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Shade tree cover criteria for non-point source pollution control in the Rainforest Alliance coffee certification program: A snapshot assessment of Costa Rica's Tarrazú coffee region

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ABSTRACT

Management of non-point source pollution is of great importance in the context of coffee agriculture, as this land use often coincides with headwater streams that influence water quality at the basin scale. Sustainability certification programs, such as the Rainforest Alliance (RA), provide management guidelines that promote non-point source pollution control in coffee. One of these practices is the maintenance of shade trees within farms, required by RA at a minimum of 40% shade tree cover. Here we assess the effectiveness of this practice in Tarrazú, a high elevation coffee growing region in Costa Rica. We monitored indicators of non-point source pollution in streams with both high and low shade tree cover. Streams with *High Shade Tree Cover* (HSTC, $N=5$ subwatersheds) had 35–55% cover, approximating or exceeding the RA recommendation of at least 40%; and streams with *Low Shade Tree Cover* (LSTC, $N=5$ subwatersheds), had 18–31% cover. We monitored the ten study streams during the dry (April & December), transition (July), and peak (October) rainfall seasons of 2013, and compared responses using *t*-tests. We found support for the effectiveness of shade tree cover in controlling non-point source pollution: HSTC streams had significantly ($p=0.042$) lower mean annual turbidity and significantly ($p=0.004$) lower turbidity during the transition season. HSTC streams also had significantly ($p=0.05$) lower conductivity values during the transition period, although this trend was weaker through the year. Subwatersheds with HSTC streams were characterized by a higher percentage of RA-certified coffee than LSTC streams. Our study provides evidence of the benefits of RA shade tree cover criteria for managing water quality within high elevation tropical agro-ecosystems, especially if implemented at the watershed scale. These results contribute to our understanding of the role of agroforestry certification on tropical ecosystem conservation, and are the first account of the effectiveness of a specific coffee certification guideline on non-point source pollution control.

1. Introduction

Coffee is among the most valuable commodities in world trade (Taugourdeau et al., 2014; FAO, 2011) and its global production has steadily increased over the last 50 years (ICO, 2014). The demand for coffee drives significant land use transformation in tropical nations, while the majority of the world's consumption occurs in the United States of America and the European Union (ICO, 2014). Coffee markets, therefore, exemplify the global environmental footprint of consumer culture on the developing tropics.

An important and understudied environmental issue associated with coffee farming is the management of non-point source pollution to streams. Non-point source pollution originates from diffuse sources, such as surface runoff, carrying natural or anthropogenic contaminants to water bodies (USEPA, 2015). Sources of contaminants within coffee farms include agrochemical inputs, primarily nitrogen based fertilizers and lime (Castro-Tanzi et al., 2012), as well as sediment from erodible dirt roads (Verbist et al., 2010). Managing non-point source pollution is critical, as coffee farms are typically situated at the headwaters of tropical watersheds, and their impact can thus extend throughout the entire river network, reaching coastal environments (Robinson and Mansingh, 1999; Freeman et al., 2007). The high slopes and heavy rainfall that characterize coffee growing landscapes exacerbate pollutant export to waterways (Ali et al., 2011).

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Awareness of the environmental and social threats associated with expanding markets for tropical agricultural goods, such as coffee, led to the creation of sustainability certification programs in the late 1980s. Certification programs outline environmental and social justice criteria, and provide economic incentives to producers that comply with such standards (Perfecto et al., 2005; Blackman and Naranjo, 2010). One of the leading certifiers in the coffee value chain is the Rainforest Alliance^{TM} (RA), which certifies close to 3.3% of the coffee produced globally (RA, 2012). This study emerged in part from a collaborative effort with RA to evaluate the organization's water quality conservation efforts (De Jesús Crespo, 2015).

For the purpose of non-point source pollution control in coffee, RA guidelines include the conservation of riparian buffers at widths that vary from 5 m to 20 m depending on slope and intensity of agrochemical use (SAN, 2010), as well as the maintenance of at least 40% shade tree cover through the coffee farm (SAN, 2010). While several other certifications have similar shade tree cover and buffer guidelines, the only other certification program with equally strict criteria for these practices as RA is the Smithsonian Migratory Bird Institute's Bird Friendly Certification (SAN, 2010; SMBC, 2002).

This study evaluates the effectiveness of one of these requirements, the preservation of shade tree cover at a 40% minimum. Shade trees have been shown to help reduce contamination of underground water sources with agrochemicals (Babbar and Zak, 1995) and in some cases, may be nearly as effective as native forest at reducing surface runoff by increasing soil organic matter and infiltration (Verbist et al., 2010). A question that has not been addressed by previous studies is how much shade tree cover would be required to reap these benefits at the landscape scale. Our study seeks to fill this information gap by evaluating the effectiveness of the levels required by RA, which have been established without empirical evidence of their role in non-point source pollution management.

To address this objective, we present a snapshot assessment of water quality indicators of non-point source pollution (turbidity and conductivity) in streams across Tarrazú, a high intensity coffee-growing region in Costa Rica, which has a predominance of high elevation coffee (i.e. >1350 masl, classified as Strictly Hard Bean, Castro-Tanzi et al., 2012). Currently, there is an increased demand for high elevation coffee from premium origins such as Tarrazú, due to the emergence of specialty coffee markets (Laderach et al., 2011; Rueda and Lambin, 2013). Furthermore, high elevation coffee may provide a more reliable supply in the future due to potentially higher resilience to temperature increases associated to climate change (Rahn et al., 2014).

This study compares turbidity and conductivity values in 10 sub-watersheds within Tarrazú: 5 with High Shade Tree Cover (HSTC, near or greater than 40%) and 5 with Low Shade Tree Cover (LSTC, less than 40%) for a period of one year. Our goal is to determine whether a 40% shade tree cover level significantly impacts non-point source pollution in coffee agroforestry systems. We also ask whether the RA certification program is associated with greater implementation of reforestation practices within coffee agroforestry landscapes by examining percentages of certified coffee in these 10 sub-watersheds. This approach aims to provide empirical data to elucidate the role of the RA sustainable coffee certification at promoting water quality conservation in tropical highland agro-ecosystems.

2. Methods

2.1. Study site

The study focuses on a coffee growing region in Costa Rica, a country that provides an exemplary case of both technified coffee farming under the green revolution paradigm (Wintgens, 2009), and a long history of engagement with environmental initiatives (Campbell, 2002). Within Costa Rica, the Tarrazú region stood out as an ideal study site because it is a high elevation, and high intensity coffee region, where two of its largest cooperatives participate in the RA certification program (Fig. 1a).

Tarrazú is part of the headwaters of the Pirris Watershed, in the central Pacific region of Costa Rica (Fig. 1a and b). Topography, climate and production intensity make Tarrazú an ideal context for addressing non-point source pollution management. The region is located at the higher end of the elevation (1200–1900 masl), rainfall and productivity gradient that characterizes coffee farming (Mitchell, 1988) in Central America. Coffee in Tarrazú is often grown on gradients as steep as 60% (Castro-Tanzi et al., 2012), rainfall averages 2400 mm/yr, which is high for coffee producing regions (ICAFE, 2012), and soils are ultisols of alluvial origin (ICAFE, 2012), which are highly erodible, prone to cation loss, and acidic (USDA-NRCS, 2014). Extreme growing conditions translate into areas of high vulnerability to water quality degradation, and thus necessitate effective watershed management.

Land use in Tarrazú consists mainly of coffee plantations (Soto-Montoya and Ortiz-Malavasi, 2008), with production averaging over 1600 kilos per hectare per year (ICAFE, 2012; Castro-Tanzi et al., 2012). Farms usually exhibit a shade monoculture pattern, meaning coffee in association with one to two upperstory shade tree species. The two most common shade trees in Tarrazú are *Erythrina* spp., a nitrogen-fixing legume, and *Musa* spp. (i.e. banana plants) (Castro-Tanzi et al., 2012). This configuration of coffee plantations is considered the most intensive form of shade grown coffee, and is characteristic of highly productive coffee enterprises (Moguel and Toledo, 1999; Mas and Dietsch, 2004). The most commonly applied agrochemicals are nitrogen based fertilizers, applied at an average of 212 kg ha^{-1} y^{-1} (±50 sd) and lime, which is applied at an average of 658 kg ha^{-1} y^{-1} (±445 sd) (Castro-Tanzi et al., 2012).

Most of the coffee farms in Tarrazú belong to one of three cooperatives: Coope Dota, Coope Tarrazú, and Coope Llano Bonito. The former two currently participate in the RA certification program (Fig. 1a), while the latter was part of the RA certification program until 2004. Although the RA program is implemented at the farm scale, our study was designed at the sub-watershed level, because our main goal was to study the effectiveness of shade tree cover at non-point source pollution management, which is driven by factors that occur at large spatial scales. Our study sites, therefore, consist of sub-watersheds within the Pirris Watershed (Fig. 1b), which include both RA certified and uncertified farms.

2.2. Landscape analysis

The study employed two adjacent multispectral, 2-meter resolution images from the Tarrazú coffee region, pansharpened with corresponding Panchromatic, sub-meter resolution images, to classify land cover (Yuen, 1999). The Worldview-2 Satellite collected the images, which were further corrected using the SRTM 900 m Digital Elevation Model. Worldview-2 captured the first image on January 31, 2012 at a 49° angle, and the second on February 27, 2012 at an angle of 41°. Analyzing images independently, as opposed to in a mosaic, allowed this study to account for accuracy issues related to dates and angle views of the individual datasets.

Land cover classes included: (1) sun coffee (i.e. conventional unshaded coffee), (2) shade tree cover (i.e. upperstory tree cover in coffee farms), (3) forest, (4) urban, (5) pastures and (6) exposed soil (Table 1). The classification process included delimiting forest patches by hand, and erasing them to avoid classification confusion with the shade tree cover category. Removing forest patches that could confound the measurement of shade in coffee, increasing image contrast to 50% and setting brightness to 16%, allowed

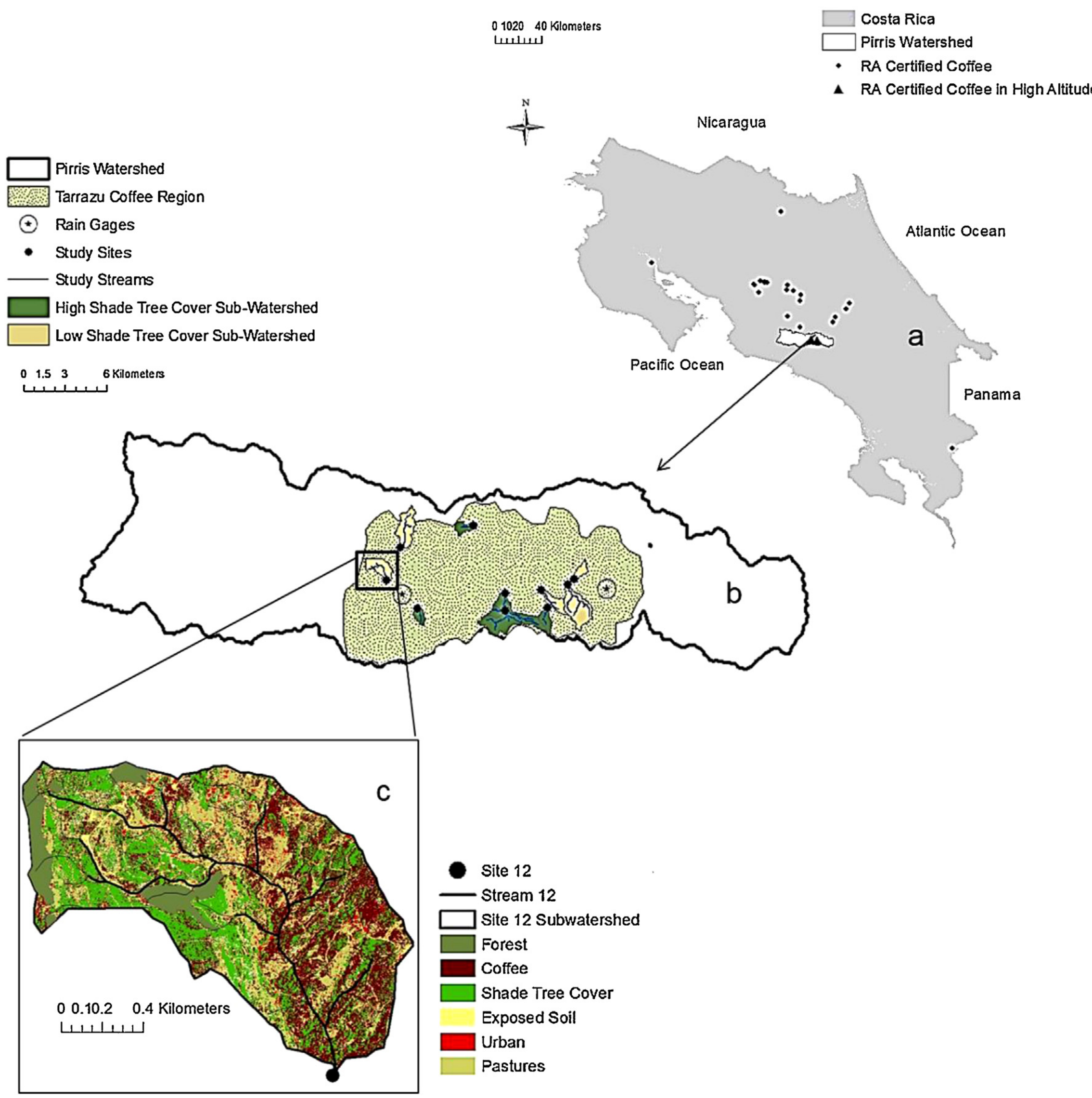

Fig. 1. Study context: (a) Coffee enterprises in Costa Rica that are certified by the Rainforest Alliance (RA) (Source: Hughell, 2014), high elevation (>1350 masl) coffee regions are identified with a triangle, the Pirris Watershed in Central Pacific, Costa Rica contains the only two RA certified coffee enterprises in a high elevation region of the Country; (b) Location of the Tarrazú region, illustrating the location of our study sites ($N = 10$) and rain-gages ($N = 2$) (Source: ICAFE, 2013); (c) Example of study site within Tarrazú above which we characterized the sub-watershed in terms of % forest, sun coffee, shade tree cover, exposed soil, urban areas and pastures. Sub-watersheds were delimited using 10 m resolution DEM's (Source: Vargas and Acevedo, 2001). Land cover classes were created using sub meter resolution imagery (Source: Worldview-2 2012). The outlines for Costa Rica and the Pirris Watershed were adapted from the Costa Rica Atlas (Soto-Montoya and Ortiz-Malavasi, 2008).

the study to reliably differentiate between the darker greens associated with coffee plants and the brighter tones associated with the upper story shade trees (*Erythrina* sp. and *Musa* sp.). Using the differing spectral signatures of shade trees and coffee plants with enhanced vegetation contrast enabled using a Maximum Likelihood supervised classification in ArcGIS (ver. 10.0). The accuracy of the classification was estimated using a confusion matrix approach and the Kappa coefficient (Campbell, 1996; Foody, 2002), were we used 300 test points (50 per land cover class), to compare classifications done manually with the Maximum Likelihood output. The confusion matrix produced accuracy estimates of 79.4% and 94.4% for Image 1 and 2, respectively. The Kappa coefficient produced accuracy estimates of 74.6% for Image 1 and 92.9% for Image 2. For the shade tree cover class, Image 1 was 98% accurate and Image 2 100% accurate.

After assessing land use accuracy, the next step included calculating watershed scale percentages of all 6 land-cover classes across the entire upstream drainage area of candidate sites for this study (i.e. 3rd to 5th order streams within Tarrazú). The goal was to pre-identify sub-watersheds with similar land use and hydrological characteristics, and isolate percent shade tree cover as the principal source of landscape variation between sampling units. To do this, we delimited the sub-watersheds of all 3rd to 5th order streams in the region using a 10 m resolution Digital Elevation Model (Vargas and Acevedo, 2001) and the process described by Perez (2012). We selected only sub-watersheds with coffee as the dominant land use (>50%), with less than 10% urban + exposed soil, and with slopes above 30% (USDA-NRCS, 1993). This selection process minimized topographical and land use variability between watersheds, but it also limited the number of candidate sub-watersheds ($N = 40$). Of the 40 potential sub-watersheds identified, many had inaccessible streams, or streams that lacked constant flow. As a result, the study was only able to conduct repeated sampling (i.e. during dry and rainy conditions) on 15 streams. Only 10 of those streams where sampled twice during the dry season and twice during the rainy season, because of difficulty locating or accessing the other

Table 1
Descriptive data for the upstream sub-watersheds of our study sites by shade tree cover category: high (~40% or more shade tree cover, $N=5$) and low (<40% shade tree cover, $N=5$). p values represent results from t-tests conducted to evaluate differences between groups in terms of hydrological and land use variables, as well as the percentage of coffee agricultural area certified by the Rainforest Alliance.

Descriptive variables	Shade tree cover category				t test
	High		Low		p
	Mean	SD	Mean	SD	
Hydrology					
Discharge (ft^3/s)	3.45	3.04	3.04	2.46	0.7786
Area (km^2)	1.53	1.97	1.80	1.03	0.7751
Slope	41.15	9.47	44.40	7.67	0.4863
Sub-watershed land use (%)					
Shade tree cover	44.40	8.46	27.01	5.31	**0.0051
Sun coffee	24.37	8.71	37.54	9.76	**0.0139
Forest	11.99	9.37	10.77	8.27	0.7851
Pastures	13.61	5.51	18.34	7.80	0.1279
Urban	3.72	1.07	3.21	1.67	0.3351
Exposed soils	1.89	0.76	3.11	0.89	**0.0116
Riparian forest (%)					
20 m buffer zone	14.07	7.76	12.80	6.52	0.7466
5 m buffer zone	14.89	8.44	13.59	7.29	0.7315

** $p<0.01$.

5 during the first sampling event. In order to use a balanced comparison approach, this study focuses its analysis on the 10 sub-watersheds sampled through the entire study period.

The 10 sub-watersheds were ranked by shade tree cover and divided into two groups. Percent cover in the top five sub-watersheds, referred to herein as the High Shade Tree Cover (HSTC) sites, ranged from 35% to 55%. Therefore, HSTC sites approximated or exceeded the RA 40% minimum guideline. The lower 5 sub-watersheds, or Low Shade Tree Cover (LSTC) sites (Table 1), had between 18% and 31% cover and thus would not meet the 40% guideline.

In addition, calculations of percentage of forest in the 5 m and 20 m buffer zones, upstream of the sampling points, assisted in controlling for any potential confounding influence of riparian buffers vs shade tree cover on non-point source pollution control.

Lastly, all sub-watersheds were characterized by the percentage of coffee area certified by RA. For this we used a GIS layer from the Costa Rica Coffee Institute (ICAFE), showing coffee farms across Costa Rica for the year 2012, delimited by property limits and identified by farm owner. Representatives from the two large local coffee cooperatives (Coope Dota and Coope Tarrazú) identified farm owners participating in the RA certification program. This allowed for the study to calculate the proportion of RA certified coffee over total coffee agricultural area in each study site.

2.3. Stream assessment

The study based its stream assessments on the rainfall patterns of the study region (IMN, 2015, Fig. 2b), sampling sites four times during 2013: (1) April (the dry season), (2) July (a transitional period to the rainy season), (3) October (peak rainy season), and (4) December (transitional period to the dry season) (Fig. 2a). Each sampling event included measurements of stream discharge, using a velocity-area method with a current meter, across reaches of length 12× their width (USDA-NRCS, 1998). Key indicators of water quality for the study included (a) conductivity and (b) turbidity, measured with the YSI 6820V2-01 multi parameter probe (YSI Inc., USA). Turbidity was selected as an indicator of watershed erosion (EPA, 2012a) and conductivity as an indicator of agrochemical pollution (EPA, 2012b). These two indicators have been shown to be effective at reflecting landscape level impacts of land use and

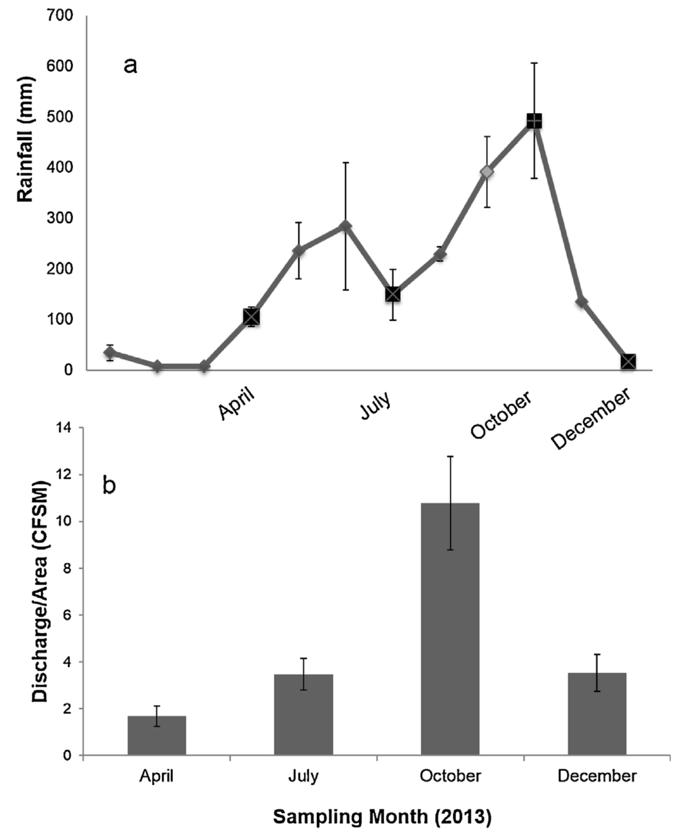

Fig. 2. General hydrological dynamics of study sites ($N=10$) during the study year of 2013: (a) mean (±SE) monthly rainfall from local gages ($N=2$), points highlighted in black represent our sampling events during the; dry season (April and December), transition season (July), peak season (October), (b) mean (±SE) discharge over sub-watershed area (cfsm) for all sampled streams during the specified sampling events.

non-point source pollution in tropical agricultural landscapes (Minaya et al., 2013).

2.4. Data analysis

To test the hypothesis that LSTC streams would exhibit higher turbidity and conductivity values than the HSTC streams, the study compared response variable by group through the sampling seasons and as annual averages using one tailed t-tests (JMP Pro 11, SAS Institute Inc., 2013). Additionally, to strengthen the understanding of how certification might lead to improved water quality through increased shade tree cover, this study conducted one tailed t-tests to evaluate the prediction that the HSTC sub-watersheds would have higher percentages of coffee area certified by the Rainforest Alliance than the LSTC sub-watersheds.

Because other land use variables, aside from shade tree cover, were also significantly different between the two test groups (i.e. sun coffee and exposed soil, Table 1), an Akaike Information Criterion (AICc) in an Information Theoretic approach (Burnham and Anderson, 2002) was applied to evaluate the best model for explaining variables that responded in accordance to our predictions.

3. Results

3.1. Hydrological, geographical, and land use trends

Rainfall in 2013 followed the historical patterns (IMN, 2015) of low precipitation from January to April, a transition period between May and August, a sharp rainfall spike between August and October, and a return to baseline levels between November and December

(Fig. 2a). Discharge varied according to rainfall, as illustrated in Fig. 2b, which shows mean discharge/area ratios for all sampling sites on each sampling season.

General characteristics for sites in each of the Shade Tree Cover groups are listed in Table 1. Average discharge ranged from 0.54 to 5.05 ft^3/s for the HSTC sites, and from 0.43 to 5.85 ft^3/s for the LSTC sites. Watershed slope ranged from 31.23% to 56.05% in the HSTC sites and from 34.9% to 55.4% in the LSTC sites. These variables did not differ significantly between the two test groups.

In terms of land use percentages (Table 1), the HSTC sites fell within the following ranges: shade tree cover (35.31–55.42%), sun coffee (12.04–34.15%), pastures (7.70–20.24%) urban (2.18–4.75%), exposed soil (0.84–2.73%), and forest (2.09–24.90%). The LSTC sites had the following ranged of land covers: shade tree cover (17.82–31.69%), sun coffee (25.78–49.23%), pastures (10.81–28.90%), urban (1.23–5.56%), exposed soil (2.11–3.98%), and forest (0.35–23.25%). Among the different land cover classifications, only shade tree cover (p = 0.005), sun coffee (p = 0.014), and exposed soil (p = 0.012) proved to be statistically different between the two study groups.

Both groups had similar levels of riparian forest cover at both the 5 and 20 m buffer scales (Table 1). For the HSTC sites, forest cover in the 5 m buffer ranged from 4.29% to 24.25%; in the 20 m buffer, it ranged from 4.21% to 23.19%. For the LSTC sites, forest cover in the 5 m buffer ranged from 2.46% to 20.48%, and from 2.48% to 18.30% in the 20 m buffer.

3.2. Water quality trends

Examination of trends within each season, revealed that for the HSTC sites, turbidity values ranged from 2.90 to 5.23 NTU in April, from 4.40 to 11.53 NTU in July, from 6.83 to 20.30 NTU in October, and from 2.56 to 7.00 in December. In the LSTC sites, turbidity values ranged from 3.13 to 5.00 NTU in April, from 4.60 to 24.70 NTU in July, from 9.10 to 24.60 NTU in October, and from 2.56 to 5.60 in December. HSTC sites had lower levels of turbidity in each sampling period, but these differences were only statistically significant in July (p = 0.0044) (Fig. 3a). After averaging across sampling months, HSTC sites had mean annual turbidity of 6.05 (±2.79) NTU, while the LSTC sites had a significantly higher (p = 0.042; Fig. 4a) mean annual turbidity of 14.75 (±5.69) NTU.

Conductivity values for the HSTC sites ranged from 233.33 to 493.66 μS/cm in April, from 89.00 to 227.00 μS/cm in July, from 85.66 to 207.00 μS/cm in October, and from 109 to 227.67 μS/cm in December. In the LSTC sites, conductivity ranged from 285.66 to 442.00 μS/cm in April, from 151.00 to 236.00 μS/cm in July, from 129 to 193.66 μS/cm in October, and from 154.66 to 216.00 μS/cm in December. While conductivity tended to be lower in the HSTC sites, the difference was only statistically significant during July (p = 0.05). Across sampling months, annual conductivity averaged 178.33 (±62.85) for the sampling year in the HSTC sites, and 214.91 (±39.12) μS/cm for the LSTC sites during 2013. LSTC had higher levels of conductivity, but the difference was not statistically significant (p = 0.13). The percentages of coffee area certified by the Rainforest Alliance ranged from 0% to 61.52% in the HSTC sub-watersheds, and from 0% to 13.82% in the LSTC sites, but this trend was not significant at the 95% confidence level (p = 0.08, Fig. 4).

3.3. Comparison of land use effect on turbidity and conductivity

The percentage (%) of sun coffee, and the percentage (%) of exposed soil differed between the HSTC and LSTC sites (Table 1). To account for these confounding factors, the study compared the goodness-of-fit among models that used % shade tree cover, % sun coffee or % exposed soil in explaining variability in turbidity and conductivity. Shade tree cover best explained turbidity trends in the transition season of July (y_1 = 44.22–0.88β_1; R^2 = 0.32; p = 0.04; AIC_c weight = 0.72) and throughout the year (y_2 = 14.18–0.19 β_1, R^2 = 0.33, p = 0.04; AIC_cw = 0.73) (Table 2). The best model for explaining conductivity levels in July was the percentage of sun coffee (y_3 = 0.11 + 0.002 β_2, R^2 = 0.13, p = 0.15; AIC_C weight = 0.43), but the model with shade tree cover had similar support (y_3 = 0.22–0.001 β_1, R^2 = 0.12, p = 0.16; AIC_c weight = 0.35) (Table 2).

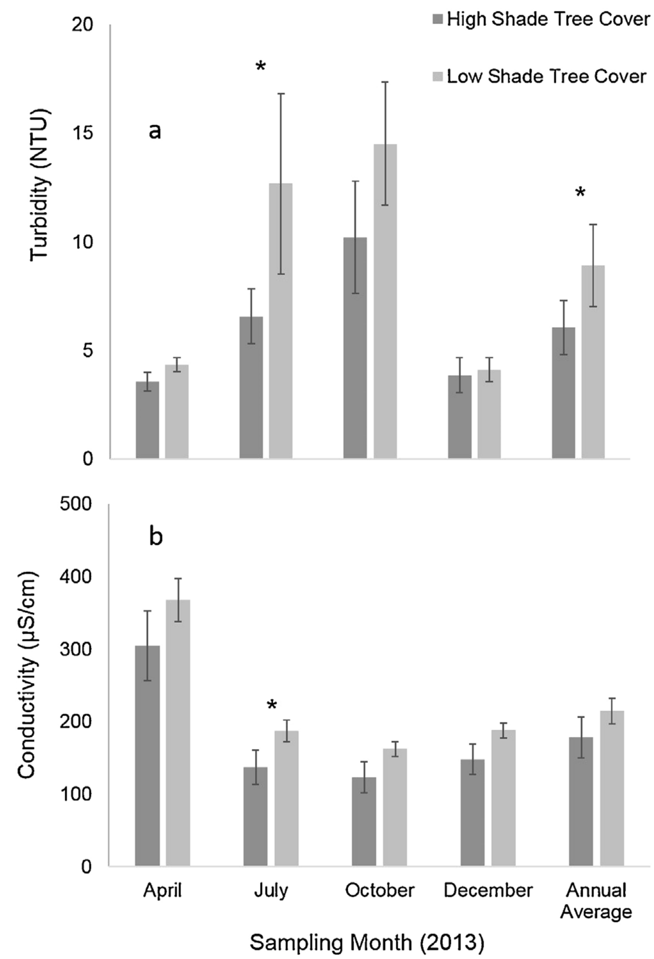

Fig. 3. Means (±SE) for (a) turbidity and (b) conductivity by shade tree cover category: High Shade Tree Cover (N = 5) and Low Shade Tree Cover (N = 5). Results are presented per sampling month: April (baseline), July (transition), October (peak rain), December (return to baseline) and annual average. *Denotes statistical significance.

4. Discussion

This study evaluated the effectiveness of the Rainforest Alliance's (RA) certification guideline of 40% minimum shade tree cover at controlling turbidity and conductivity, two indicators of non-point source pollution, in coffee agroforestry systems. We provide the first account of a correlation between these variables and different levels of shade tree cover at the sub-watershed scale. Our study showed that the HSTC sub-watersheds, which were near or exceeded RA's 40% minimum shade tree cover, had lower stream turbidity on an annual basis and lower turbidity and conductivity during the transition period from dry to rainy season (July). We also found that sub-watersheds that complied with RA's shade tree cover criteria tended to have higher percentages of RA certified farms (although this trend was not significant at an alpha level of 0.05).

Table 2
Candidate models of sub-watershed land use to explain significant difference in non-point source pollution between the two shade tree cover category groups. Percent shade tree cover was the best predictor of turbidity in July ($y_1 = 44.22–0.88\ \beta_1$, $R^2 = 0.32$, $p = 0.04$) and mean annual turbidity ($y_2 = 14.18–0.19\ \beta_1$, $R^2 = 0.33$, $p = 0.04$). Conductivity in July was explained similarly by the percentage of sun grown coffee ($y_3 = 0.11 + 0.002\ \beta_2$, $R^2 = 0.13$, $p = 0.15$) and shade tree cover ($y_3 = 0.22–0.001\ \beta_1$, $R^2 = 0.12$, $p = 0.16$).

Candidate models		Model ranking			
Responses	Predictive variables	Rank	AIC	ΔAIC	AIC weight
Turbidity in July	% Shade tree cover	1	73.03	0	0.7195
	% Exposed soil	2	75.87	3.82	0.1739
	% Sun coffee	3	76.85	2.84	0.1065
Mean annual turbidity	% Shade tree cover	1	59.34	0	0.7338
	% Exposed soil	2	62.41	3.07	0.1581
	% Sun coffee	3	63.17	3.83	0.1081
Conductivity in July	% Sun coffee	1	−24.45	0	0.4265
	% Shade tree cover	2	−24.06	0.39	0.3509
	% Exposed soil	3	−23.15	1.3	0.2226

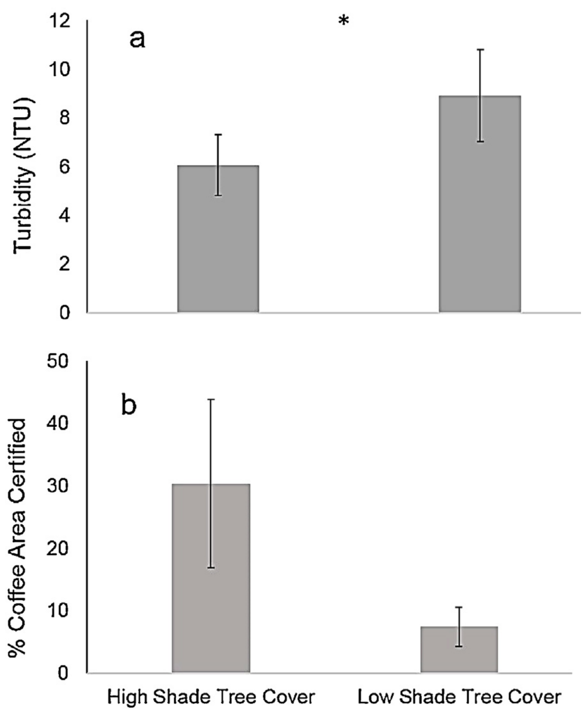

Fig. 4. Means (±SE) for (a) turbidity ($p = 0.042$), (b) average % of the sub-watershed's coffee growing area that is certified by the Rainforest Alliance ($p = 0.0823$) in 2013. Comparisons are presented by shade tree cover category: High Shade Tree Cover ($N = 5$) and Low Shade Tree Cover ($N = 5$). *Denotes statistical significance.

These results support the potential of shade reforestation within coffee farms to impact non-point source pollution control at the sub-watershed scale, and suggest a spatial association between the implementation of this practice and the RA certification program. To our knowledge, this is the first study to empirically assess the effectiveness of an RA guideline on non-point source pollution management, contributing to our existing knowledge on the role of agroforestry certification programs on ecosystem service conservation (Mas and Dietsch, 2004).

4.1. The role of shade trees in non-point source pollution control

Observations in July showed the strongest within-month effects of shade tree cover on turbidity. These corresponded with the transition from dry to rainy season, a period during which the "first flush" effect causes loose detached soil to wash into the streams at a higher rate (Ziegler et al., 2000). As the rainy season progresses, higher discharge within streams could cause greater rates of bank erosion, leading to turbidity increases unrelated to non-point source pollution from land use practices. Indeed, the difference between turbidity in HSTC and LSTC streams did not differ significantly during the October rainy season sampling. During the dry season (April and December), both groups tested with low turbidity levels, likely due to stable discharge and low runoff across sites.

These results are meaningful for stream ecosystem conservation, as aquatic biota show sensitivity to turbidity levels as low as 10 NTU (DEQ, 2014). The HSTC sites maintained turbidity levels below 10 NTU through the year, except for one site that surpassed this value during July (transition season, 11 NTU), and two sites that surpassed it in October (peak rain, 10.1 and 20.3 NTU). In contrast, three of the LSTC sites surpassed this level in July (24.7, 12.7 and 20.5 NTU) and four during October (24.3, 17.4, 11.9 and 14.5 NTU). Coffee agroforestry sub-watersheds with shade tree cover at or above 40% may thus promote aquatic ecosystem conditions that favor optimal biological health during a greater part of the year.

When the study examined conductivity as an indicator of agrochemical pollution, it found seasonal variation trends, but fewer differences between HSTC and LSTC sites than for turbidity. Across all sites, conductivity was higher during the month of April, which represents the baseline conditions and the end of the dry season. This trend could be explained by a greater proportion of groundwater inputs during this period, lack of dilution and heightened evaporation (Carusso, 2002). With the onset of the rainy season, conductivity experienced dilution by precipitation and stream flow. During the transition period (July), conductivity was significantly lower for the HSTC streams, implying a faster rate of dilution at these sites, maybe due to lower agrochemical inputs from runoff. However, according to the AICc analysis, shade tree cover and sun coffee percentages were equally likely to be driving this pattern. Either higher levels of exposed sun coffee lead to greater agrochemical inputs, and/or lower shade tree cover promotes less on-site agrochemical retention. These propositions are not mutually exclusive, and while the latter corresponds directly to the predictions of this study, the former corresponds to predictions by other authors suggesting greater rates of agrochemical application in full sun coffee vs shade coffee (Moguel and Toledo, 1999). It is therefore possible that the potential benefits of shade tree cover to regulate agrochemical exports to streams may have been confounded by unobserved farm-level agrochemical practices. Across the Tarrazú coffee region, nitrogen application varies from 113 to 374 kh/ha (mean 212 (±50)) and lime application varies from 0 to 2048 kg ha^{-1} (mean 658 (±445)) (Castro-Tanzi et al., 2012). The relative importance of shade tree cover vs percentage of sun coffee in driving agrochemical trends, and the mechanisms behind these trends, should be an important topic for future research.

In terms of conservation implications, conductivity values under 300 μS/cm are acceptable for the preservation of freshwater fauna (USEPA, 2010) in streams that are naturally low in solutes (which we assume should be the case in our study system). Both groups had average conductivity values that exceeded this level during April, while both maintained relatively low conductivity levels during the rest of the year. This suggests that the impact of agrochemical pollution is best detected before the onset of the rainy season, and that preserving 40% shade tree cover may not in itself sufficiently mitigate agrochemical runoff. Since our high and low shade tree cover groups differed in terms of proportion of RA certified farms, similar levels of conductivity in both groups suggests that although RA may have been positively associated with implementing shade tree cover reforestation, it may currently have limited impact on agrochemical reduction. This trend, however, warrants further evaluation.

4.2. The role of the Rainforest Alliance certification on non-point source pollution control

The data in this study suggest that the benefits of shade trees for erosion control are achieved by having ∼40% or more shade tree cover at the watershed scale. This provides empirical support for the RA certification requirements. The study also shows that sub-watersheds with high percentage of shade tree cover have a higher proportion of RA certified farms. Although the trend was not significant at the $\alpha = 0.05$ level, it was significant at a $\alpha = 0.10$ level, and is consistent with findings from studies by Rueda et al. (2014), showing that RA certification increased landscape level shade cover in coffee growing regions in Colombia. Our low sampling size and lack of statistical significance suggests that more studies are needed to verify the implications of results in Costa Rica. Moreover, this study did not test whether the higher shade tree cover is a consequence of the RA requirements, or if having higher shade tree cover led to the inclusion of these farms in the certification program. Follow-up studies in Tarrazú should focus on evaluating the same farms before and after becoming RA certified to determine whether RA program exerts a positive influence on shade tree cover reforestation, as they did in Colombia (Rueda et al., 2014).

According to this study, potential limitations of the RA program regard the implementation of agrochemical management practices (discussed earlier) and riparian buffer guidelines. The sub-watersheds in this study all averaged between 12% and 14% forest cover in the 20 m riparian buffer, and between 14% and 15% in the 5 m buffer zone, regardless of the proportion of farms that were certified. This level of riparian forest degradation could have consequences for the condition of aquatic ecosystems draining coffee farms. For example, parallel studies conducted in the Tarrazú coffee region (De Jesús Crespo, 2015), found that among the most notable changes in stream bio-integrity for streams draining coffee farms was a reduction in shredder macroinvertebrate taxa, which could be associated with a loss of high quality leaf litter from native riparian trees. RA requires riparian buffer preservation, but this is not a widespread practice in coffee agroforestry systems in Tarrazú, even within those sub-watersheds with higher shade tree cover and RA certified farms.

Finally, although our study was conducted at the sub-watershed scale, sustainability certification, including RA's, happens at the farm scale. For greater environmental impact, certification programs need to establish connections with broader ecosystem protection initiatives in order to achieve landscape level impact and more effectively advance conservation goals (Tscharntke et al., 2014). Expanding shade tree requirements to the sub-watershed scale may be more feasible though partnerships between sustainability certification programs and other conservation initiatives. For example, a pilot program sponsored by the Costa Rica National Forestry Fund (FONAFIFO) and the Costa Rica Coffee Institute (ICAFE), among other government entities, uses payment for ecosystem services to promote the use of shade trees within coffee plantations by paying up to $70 per hectare to eligible farmers (FONAFIFO et al., 2014). Partnerships with such programs may allow RA, and similar certifiers, to scale up their efforts to ensure ecologically meaningful water quality outcomes.

5. Conclusion

Elucidating strategies for watershed management in high elevation coffee allows for more targeted efforts in an increasingly important agricultural sector. This study provides a stepping-stone toward this goal by providing evidence for the importance of shade trees in sediment control at a minimum of ∼40% shade tree cover. This level of shade tree cover corresponds to guidelines included in the Rainforest Alliance and Smithsonian Bird Friendly certification. Therefore, our study provides some evidence to support the guidelines used in these programs for tropical highland water quality management.

Our research showed limited impact of shade tree cover on regulating conductivity, our indicator of agrochemical pollution. This trend could be attributed to the fact that we did not control for differences in the rates of agrochemical application among the high and low shade tree cover groups. However, because shade tree cover showed landscape associations with the percentage of RA certified farms, this trend suggests that RA certification may have limited effectiveness at reducing agrochemical use in the Tarrazú region, but more work is needed to assess these findings further.

In order to corroborate the role of shade tree cover in reducing agrochemical exports, future studies should aim to conduct more frequent analysis of stream physicochemical patterns through the year and to select sites controlling for agrochemical applications among comparison groups. Future studies should also include additional non-point source pollution indicators, such as heavy metals, nitrogen and phosphorus, and more detailed quantification of sediment exports from sites above and below 40% shade tree cover.

Conflict of interest

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2016.01.025. These data include Google maps of the most important areas described in this article.

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