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Research Article

A preliminary assessment of water quality in silvopastoral systems of Panama's dry tropical forest

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Abstract

Dry tropical forests are unique, biodiverse ecosystems threatened by human development, especially deforestation for agricultural land use. Deforestation reduces carbon sequestration in landscapes and, in turn, pollutes nearby waterways. Agroforestry practices, like silvopastoralism, can mitigate these impacts by integrating trees into working landscapes, but their effect on stream water quality has not been studied. We assessed the stream condition on five silvopastoral farms in Panama's Azuero Peninsula by utilizing aquatic macroinvertebrates as indicators. We collected aquatic macroinvertebrates and calculated the percent EPT, Diptera, and Odonata. Using ArcGIS, we measured distance to live fence, riparian connectivity, and forest patch size. We also measured tree carbon stored in the riparian area and throughout each farm. We analyzed the relationships between landscape or habitat variables and water quality scores using single linear regressions in R Studio. Percent EPT, Odonata, and diversity were positively predicted by riparian tree carbon, while percent Diptera was negatively predicted by riparian tree carbon. Our results highlight the importance of expanding agroforestry in this region and suggest that increasing tree cover in agricultural landscapes may be beneficial to stream condition, but additional research is needed.

Key words: dry tropical forest, macroinvertebrates, neotropics, riparian, stream restoration

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Introduction

Tropical dry forests experience high seasonal drought stress; they accumulate 1300–1700 millimeters (mm) of precipitation annually, but primarily during only half of the year (Dexter et al. 2018; Griscom 2020). These climatic conditions result in deciduous forests and support remarkable biodiversity. For example, a previous study in Costa Rica's dry tropical forests found high Coleoptera (beetle) diversity in rivers, and high overall biodiversity regardless of surrounding land use (Kohlmann et al. 2021).

Unfortunately, human land usage has fragmented many dry tropical forests, producing smaller secondary forest fragments, reducing habitat, and diminishing the carbon stored in the landscape (Dexter et al. 2018). Land fragmentation and habitat loss can detrimentally impact ecosystems, particularly by reducing biodiversity and water quality (Mendenhall et al. 2016; Tanaka et al. 2016). Previous research has shown that land fragmentation negatively influences the flow of water and nutrients into streams (Quinn et al. 1997; Goldstein et al. 2007; Clapcott et al. 2012). On cattle pastures specifically, manure can enter nearby streams, carrying harmful digestive bacteria known as coliforms, and increasing nutrient inputs (Horak et al. 2019; Inamdar et al. 2001).

Areas, including forests, and surrounding streams are known as riparian zones. Streams with low density riparian areas, such as those in fragmented landscapes, store less carbon and are found to contain a lower biodiversity of aquatic macroinvertebrates, which are useful indicators of stream biological condition (Nislow and Lowe 2006). Open canopy riparian areas also often have decreased water quality, such as higher nitrogen levels and water temperature, according to physicochemical parameters (Taniwaki et al. 2017). Compared to larger fragments, smaller riparian forest fragments support a lower proportion of pollution-sensitive aquatic macroinvertebrate species, like mayflies (Ephemeroptera) and caddisflies (Trichoptera) (Stewart et al. 2001).

One practice that can reduce fragmentation and increase habitat and carbon storage in agricultural areas is agroforestry (Pimentel et al. 1992). Agroforestry is an overarching term used to describe multiple land management practices including incorporating trees into agricultural landscapes. Silvopastoralism is one type of agroforestry that specifically integrates trees into animal pastures, including cattle pastures. Previous research has found that silvopastoralism improves soil quality, increases shade and fodder for livestock, increases carbon storage, and provides commercial products for landowners (Chapman et al. 2020; Jose and Dollinger 2019; Metzel and Montagnini 2014). However, the effect of silvopastoral practices on water quality has not yet been studied in any region.

To evaluate the biotic health of agricultural ecosystems, a common approach involves surveying the organisms inhabiting the streams. Complementing this assessment, measuring water chemistry (including nutrients, dissolved oxygen, and temperature) is frequently conducted to gauge the water quality. While water chemistry analysis offers a snapshot of the immediate water condition, the presence and diversity of macroinvertebrates serve as indicators of the long-term biological state within streams. These macroinvertebrates are particularly sensitive to habitat changes, and their diversity can be used to monitor the overall health of aquatic environments over time (Berkman et al. 1986; Karr 1999; Ramírez et al. 2006). Therefore, analyzing physicochemical parameters in addition to macroinvertebrates is essential for a comprehensive assessment of streams and water quality.

We focused our research on the dry tropical forests of Panama. Formerly abundant along the Panamanian Pacific coast, these forests are now mainly fragmented remnants along waterways due to agricultural expansion (Harvey et al. 2005; Griscom and Ashton 2011). Our investigation assessed water quality in riparian areas of agroforestry farms and evaluated their relationships with various landscape and habitat parameters (as described in Table 2). We hypothesized that (1) riparian area size, (2) carbon stored on the farm, and (3) distance from surrounding forests would be the most significant predictors of water quality. Specifically, we predicted that larger forested riparian areas, farms with higher carbon storage, and greater forest connectivity would all predict higher water quality according to biotic metrics and water chemistry.

Methods

Aquatic invertebrates were surveyed on five farms in the Azuero Peninsula, Los Santos Province, Panama during the dry season (Fig. 1). Each farm participated in the Environmental Leadership and Training Initiative (ELTI), a program aiming to increase forest cover on agricultural land through agroforestry practices (ELTI 2022). Created by the Forest School at the Yale School of the Environment, ELTI introduced a new, bottom-up approach to land conservation and restoration by mentoring local peoples and organizations. ELTI collaborates with key partners in Panama, Columbia, Brazil, Philippines and Indonesia (ELTI 2022). A variety of land types occupy the five ELTI farms surveyed, including pasture, forestry plantations, home gardens, riparian forests, and live fences. All five farms had comparable riparian area and total farm sizes, except for SP3, which was the largest (Table 3).

At each farm, we selected four distinct stream sections, evenly distributed throughout the farm's riparian area (Fig. 1). As water flow during the sampling period was low, riffles could not be consistently found; thus, sample pools comparable in size and structure were selected, one per stream section. All sample sites had primarily sandy/silty bottoms with few pieces of cobble. At each sample site, three pH and temperature readings were measured with a combination pH and temperature sensor (Hanna Instruments, Woonsocket, RI). Fecal coliform bacteria presence was assessed with a field coliform test kit at each site (WaterSafe, Azusa, CA). All sites were sampled between 14 and 18 March, 2022.

Following Kohlmann et al. (2021), aquatic macroinvertebrates were surveyed by disturbing the substrate at the bottom of the stream for ten seconds. This procedure was repeated three times per sample site. Each time, a 500 μm sieve was used to collect displaced macroinvertebrates. The invertebrates were washed from the sieve into a tub of water, sorted morphologically using an ice cube tray, identified to order, and then returned to the stream (Merritt, Cummins, Berg 2008; Kohlmann et al. 2021). Crustaceans were not counted. These data were used to calculate seven stream condition metrics (Table 1).

These stream metrics were compared against landscape and habitat metrics, as summarized in Table 2. Using a fish-eye lens attachment on a smartphone, a canopy image was captured at each sample site (Bianchi et al. 2017). Images were converted to black and white pixels with the caiman package in R Studio to calculate the percent canopy cover (Diaz 2018). We measured live fence length, live fence connectivity, riparian area, riparian width, and forest connectivity using ArcGIS Pro v2.6 (Esri, Redlands, CA; Table 2).

Total and riparian area tree carbon were assessed on each farm by measuring and identifying all trees over 5 cm diameter within a randomly selected 30 m by 30 m plot. This served as an indicator of forest habitat available as well as carbon stored in the landscape. Carbon storage was calculated using the Model 7 allometric equations (Chave et al. 2014; Griscom 2020).

For each water quality metric, a Shapiro Wilk test was conducted to test for normality in R Studio v4.13. Shannon diversity, richness, canopy cover, and closest forest patch were normally distributed ($p > 0.05$), while all other variables were not. Either an ANOVA or Kruskal Wallis test was used to compare aquatic water quality metrics across farms, depending on the metric's distribution. If the test was significant, a Tukey HSD test was used to identify pairwise differences for normally distributed metrics and a Nemenyi all-pairs comparisons test was used for nonparametric differences. Single linear regressions were conducted to evaluate correlations between water quality and habitat variables (Tables 1, 2).

Table 1. Description of stream condition metrics used.

Name	Description
EPT Index	Percent Ephemeroptera, Plecoptera, and Trichoptera (mayflies, stoneflies, and caddisflies, pollution-sensitive taxa) in sample
EPT Index no H	Percent Ephemeroptera, Plecoptera, and Trichoptera in sample without Hydropsychidae (a pollution-tolerant family within Trichoptera)
% Diptera	Percent Diptera (true flies, pollution-tolerant) in sample
% Odonata	Percent Odonata (dragonflies and damselflies, pollution-sensitive) in sample
Taxonomic Richness	Number of unique orders in sample.
Abundance	Total number of macroinvertebrates in each sample.
H'	Shannon Diversity Index

Table 2. Description of predictor variables.

Name	Description
Total Carbon (MgC/ha)	Total aboveground biomass on each farm.
Riparian Area Carbon (MgC/ha)	Aboveground biomass of only riparian areas on each farm.
Riparian Area (ha)	Total riparian area on each farm. Measured with ArcGIS Pro v2.8 (Esri, Redlands, CA).
Riparian Width (m)	Average width of riparian areas per farm. This includes stream width. Measured with ArcGIS Pro v2.8 (Esri, Redlands, CA).
Percent Canopy Coverage	Percentage of sky that is covered by tree canopy directly above each sample site. Grouped by farm to obtain average percent canopy coverage per farm.
Live Fence Length (m)	Total live fence length per farm.
Proportion Live Fence Coverage	Total live fence length divided by total farm area. Measured per farm.
Live Fence Connectivity (m)	Distance to closest live fence from each sample site.
Closest Forest Patch (m)	Distance to closest forest patch (greater than five ha) from each sample site.
Riparian Connectivity (100)	Percentage of area within 100 ha of each farm that is riparian area. This area was centered around each farm, forming a square.
Riparian Connectivity (500)	Percentage of area within 500 ha of each farm that is riparian area. This area was centered around each farm, forming a square.
Riparian Connectivity (1000)	Percentage of area within 1000 ha of each farm that is riparian area. This area was centered around each farm, forming a square.

Table 3. Riparian area and total size (hectares) of the five farms surveyed.

Farm Code	SP1	SP2	SP3	SP4	SP5
Riparian Area Size (ha)	1.15	1.98	3.87	1.21	2.07
Total Farm Area (ha)	10.82	11.89	46.62	8.29	17.79

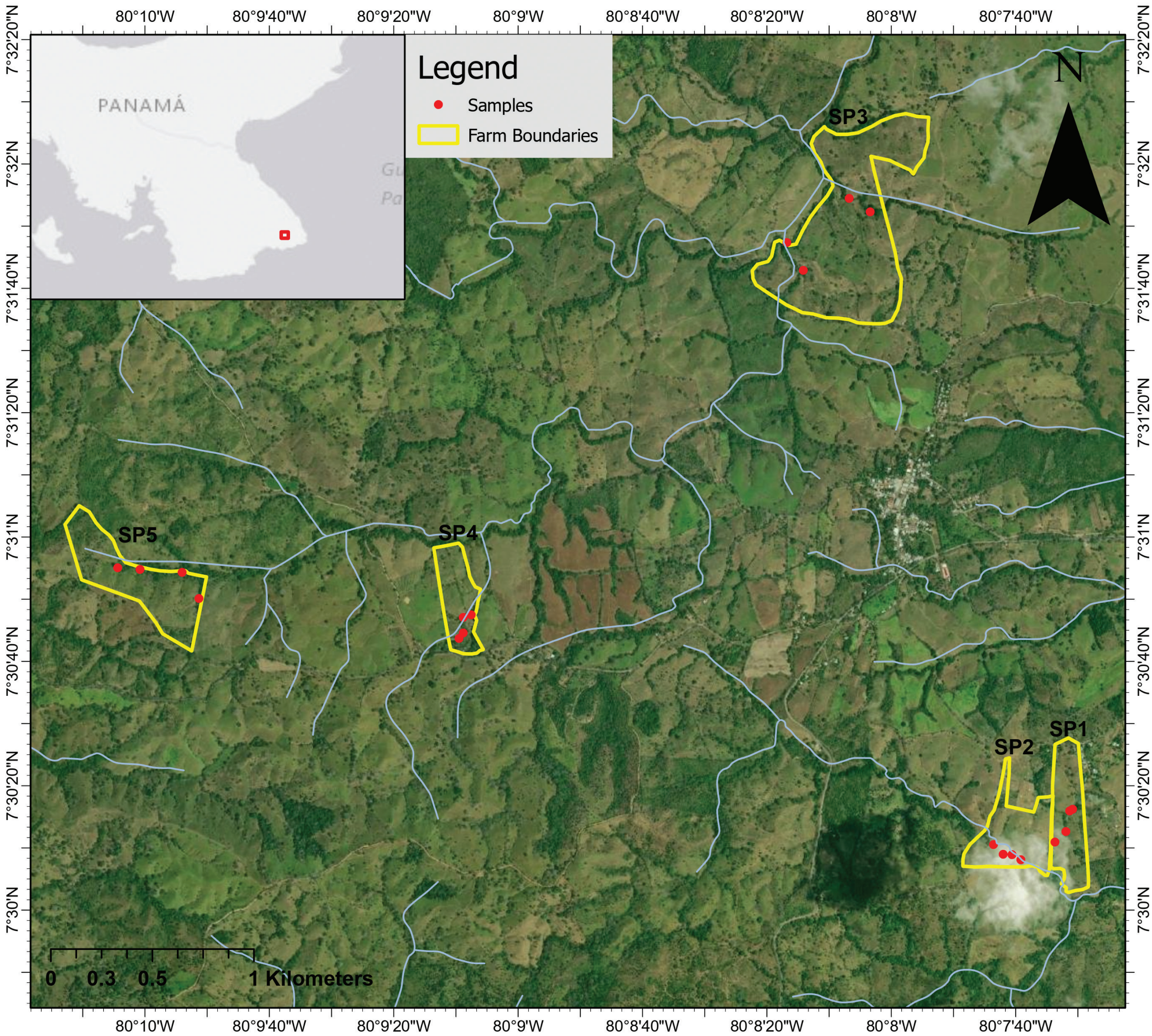

Figure 1. Map of samples (red dots) collected at each of five farms (outlined in yellow) (ELTI 2022). Farms are labeled by site code and streams are indicated with blue lines.

Results

Overall, 852 invertebrates were identified across thirteen orders (summarized in Table 4). At three of the five farms, Diptera (indicators of poor biological condition) comprised the greatest proportion of the community, while Ephemeroptera (indicators of better biological condition) were more prevalent at the other two farms. In total, 358 Diptera were sampled, followed by 189 Ephemeroptera. Only one Hirudinea and one Bivalvia were collected, both at farm SP1. On average, Shannon diversity (H') and richness were greatest at SP5 (1.49, 6.75) and lowest at SP3 (0.62, 3.75). Median abundance was highest at SP5 (52) and lowest at SP1 (27). Farm SP4 had the highest percent Odonata, EPT, and EPT no H, as well as the lowest percent Diptera (16.1%, 55.6%, 52.3%, 7.7%, respectively). Farm SP3 had the lowest percent Odonata, EPT, and EPT no H, as well as the highest percent Diptera (3.2%, 12.2%, 12.2%, 58.7%, respectively).

Table 4. Summary of macroinvertebrate orders and abundances collected at each farm.

Order (scientific name)	Order (common name)	Farm					Sum
		SP1	SP2	SP3	SP4	SP5	
Bassomatophora	Lunged snails	8	11	4	9	6	38
Bivalvia	Bivalves	1	0	0	0	0	1
Coleoptera	Beetles	11	2	4	9	0	26
Diptera	True flies	92	13	20	34	199	358
Ephemeroptera	Mayflies	16	54	25	74	20	189
Gastropoda	Gilled snails	3	1	0	6	0	10
Hemiptera	True bugs	12	0	2	2	22	38
Hirudinea	Leeches	1	0	0	0	0	1
Hydracarina	Water mites	3	3	13	25	0	44
Odonata	Dragonflies and damselflies	12	26	4	30	6	78
Trichoptera, Hydropsychidae	Netspinning caddisflies	0	9	4	7	0	20
Trichoptera, not Hydropsychidae	Non-netspinning caddisflies	0	14	1	5	0	20
Turbellaria	Flatworms	0	21	3	5	0	29
Sum		159	154	80	206	253	852

Fecal coliform bacteria were present in all samples. Canopy cover ranged from 52.83% to 84.75%, pH values were very consistent, ranging from 6.93 to 7.18, and water temperatures ranged from 24.4 degrees Celsius to 26.4 degrees Celsius.

Length of live fences ranged from 2.9 km (SP1) to 6.5 km (SP3). Median distance to live fence ranged from 4.5 m (SP4) to 33.3 m (SP3). Median riparian and total carbon were greatest at SP5 (138.4 MgC/ha, 80.4 MgC/ha). Median riparian carbon was lowest at SP3 (65.1 MgC/ha) and total carbon was lowest at SP1 (26.4 MgC/ha). Median riparian connectivity at all scales was lowest at SP5 (8.1%, 7.8%, 7.4%, respectively), while 100 m was highest at SP4 (14.3%), and 500 and 1000 m were highest at SP1 (12.1%, 10.3%).

The distance to the closest forest patch differed significantly between farms ($F = 56.3$, $p < 0.001$), with farm SP3 having significantly higher distances than any other farm (1184 m) and farm SP1 having significantly lower distances than any other (271 m). pH was significantly lower at farm SP5 than SP2, although no other differences were detected ($KW = 12.96$, $p = 0.001$). Percent Odonata differed significantly overall between farms ($KW = 9.63$, $p = 0.047$), but a pairwise test did not reveal any significant differences between farm pairs. Median percent Odonata was highest at farm SP4 (16.1%) and lowest at farm SP1 (2.6%).

The EPT Index was significantly predicted by increasing live fence connectivity ($R^2=0.215$, $p=0.039$, Fig. 2A). H’ was significantly predicted by increasing total carbon and riparian area carbon ($R^2 = 0.232$, $p = 0.031$; $R^2 = 0.216$, $p = 0.039$; Fig. 2B, C). The EPT Index and the EPT Index no H were significantly predicted by increasing riparian area carbon ($R^2 = 0.222$, $p = 0.036$; $R^2 = 0.2045$, $p = 0.045$, Fig. 2D, E).

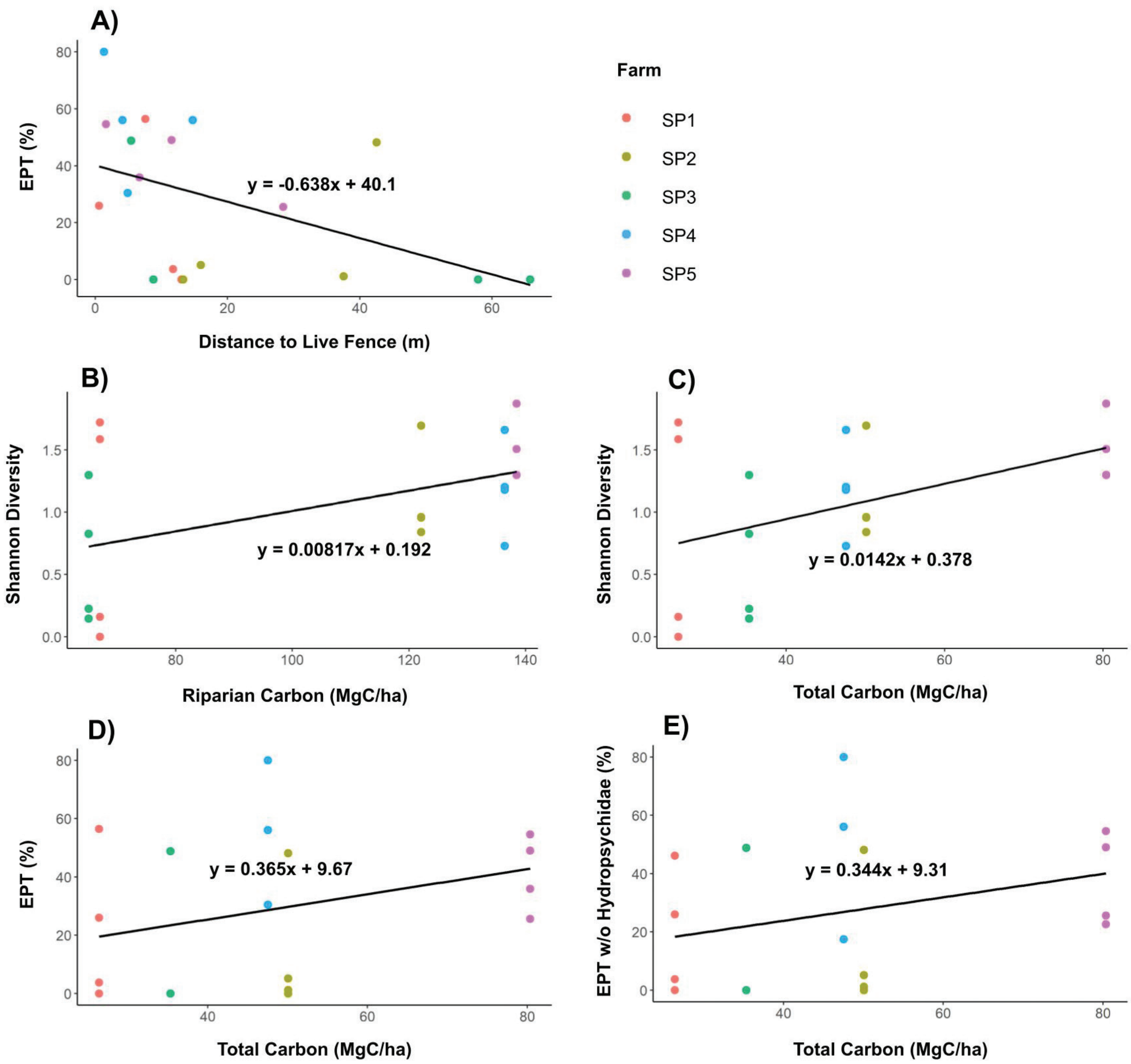

Figure 2. Comparing riparian area metrics to aquatic biological condition metrics **A** only 21.5% of EPT variation can be explained by live fence connectivity ($R^2 = 0.215$, $p = 0.039$). Shannon Diversity increases as **B** Riparian Area Carbon (MgC/ha) ($p = 0.031$, $R^2 = 0.232$) and **C** Total Carbon (MgC/ha) ($p = 0.039$, $R^2 = 0.216$) increases. Increased Total Carbon predicts a higher **D** EPT Index ($R^2 = 0.222$, $p = 0.036$) and **E** EPT Index no H ($R^2 = 0.205$, $p = 0.045$).

Discussion

Our initial predictions that: (1) riparian area and (2) closest forest patch would positively influence water quality were not supported by our data, although the distance to the closest forest patch did differ between farms. We found that (1) live fence connectivity, (2) total carbon and (3) riparian area carbon improved multiple water quality metrics. One explanation is that live fences absorb excess nutrients and run-off with their root system, as most of their carbon is stored below ground (Chave et al. 2014). In general, trees have stabilizing effects on soil, such as live fences helping to stabilize stream banks (Abernethy and Rutherfurd 2000; Albrecht and Kandji 2003; Chacón and Harvey 2006).

The invertebrate communities that we found in Panamanian dry tropical forest streams differed somewhat from other studies conducted in dry tropical regions. For example, Kohlmann and colleagues (2021) found a higher sample proportion of Coleoptera than in our study, as well as the orders Megaloptera, Lepidoptera, and Sphaeriida, which were not found in our samples. In six lowland Costa Rica tropical streams, Ramírez et al. (2006) documented similar insect orders as our study, yet with a higher density of Coleoptera across all six sample sites. Although they did not specify abundance by orders, Tanaka et al. (2016) found EPT index scores in southeastern Brazil streams that were similar to ours and H' scores that were slightly higher.

The physicochemical parameters that we measured seem consistent with other studies in the region; Taniwaki et al. (2017) found comparable water temperatures in their pasture sites, 21.32 degrees Celsius on average in the dry season. Ramírez et al. (2006) found little correlation between insect diversity and physicochemical variables, such as flooding and pH. Similarly, our study found pH to be a poor predictor of insect diversity. On the contrary, Tanaka et al. (2016) found much greater variation in pH values in SE Brazil than our study, potentially due to their inclusion of both sugarcane and pasture sites. These differences may be due to geographic constraints, sampling time, or habitat type sampled; future studies would benefit from assessing more physicochemical parameters than our study and exploring more nuanced variation in macroinvertebrate metrics across Central America.

The relationship between land use and water quality is complex and can be influenced by many factors on both local and broad geographic scales (Goldstein et al. 2007). Small-scale agroforestry techniques, such as silvopastoral systems, have been shown to be more effective for maintaining stream condition than large-scale reforestation in Panama (Anderson 2007). At small scales, numerous studies have found that increased riparian forest area in the dry tropics leads to improved stream condition according to nitrate levels, macroinvertebrate communities, and water temperature (Tanaka et al. 2016; Taniwaki et al. 2017). In contrast, our study found that increased forested riparian area did not significantly correlate with increased aquatic water quality, yet carbon storage did. One possible explanation for these findings is that riparian tree carbon storage could serve as a proxy for riparian area quality (e.g., more trees, larger trees) rather than riparian area size. Our results suggest that implementing agroforestry in dry tropical forests could improve water quality, although more data are needed.

Tree carbon is not the only factor affecting water quality. Livestock, particularly cattle, are also likely to have an important impact on stream condition, as evidenced by our preliminary analysis and previous studies (Horak et al. 2019). Cattle had access to all but two sample locations at site SP4, out of 20 samples in total. Anecdotally, we found a greater macroinvertebrate diversity within taxonomic orders at those two sites than at sites allowing cattle access. However, considerably more survey effort is needed to draw any conclusions, as our findings here may have been coincidental.

Conclusion

Our study provides useful preliminary information for assessing the impact of agroforestry in the dry tropical region of Panama. Although riparian area size and width did not significantly influence water quality, the above ground biomass, and thus the riparian area quality did significantly predict greater water quality. Preliminarily, we posit that implementing agroforestry practices, such as silvopastoralism, could increase stream condition in the cattle pastures of dry tropical regions.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

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No funding was reported.

Author contributions

Conceptualization: BHS, JMP, HPG, GHD. Data curation: JMP, GHD. Formal analysis: GHD, JMP. Funding acquisition: HPG. Investigation: GHD, JMP, BHS. Methodology: HPG, GHD, JMP, BHS. Project administration: HPG. Resources: HPG. Supervision: JMP, HPG. Visualization: GHD, JMP. Writing – original draft: GHD, JMP. Writing – review and editing: HPG, JMP, BHS, GHD.

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Data availability

All of the data that support the findings of this study are available in the main text. The data underpinning this manuscript can be found on Open Science Framework: https://osf.io/drpwh/?view_only=17d651ee2109491e9dd807abfe53faae.

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