classification results is described on inogo. info and shows high accuracy land cover detections for all relevant land covers used in this study. The land use classifications were simplified into three focal land use categories: native forest (old growth or secondary), agriculture, or other (Fig. 1).

Land use at three riparian buffer widths (15, 50, and 100 m) and three riparian buffer lengths (100, 500, and 1000 m) was extracted, selected based on Costa Rican legislation and previous studies (Allan, 2004; de Jesús-Crespo and Ramírez, 2011; Iñiguez-Armijos et al., 2014; Valle et al., 2013). Riparian buffers of 15, 50, and 100 m on either side of each stream were digitized using the MultiRing rivers buffer tool in QGIS. At each sampling point, polygons were manually drawn ending 100, 500, and 1000 m upstream, following the path of the stream. These 3 upstream polygons were clipped to the three different buffer widths. Then, for each sampling location, land use was extracted in nine upstream buffer sizes: 15 m wide by 100 m upstream, 50 by 100, 100 by 100, 15 by 100–500, 50 by 100–500, 100 by 100–500, 15 by 500–1000, 50 by 500–1000, and 100 by 500–1000 (see Fig. 1). Additionally, the land use at the specific sampling point was extracted. Pivot tables were used to combine the land use data in the segments to generate the land use 0–500 m upstream and 0–1000 m upstream, and then calculate percentage of each of the three land use classifications in each of the nine buffer sizes for each sampling point.

In addition to the broad land use types (forest and agriculture), the dominant agricultural crop within the best supported buffer length and width was calculated (described in 2.4). Dominant crop type was defined as the crop which constituted the highest percentage coverage in each buffer configuration (available crops: grassland, oil palm, rice,

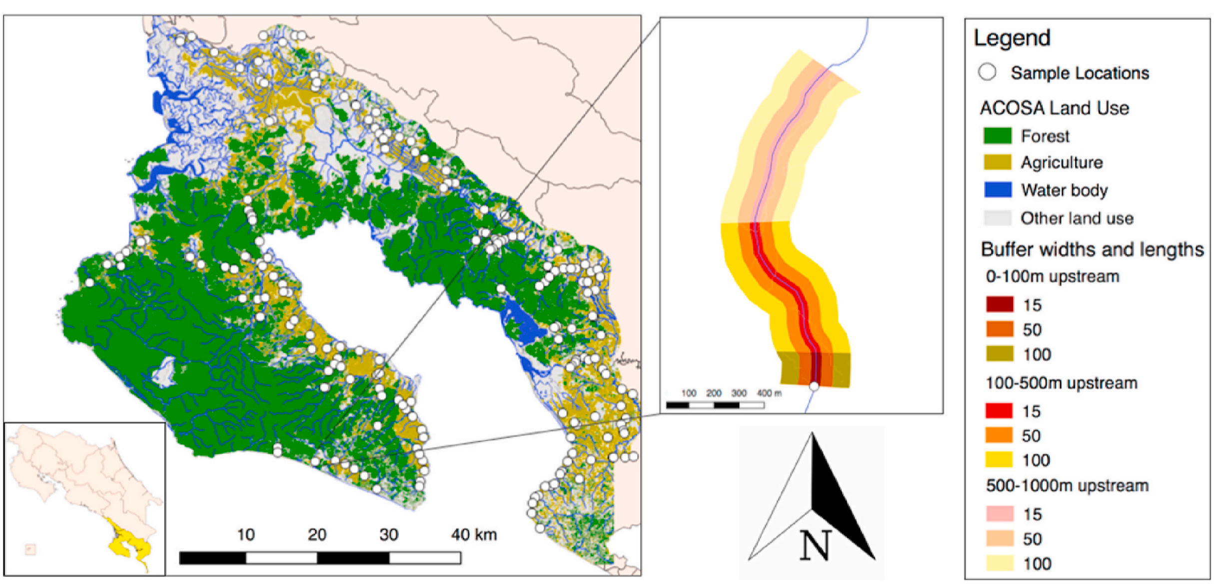

Fig. 1. Bottom left: Osa Peninsula within Costa Rica highlighted in yellow. Left: Location of sampling points and focal land uses in the region. Dark green indicates native forest (e.g. old growth & secondary), light green indicates agriculture (e.g. cattle pasture, oil palm plantation), blue indicates inland water body, and grey indicates other land uses (e.g. urbanization, mangrove, wetland). Right: Zoomed in subset giving an example illustration of the 9 riparian buffer sizes analyzed for each site in this paper. The white dot is the sampling point. Red indicates 15 m on either side of each river, orange is 50-m-wide buffers, and yellow is 100-m-wide buffers. The darkest shades represent 0–100 m upstream of sampling points, the brightest shades represent 100–500 m upstream, and the lightest shades represent 500–1000 m upstream. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

banana, or tree plantation). A suite of environmental and societal variables was extracted for each survey location: rock type, biological corridor, protected area, and river category. Euclidean distance from each sampling point to the nearest road and the nearest population was calculated. Distance from each sampling point to the river source was calculated along the length of the river. Elevation was extracted from a DEM of the study location.

2.4. Statistical analysis

The analysis of the factors influencing water quality involved two response term types: a single water quality factor and individual water quality parameters. Given that this study aims make general recommendations on how to improve water quality within the focal region and water quality parameters are often non-independent, a simplified Water Quality Factor (WQF) was derived using a principal component analysis (PCA) in order to compress all of the water quality parameters into a principle axis of variation using the full 194 point dataset. The water parameters included water temperature, pH, dissolved oxygen, and conductivity, factors which were measured at all sites. The percentage variation explained by the WQF was 43% (Fig. 2). Repeating the PCA on a reduced dataset including nitrite, ammonia, and phosphate, which were measured at a subset of sites, yielded similar results (Appendix B). Each individual water quality parameter was analyzed in turn. This included all of the factors included in the original PCA, plus nitrite, ammonia, and phosphate.

The data analysis occurred in two steps: i) determining the most influential riparian buffer configuration, and ii) determining the factors in addition to buffer size that influence water quality. Each step is addressed below:

2.4.1. Determining the most influential riparian buffer configuration

The buffer configuration from those outlined above which best explained variation in the Water Quality Factor was determined, resulting in eleven competing models: a null model with no land use information; a point model with the land use at the sampling location; three models with a 15-m-wide buffer and lengths of 100 m, 500 m, and 1000 m; three models with a 50-m-wide buffer and lengths of 100 m, 500 m, and 1000 m; and three models with a 100-m-wide buffer and lengths of 100 m, 500 m, and 1000 m (Appendix D). For the buffer models, both the proportion of forest in the buffer region and the proportion of agricultural land were included as covariates. Each model contained watershed identity (to account for non-independence of samples from the same watershed) and hour of the day (to account for diel variation in water quality parameters) as random intercept terms, using a mixed modeling approach with the lme4 package (Bates et al., 2014) in the R statistical environment (R Core Team, 2013). To select between competing models, the information theoretic approach to model selection was adopted (Burnham and Anderson, 2002). Models were ranked based on their Akaike Information Criterion corrected for small sample size (AICc) and a “top model set” was defined using a conservative cut-off of $\Delta AICc \leq 6$ from the best-supported model

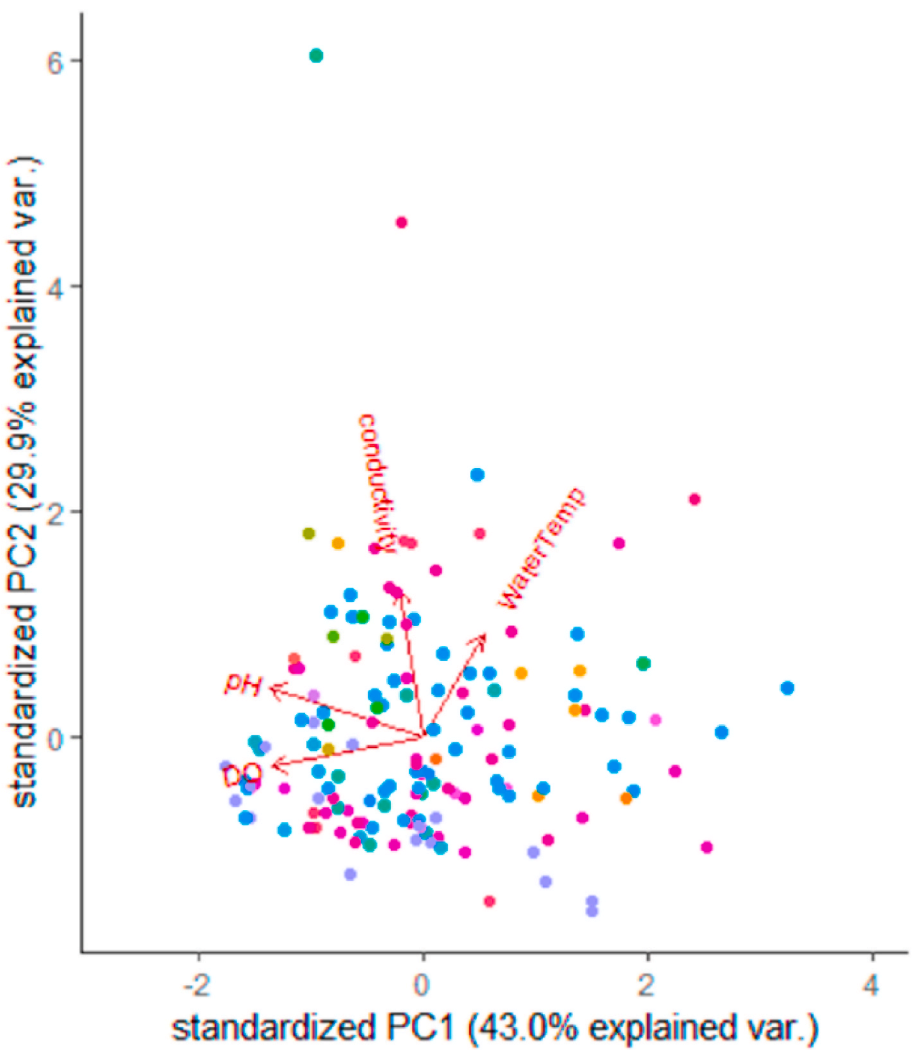

Fig. 2. Plot of the first and second factors in the PCA conducted to compress all water quality parameters into a single access of variation in order to make general recommendations about water quality management in the focal area. The first factor (PC1) was used to create the Water Quality Factor (WQF). Points are sampling locations, and colors are watershed identity. Arrows show the direction in which each variable loads onto Factor 1 and Factor 2. For color codes, see Appendix C. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

(Richards et al., 2011). Goodness of fit was determined through standard residual plots and calculation of the conditional R^2 formulation (Nakagawa and Schielzeth, 2013).

2.4.2. Covariates influencing water quality

Using the best-supported riparian buffer configuration defined in step one, the relative support for the additional covariates thought to influence water quality was explored. For each response term (water quality factor, water temperature, pH, dissolved oxygen, conductivity, nitrite, phosphorus, and ammonia), models containing all combinations of road distance, town distance, whether the location resides within a biological corridor, river category, distance to river source, dominant crop type, elevation, and rock type were ranked by their AICc. Each model contained watershed identity and hour of the day as random intercept terms. The effect size of each covariate is presented only if they are included in the best-supported model for each response term. Model fit was assessed using standard residual approaches. The conductivity response term was log-transformed to ensure normality; ammonia and phosphates were modeled using a negative binomial distribution to accommodate over-dispersion. The variance explained by the best-supported model was explained using the R^2 formulation for mixed models by Nakagawa and Schielzeth (2013).

3. Results

3.1. Determining efficient riparian buffer sizes

The results provide strong evidence to suggest that land use in the buffer regions surrounding the sampling locations influenced the WQF. The longer the length of buffer considered, the greater the relative support for influencing WQF (1000 m > 500 m > 100 m; Table 1). The relative strength of support was less sensitive to buffer width, with all widths yielding similar support within each length class (Table 1). That said, the 15 m width was the best supported for both the 1000 m and 500 m riparian buffer lengths. The best-supported model (1000 m long, 15 m wide) explained 28.8% of the variation in the WQF.

Increasing the percentage of agriculture within the riparian zone had a consistently negative effect on WQF across the buffer configuration classes (Fig. 3A; Table 1). Increasing forest cover had a positive effect on WQF (Fig. 3B; Table 1). However, the relative effect size of agriculture was ~8 times larger than that of forest cover (Table 1), suggesting the presence of agriculture has a stronger effect on the WQF than the presence of forest.

3.2. Covariates influencing water quality parameters

When considering the WQF, the only other covariates that strongly affected water quality was whether the sampling point was located within the biological corridor and rock type. Points located within corridors had higher WQF scores than those located outside corridors. Rocks defined as compact had a higher estimated WQF (1.42), than hard, unconsolidated, and soft rock types (−0.11, −0.19, and 0.05, respectively). Road distance, town distance, river category, elevation, dominant crop type, and distance to source were not found to consistently influence the WQF (Table 2).

Assessing the water quality parameters that comprise the WQF individually yielded varying correlations to different social and ecological covariates (Table 2). The pH was negatively affected by the percent of agricultural land cover in the riparian strip and positively affected by its location within the biological corridor. Rock type affected pH; survey locations with rocks defined as compact had an estimated pH of 8.55, hard had a pH of 7.79, unconsolidated had a pH of 7.76, and soft had a pH of 7.88. Water conductivity was strongly negatively correlated with road distance and elevation. Dominant crop type affected water conductivity. The support for crop type in the conductivity model is due to conductivity around rice fields and oil palm increasing. Conductivity was also affected by mean road distance, elevation, and sampling location rock type; estimated conductivity for compact rocks is 5.88, hard 5.29, unconsolidated 5.48, and soft 5.75. Dissolved oxygen was negatively correlated with increasing agricultural land use in the buffer zone and higher within biological corridors. Water temperature was negatively correlated with the percentage of forest cover in the riparian buffer zone, road distance, and elevation. It was lower within biological corridors, while it was positively affected by town distance. The support for dominant crop type in the water temperature model is due to increased water temperature where oil palm is the dominant crop type. Nitrite levels were associated with the river category and negatively correlated with distance from river source. Ammonia and phosphates were not predicted to be affected by any of the covariates assessed (Table 2).

Table 1
Model selection output for riparian zone length and width. Numbers in the Riparian Zones column indicate the length (L) and width (W) of riparian zones considered in the analysis. Agriculture is the β-coefficient for the effect of the percent of agriculture land cover within each riparian zone, and Forest is the β-coefficient for the effect of the percent of forest cover within each riparian zone. Point (✓) is the land use at the exact point of sampling. Degrees of freedom are represented by df. AICc is Akaike's information criterion corrected for small sample size, and ΔAICc is the deviation in AICc from the best-supported model. The model weight is indicated in the Wt column, and AWt indicates the adjusted model weight after removal of the model outside of the top model set. The top models are selected in grey shading, and the best-supported model is bold. See Appendix D for model structure, and Fig. 3 for the effect size and direction of model coefficients.

Riparian Zone	Agriculture	Forest	Point	Intercept	df	AICc	ΔAICc	*Wt*	*AWt*
1000L 15W	**-0.366**	**0.047**	**-**	**0.022**	**6**	**514.9**	**0.00**	**0.53**	**0.56**
1000L 50W	-0.339	0.071	-	0.024	6	515.9	1.02	0.32	0.34
1000L 100W	-0.300	0.084	-	0.028	6	518.2	3.32	0.10	0.11
500L 15W	-0.279	0.027	-	0.034	6	521.4	6.53	0.02	0.08
500L 50W	-0.239	0.070	-	0.035	6	522.2	7.33	0.01	0.07
500L 100W	-0.229	0.074	-	0.037	6	522.6	7.68	0.01	0.05
Null	-	-	-	0.062	4	525.8	10.94	0.00	0.00
Point	-	-	✔	0.160	5	526.5	11.66	0.00	0.00
100L 100W	-0.111	0.020	-	0.059	6	528.6	13.77	0.00	0.00
100L 15W	-0.089	-0.001	-	0.062	6	529.3	14.46	0.00	0.00
100L 50W	-0.050	0.042	-	0.057	6	529.5	14.61	0.00	0.00

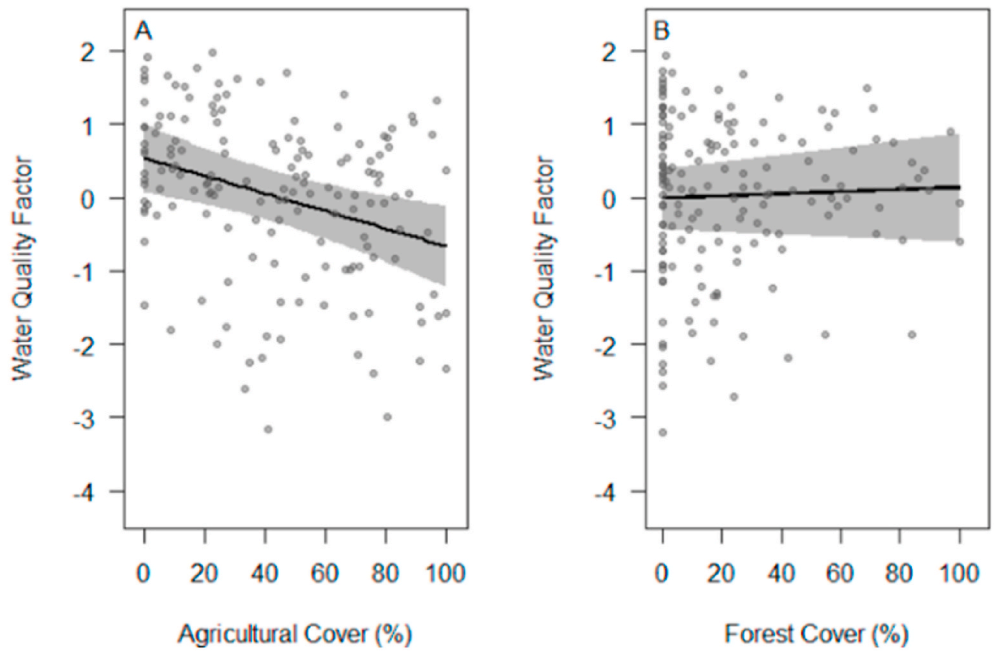

Fig. 3. Model predictions and 95% confidence intervals for the effect of agriculture (3A) and forest cover (3B) in riparian zones on the WQF. Black lines are model predictions, and grey polygons are 95% model predictions for the fixed effects. Grey points are partial residuals from the best-supported riparian zone size model (1000 m long and 15 m wide).

Table 2
Table showing the β-coefficients from the best-supported covariate model (1000 m long and 15 m wide) for the WQF and individual water quality parameters. Cond is conductivity, DO is dissolved oxygen, Temp is temperature, Amm is ammonia, and Phos is phosphate. R^2 is the variation explained by the model, including fixed and random effects. Int is the intercept. For is the β-coefficient for the effect of the percent of forest cover within each riparian strip, and Ag is the β-coefficient for the effect of the percent of agricultural cover within each riparian strip. Road dist and Town dist are the β-coefficients for the distance from the sampling point to the nearest road or town, respectively. Cor is the β-coefficient for a point being inside versus outside the Osa Biological Corridor. Riv cat is the β-coefficient for the river category (intermittent versus permanent). Elev is the β-coefficient for the elevation of the sampling point. RT is rock type. Sou dist is the distance of the sampling point from the river source. Crop is support for dominant crop type. Model validity was checked using standard residual approaches. The conductivity response term was log-transformed to ensure normality. Ammonia and phosphates were modeled using a negative binomial distribution to accommodate overdispersion. ✓'s denote multi-level factors.

Variable	R^2	Int	For	Ag	Road dist	Town dist	Cor	Riv cat	Elev	RT	Sou dist	Crop
WQF	33.4	1.42	0.039	−0.244			0.564			✓		
pH	18.4	8.55		−0.091			0.158			✓		
Cond	0.64	5.90			−0.123				−0.074	✓		✓
DO	28.7	5.77		−0.446			1.300					
Temp	60.1	27.28	−0.299		−0.196	0.203	−0.482		−0.459			✓
Nitrite	60.2	5.02						0.711			−1.174	
Amm	90.3	−1.57										
Phos	19.3	0.42										

4. Discussion

This study indicates that land use in wider riparian buffers does not have significantly larger effects on water quality than narrower buffers, and that the most efficient riparian forest buffer width to maintain water quality while maximizing agricultural land is 15 m. The findings suggest that the length of riparian forest buffers is important to maintain water quality because riparian land use has a strong effect on water quality for at least 1 km downstream. Additionally, the results indicate that surveys linking land use immediately around sampling points to water quality potentially fail to shed light on the effects of upstream land use. The recently designated Osa Biological Corridor protects stream reaches with higher water quality than those outside of the corridor. Below is a discussion of each of these results in detail and how they can be applied in context to inform management decisions.

4.1. Efficient riparian buffer widths

Forest cover in the 15 m directly adjacent to the river performed comparably—and in some cases better—at protecting river water quality as wider buffers, a result found in other Neotropical watersheds (Appendix 1; Lorion and Kennedy 2009; Moraes et al., 2014). The results indicate that conservation of the 15-m-wide riparian forest buffers protected under Costa Rican Forestry law positively impacts water quality. Narrow, continuous buffers may provide the largest return on conservation investment and maximize area for agricultural production (Luke et al., 2018; Stanford et al., 2019). Local landowners, many of whom depend on agriculture as their primary sources of income, may be more likely to conserve narrow riparian zones than wider areas if they consider it a small sacrifice while receiving a myriad of benefits; including prevention of erosion and flooding, water quality conservation, and shade. More economic analyses are needed to assess the economic benefits of these relatively small land trade-offs. These analyses could compare ecosystem service benefits and avoided costs with the opportunity cost of another land use and the cost of riparian restoration.

It is important to note that while narrow riparian forest buffers might serve well to protect water quality, in riparian management that aims to prioritize terrestrial wildlife conservation, 15 m may not be enough. For example, Amaral Pereira et al. (2019) recommend riparian zones of ≥120 m to conserve Amazonian bat communities, and Lees and Peres

(2008) recommend ≥200 m to conserve Amazonian birds and mammals. As Osa's lowland tropical forests host somewhat similar terrestrial wildlife communities to Amazonia, it is likely that similar buffer sizes might be required to conserve wildlife in the region. Wider buffers might be needed in key areas where land managers want to establish riparian corridors that support the movement of wildlife between protected areas.

4.2. Riparian buffer length influences more than width

Results indicate that upstream land use influences water quality. Riparian land use may affect river water quality for long distances downstream, and thus long riparian buffers can improve water quality even if they are narrow. The length of the riparian zone considered influenced the WQF more than the width, as demonstrated by the AIC values in Table 1. Models considering land use just at the sampling point or 100 m upstream did not improve the null model even if they were wide (Table 1), indicating that land use short distances upstream has no detectable impact at the water quality at the sampling point. The conservation of the integrity of tropical riparian forests for at least a kilometer upstream provides higher water quality to local communities and coastal ecosystems, a result also found in Puerto Rico's Rio Piedras Watershed (de Jesús-Crespo and Ramírez, 2011). Studies of riparian restoration indicate that the length of restored portion of river affects the ability of the restoration initiative to improve ecosystem quality (Belletti et al., 2018). Restoration and conservation of short, isolated patches of riparian forest are not likely to improve water quality, even if they are wide. The conservation of continuous riparian forest corridors can also increase connectivity, facilitating the movement of terrestrial and aquatic wildlife, genetic exchange, pollination, seed dispersal, and other ecosystem services (Amaral Pereira et al., 2019; Bentrup et al., 2012; Iñiguez-Armijos et al., 2014; Stanford et al., 2019).

Implementing continuous riparian corridors will require strategic, coordinated efforts between landowners and governmental support. Both top-down and bottom-up management practices are necessary, especially in rural areas like the Osa Peninsula (Meli et al., 2019). Community management of water resources empowers local stakeholders to create watershed master plans, while government infrastructure, such as forestry laws and payment for ecosystem services programs, provide a legal framework. Costa Rica already has substantial infrastructure for river conservation. The country has a network of local associations that administer aqueduct systems, called ASADAS (Administrative Associations for Aqueduct and Sewers, by Spanish acronym). Over 2000 of these non-profit ASADAS independently manage community water resources across the country. ASADAS are natural platforms to implement a watershed-scale master plan, because rural landowners are more likely to conserve their riparian zones if local stakeholders create a normative climate for riparian buffer management (Fielding et al., 2005). Costa Rica's top-down river conservation framework includes the Forestry Law, which renders deforestation in 15-m-wide riparian buffer zones in rural areas illegal. This is a promising start, but this law does not require landowners to reforest already degraded riparian strips, and enforcement is difficult in this rural, mountainous region. Costa Rica's Payment for Ecosystem Services (PES) program provides financial incentives to landowners to protect and restore forest, but there is no legal mandate. Moreover, the payments are too low to be economically viable in most cases (Ortiz, 2004). Future PES schemes and legislation could further protect water quality in a competing landscape by providing additional financial incentives for continuity of riparian forests, thus encouraging neighboring farms to collaborate in restoration and conservation initiatives to optimize downstream water quality benefits.

4.3. Standardization in methodology

Given the natural flow of the river, water quality at a sampling point is not solely dependent on adjacent riparian land use; rather it is affected by upstream land use as well. Future studies on the effects of land use on water quality in similar ecosystems should standardize their methodologies and analyze at least 1 km upstream and 15 m wide. The models including riparian land use at the exact sampling point or just 100 m upstream did not improve upon the null model (Table 1). If this study had only considered immediate land use around the sampling point, as many studies have done previously (ex. Quinn et al., 1997; Ngoye and Machiwa 2004), these results would have indicated that land use has little to no influence on water quality parameters. Methodological standardization will provide comparable results, allowing more conclusive interpretations and accurate comparisons between studies.

The negative effects of agriculture on river water quality were eight times stronger than the positive effect of forest cover. This suggests that upstream agriculture could have a negative effect on downstream water quality, even when downstream riparian zones are forested (Fig. 3). Riparian agriculture is correlated with lower dissolved oxygen content and more acidic pH. Conductivity increased where oil palm and rice were the dominant crop types, and water temperature increased when oil palm was the dominant crop type, likely due to the decrease in erosion control and shade from these agricultural land uses (Table 2). These changes in water physiochemistry make the river less hospitable for wildlife and water less safe for human consumption (Fondriest Environmental, 2020). These results highlight the importance of avoiding even small patches of agriculture in riparian zones. Future studies on the effects of riparian land use on river water quality should therefore analyze riparian agriculture, not just forest cover.

4.4. Biological corridor and other social and geographic parameters

In the designation of future biological corridors and protected areas, it could be important to take a baseline of water quality data, to ensure that key watersheds are protected and that ongoing monitoring can detect potential improvements or degradation. Sampling points located within the newly-designated Osa Biological Corridor tended to have higher WQF than points outside of the corridor, with higher dissolved oxygen and pH and lower water temperatures, trends that enable these rivers to sustain aquatic life (Table 2; Fondriest Environmental, 2020). The Osa Biological Corridor is well-placed to conserve rivers of high water quality if managed and enforced well to keep agriculture from encroaching. These results can be applied to further increase connectivity between intact forest patches, such as national parks.

Distance to roads and towns, elevation, bedrock type, distance from source, and river category all affect at least one water chemistry parameter. Water samples collected close to roads had significantly higher conductivity and water temperature than sampling points far from roads, likely due to the increase in sediment and minerals that enter the water column due to car passages and the lack of shade due to deforestation around roads. Points close to towns had lower water temperatures than farther from towns. This could be because communities in the small rural towns in the region maintain some vegetation around streams to protect water quality, prevent erosion, beautify the area, and attract wildlife for tourism, while in large agricultural fields farther from towns, streams are more likely to be entirely deforested. The higher the elevation of the sampling point, the lower the water temperature and conductivity. This is likely because the riparian zones tend to be more intact at higher elevations, with more trees providing shade and preventing erosion. Bedrock type affected pH and conductivity, two parameters which have been found to be affected by geology in previous studies (Nelson et al., 2011).

4.5. Study limitations

While this study focused on a rapid survey of the effects of riparian land use on river water quality, future studies could analyze additional buffer sizes and other corridor aspects, including channel morphology, bank material, soil drainage, and flow types, following a standardized protocol (Burdon et al., 2020; Parsons et al., 2002; Raven et al., 1998). Future studies could analyze the effectivity of narrow, continuous riparian buffers of preventing pesticide runoff into streams. This is particularly important in Costa Rica since the country has one of the highest intensities of pesticide use in the world, much of which runs into water bodies (Willis, 2016). Biological indicators of water quality may be used in future studies to support the findings (Lorion and Kennedy, 2009; Stanford et al., 2019). Finally, it is important to note that sampling in this study only occurred in a single season, so annual and seasonal variations were not considered. Seasonal variation is expected to be limited however, as water quality in the region tends to be consistent seasonally (Calvo-Brenes and Mora-Molina, 2015).

5. Conclusions

This study suggests that riparian forest buffers that are at least 15 m wide and 500 m long conserve river water quality in tropical forest ecosystems. This approach can be replicated globally to assess riparian buffer configurations to maximize trade-offs between water quality and human development more broadly. This study provides a standardized rapid methodology for research that assesses the effects of land use on water quality, suggesting that future studies analyze land use in riparian zones that are 15 m wide and 1000 m upstream of the sampling point.

A land management approach that focuses on conserving long, narrow riparian forest buffers may maximize return on conservation investments. To implement long riparian corridors in fragmented landscape with multiple landowners, existing intact riparian corridors should be conserved and connected. Local governmental and non-governmental organizations can facilitate collaboration and consistency throughout watersheds. While existing legislation protecting riparian buffers in many countries may already conserve effective riparian buffer sizes, such as the case in Costa Rica, enforcement and financial incentives to promote collaborative restoration often need to be strengthened. If consistent, relatively small steps to protect narrow buffers around degraded agricultural rivers could have a cumulative large effect on downstream ecosystems and communities.

Credit author statement

Hilary Brumberg: Conceptualization, Formal analysis, Visualization, Writing – original draft. Chris Beirne: Formal analysis, Visualization, Writing – original draft. Eben Broadbent: Conceptualization, Investigation, Writing – review & editing. Angelica Almeyda Zambrano: Investigation. Sandra Almeyda Zambrano: Investigation. Carlos Quispe Gil: Investigation. Beatriz Lopez Gutierrez: Investigation; Writing – review & editing. Rachael Eplee: Writing – review & editing. Andrew Whitworth: Conceptualization, Supervision, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are thankful for the help of all staff, visitors, and volunteers of Osa Conservation, especially Rebecca Cole and Cristina Chaminade for revising the manuscript and to Lucy Kleiner for creating the graphical abstract. Thanks to the Bobolink Foundation, KEEN Effect, and the Troper Wojcicki Foundation for supporting HB, AW, and this research, and to the International Conservation Fund of Canada, the Moore Family Foundation, and the Gordon and Betty Moore Foundation for their support of conservation in Osa. Thanks to the owners and managers of Casa de Rodden in Playa Sandalo for logistical assistance during data collection. The study complies with all current laws in Costa Rica, where the study was conducted. Thank you to three anonymous reviewers for your recommendations.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.112132.

References

Aguiar, T.R., Bortolozo, F.R., Hansel, F.A., Rasera, K., Ferreira, M.T., 2015. Riparian buffer zones as pesticide filters of no-till crops. Environ. Sci. Pollut. Res. 22, 10618–10626. https://doi.org/10.1007/s11356-015-4281-5.

Allan, J.D., 2004. Landscapes and riverscapes: the influence of land use on stream ecosystems. Annu. Rev. Ecol. Evol. Syst. 35, 257–284. https://doi.org/10.1146/annurev.ecolsys.35.120202.110122.

Amaral Pereira, L.G. do, Capavede, U.D., Cunha Tavares, V. da, Magnusson, W.E., Dineli Bobrowiec, P.E., Beggiato Baccaro, F., 2019. From a bat's perspective, protected riparian areas should be wider than defined by Brazilian laws. J. Environ. Manag. 232, 37–44. https://doi.org/10.1016/j.jenvman.2018.11.033.

Bates, D., Maechler, M., Bolker, B., Walker, S., 2014. lme4: linear mixed-effects models using Eigen and S4. R Packag 1, 1–23.

Belletti, B., Nardi, L., Rinaldi, M., Poppe, M., Brabec, K., Bussettini, M., Comiti, F., Gielczewski, M., Golfieri, B., Hellsten, S., Kail, J., Marchese, E., Marcinkowski, P., Okruszko, T., Paillex, A., Schirmer, M., Stelmaszczyk, M., Surian, N., 2018. Assessing restoration effects on river hydromorphology using the process-based morphological quality index in eight European river reaches. Environ. Manage. 69–84. https://doi.org/10.1007/s00267-017-0961-x.

Bentrup, G., Dosskey, M., Wells, G., Schoeneberger, M., 2012. Connecting landscape fragments through riparian zones. Forest Landscape Restoration, pp. 93–110.

Boulton, A.J., Boyero, L., Covich, A.P., Dobson, M., Lake, S., Pearson, R., 2008. Are tropical streams ecologically different from temperate streams? Trop. Stream Ecol. 257–284.

Bradshaw, C.J., Navjot, S., Brook, B., 2009. Tropical turmoil: a biodiversity tragedy in progress. Front. Ecol. Environ. https://doi.org/10.1890/070193.

Braun, B.M., Pires, M.M., Stenert, C., Maltchik, L., Kotzian, C.B., 2018. Effects of riparian vegetation width and substrate type on riffle beetle community structure. Entomol. Sci. 21, 66–75. https://doi.org/10.1111/ens.12283.

Broadbent, E.N., Almeyda Zambrano, A.M., Dirzo, R., 2012. INOGO Mapas 2012 : a High Resolution Map of Land Cover in the Osa and Golfito Region of Costa Rica.

Burdon, F.J., Ramberg, E., Sargac, J., Anne, M., Forio, E., Saeyer, N. De, Mutinova, P.T., Moe, T.F., Pavelescu, M.O., Dinu, V., Cazacu, C., Witing, F., Kupilas, B., Grandin, U., Volk, M., Rî, G., 2020. Assessing the benefits of forested riparian zones: a qualitative index of riparian integrity is positively associated with ecological status in European streams. Water 12.

Burnham, K., Anderson, D.R., 2002. Model Selection and Multi-Model Inference: a Practical Information-Theoretic Approach. Springer.

Calvo-Brenes, G., Mora-Molina, J., 2015. Water quality evaluation in Tigre and Rincón rivers of península de Osa in two different periods of time. Tecnol. en Marcha. https://doi.org/10.18845/tm.v28i3.2411.

Capon, S.J., Chambers, L.E., Nally, R. Mac, Naiman, R.J., Davies, P., Marshall, N., Pittock, J., Reid, M., Capon, T., Douglas, M., Catford, J., Baldwin, D.S., Stewardson, M., Roberts, J., Parsons, M., Williams, S.E., 2013. Riparian ecosystems in the 21st century: hotspots for climate change. Ecosystems 16, 359–381. https://doi.org/10.1007/s10021-013-9656-1.

de Jesús-Crespo, Ramírez, A., 2011. Effects of urbanization on stream physicochemistry and macroinvertebrate assemblages in a tropical urban watershed in Puerto Rico. J. North Am. Benthol. Soc. 30, 739–750. https://doi.org/10.1899/10-081.1.

de Oliveira, L.M., Maillard, P., de Andrade Pinto, É.J., 2016. Modeling the effect of land use/land cover on nitrogen, phosphorous and dissolved oxygen loads in the Velhas River using the concept of exclusive contribution area. Environ. Monit. Assess. 188 https://doi.org/10.1007/s10661-016-5323-2.

Fielding, K.S., Terry, D.J., Masser, B.M., Bordia, P., Hogg, M.A., 2005. Explaining landholders' decisions about riparian zone management: the role of behavioural, normative, and control beliefs. J. Environ. Manag. 77, 12–21. https://doi.org/10.1016/j.jenvman.2005.03.002.

Fondriest Environmental, 2020. Fundamentals of environmental measurements. https://www.fondriest.com/environmental-measurements/.

Iñiguez-Armijos, C., Leiva, A., Frede, H.G., Hampel, H., Breuer, L., 2014. Deforestation and benthic indicators: how much vegetation cover is needed to sustain healthy Andean streams? PloS One 9. https://doi.org/10.1371/journal.pone.0105869.

Kibena, J., Nhapi, I., Gumindoga, W., 2014. Assessing the relationship between water quality parameters and changes in landuse patterns in the Upper Manyame River, Zimbabwe. Phys. Chem. Earth 67 (69), 153–163. https://doi.org/10.1016/j.pce.2013.09.017.

Laurance, W.F., 1999. Reflections on the tropical deforestation crisis. Biol. Conserv. 91, 109–117.

Lee, P., Smyth, C., Boutin, S., 2004. Quantitative review of riparian buffer width guidelines from Canada and the United States. J. Environ. Manag. 70, 165–180. https://doi.org/10.1016/j.jenvman.2003.11.009.

Lees, A.C., Peres, C.A., 2008. Conservation value of remnant riparian forest corridors of varying quality. Conserv. Biol. 22, 439–449. https://doi.org/10.1111/J.1523-1739.2007.O087O.X.

Li, S., Gu, S., Liu, W., Han, H., Zhang, Q., 2008. Water quality in relation to land use and land cover in the upper Han River. Catena 75, 216–222. https://doi.org/10.1016/j.catena.2008.06.005.

Lind, L., Maher, E., Laudon, H., 2019. Towards ecologically functional riparian zones : a meta-analysis to develop guidelines for protecting ecosystem functions and biodiversity in agricultural landscapes. J. Environ. Manag. 249 https://doi.org/10.1016/j.jenvman.2019.109391.

Little, C., Cuevas, J.G., Lara, A., Pino, M., Schoenholtz, S., 2015. Buffer effects of streamside native forests on water provision in watersheds dominated by exotic forest plantations. Ecohydrology 8, 1205–1217. https://doi.org/10.1002/eco.1575.

Lorion, C.M., Kennedy, B.P., 2009. Relationships between deforestation, riparian forest buffers and benthic macroinvertebrates in neotropical headwater streams. Freshw. Biol. 54, 165–180. https://doi.org/10.1111/j.1365-2427.2008.02092.x.

Luke, S.H., Slade, E.M., Gray, C.L., Annammala, K.V., Drewer, J., Williamson, J., Agama, A., Ationg, M., Mitchell, S., Vairappan, C.S., Struebig, M.J., 2018. Riparian buffers in tropical agriculture: scientific support, effectiveness and directions for policy. J. Appl. Ecol. 85–92. https://doi.org/10.1111/1365-2664.13280.

Maillard, P., Pinheiro Santos, N.A., 2008. A spatial-statistical approach for modeling the effect of non-point source pollution on different water quality parameters in the Velhas river watershed – Brazil. J. Environ. Manag. 86, 158–170. https://doi.org/10.1016/j.jenvman.2006.12.009.

Martínez-Fernández, V., Oorschot, M. Van, Smit, J. De, González, M., Buijse, A.D., 2018. Modelling feedbacks between geomorphological and riparian vegetation responses under climate change in a Mediterranean context. Earth Surf. Process. Landforms 43, 1825–1835. https://doi.org/10.1002/esp.4356.

Meli, P., Calle, A., Calle, Z., Ortiz-Arrona, C.I., Sirombra, M., Brancalion, P.H.S., 2019. Riparian-forest buffers: bridging the gap between top-down and bottom-up restoration approaches in Latin America. https://doi.org/10.1016/j.landusepol.2019.104085 Received.

Mello, K. De, Randhir, T.O., Averna, R., Alberto, C., 2017. Riparian restoration for protecting water quality in tropical agricultural watersheds. Ecol. Eng. 108, 514–524. https://doi.org/10.1016/j.ecoleng.2017.06.049.

Ministerio de Planificación Nacional y Política Económica, 2017. Índice de Desarrollo Social 2017.

Monteiro, J.A.F., Kamali, B., Srinivasan, R., Abbaspour, K., Gücker, B., 2016. Modelling the effect of riparian vegetation restoration on sediment transport in a human-impacted Brazilian catchment. Ecohydrology 9, 1289–1303. https://doi.org/10.1002/eco.1726.

Moraes, A.B., Wilhelm, A.E., Boelter, T., Stenert, C., Schulz, U.H., Maltchik, L., 2014. Reduced riparian zone width compromises aquatic macroinvertebrate communities in streams of southern Brazil. Environ. Monit. Assess. 186, 7063–7074. https://doi.org/10.1007/s10661-014-3911-6.

Nakagawa, S., Schielzeth, H., 2013. A general and simple method for obtaining R2 from generalized linear mixed-effects models. Methods Ecol. Evol. 4, 133–142. https://doi.org/10.1111/j.2041-210x.2012.00261.x.

Nelson, M.L., Rhoades, C.C., Dwire, K.A., 2011. Influence of bedrock geology on water chemistry of slope wetlands and headwater streams in the southern rocky mountains. Wetlands 31, 251–261. https://doi.org/10.1007/s13157-011-0157-8.

Ngoye, E., Machiwa, J.F., 2004. The influence of land-use patterns in the Ruvu river watershed on water quality in the river system. Phys. Chem. Earth 29, 1161–1166. https://doi.org/10.1016/j.pce.2004.09.002.

Ortiz Malavasi, E., 2004. Efectividad del Programa de Pago de Servicios Ambientales por Protección del Bosque (PSA-Protección) como instrumento para mejorar la calidad de vida de los propietarios de bosque en zonas rurales. Kurú Rev. For. 1, 1–11.

Parsons, M., Thoms, M., Norris, R., 2002. Australian River Assessment System: AusRivAS Physical Assessment Protocol (Canberra, Australia).

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, hill-country streams. N. Z. J. Mar. Freshw. Res. 31, 579–597. https://doi.org/10.1080/00288330.1997.9516791.

R Core Team, 2013. R: a language and environment for statistical computing. R Found. Stat. Comput.

Raven, P.J., Holmes, N.T.H., Dawson, F.H., Fox, P.J.A., Everard, M., Fozzard, I.R., Rouen, K.J., 1998. River Habitat Quality: the Physical Character of Rivers and Streams in the UK and Isle of Man (Bristol, UK).

Rhoades, H., 2016. UnderMining the Water Cycle: Extractive Industries and a Planetary Water Crisis.

Richards, S., Whittingham, M., Stephens, P., 2011. Model selection and model averaging in behavioural ecology: the utility of the IT-AIC framework. Behav. Ecol. Sociobiol. 77–89.

Sachs, J., 2001. Tropical Underdevelopment (No. 8119). NBER Working Paper, Cambridge, MA.

Soto, M., 2013. Solo el 4% de las aguas residuales generadas en Costa Rica es tratado antes de ir a los ríos. La Nación.

Stanford, B., Holl, K.D., Herbst, D.B., Zavaleta, E., 2019. In-stream habitat and macroinvertebrate responses to riparian corridor length in rangeland streams. Restor. Ecol. 1–12 https://doi.org/10.1111/rec.13029.

Taylor, P., Asner, G., Dahlin, K., Anderson, C., Knapp, D., Martin, R., Mascaro, J., Chazdon, R., Cole, R., Wanek, W., Hofhansl, F., Malavassi, E., Vilchez-Alvarado, B., Townsend, A., 2015. Landscape-scale controls on aboveground forest carbon stocks on the Osa Peninsula , Costa Rica. PloS One 1–18. https://doi.org/10.1371/journal.pone.0126748.

Tockner, K., Stanford, J.A., 2002. Riverine flood plains: present state and future trends. Environ. Conserv. 29, 308–330. https://doi.org/10.1017/S037689290200022X.

Tran, C., Bode, R., Smith, A., Kleppel, G., 2010. Land-use proximity as a basis for assessing stream water quality in New York state (USA). Ecol. Indicat. 10, 727–733. https://doi.org/10.1016/j.ecolind.2009.12.002.

Valle, I., Buss, D., Baptista, D., 2013. The influence of connectivity in forest patches, and riparian vegetation width on stream macroinvertebrate fauna. Braz. J. Biol. 73, 231–238. https://doi.org/10.1590/S1519-69842013000200002.

Willis, S., 2016. Highly Hazardous Pesticides Phase Out and Alternatives in Costa Rica. Brighton, UK.