Ciencia, Tecnología y Salud, Vol. 9, Núm. 1, 2022
ISSN: 2410-6356 (impreso) / 2409-3459 (electrónico)
https://doi.org/10.36829/63CTS.v9i1.921

Artículo Científico / Scientific Article

Water quality in the Lachuá Ecoregion Landscape: Comparing streams from Forest, Milpa, and an Oil Palm plantation

Calidad del agua en el paisaje de la Ecorregión Lachuá: Comparando arroyos en bosques, milpa y palma africana

Oscar Rojas[1,2], Carlos Avendaño[1,2], & Ryan Isakson[3]

[1]Escuela de Biología, Facultad de Ciencias Químicas y Farmacia, Universidad de San Carlos de Guatemala, Guatemala
[2]Grupo de Ciencias de la Tierra y Resiliencia Planetaria, Ciudad de Guatemala
[3]Department of Geography & Planning, University of Toronto, Canada

***Autor al que se dirige la correspondencia:** oscaralbertorojascastillo@hotmail.com

Recibido: 27 de mayo 2020 / Revisión: 12 de mayo 2021 / Aceptado: 2 de febrero 2022

Abstract

The hydrological network in the Lachuá Ecoregion (EL), Alta Verapaz, Guatemala, hosts high levels of biodiversity and supplies water to 44 Mayan communities. Despite this critical fact, this network has been threatened by scarcely monitored industrial activities including the rapidly expanding oil palm monoculture (*Elaeis guineensis* Jacq). Regardless of Lachua's freshwaters importance, there is little information on how this monoculture impacts them. We compared water-quality properties from streams in oil palm plantations (P), paddock and *milpa* systems (M), and primary forests (F) in the EL. During 2015-2016, 13 rivers were sampled (5 times) for water temperature, pH, dissolved oxygen (DO), conductivity, hardness, chemical and biochemical oxygen demand (COD and BOD), and concentration of silica, nitrates, phosphates, and ammonia. Several parameters showed significant differences. P were 2.7 ºC and 1.8 ºC warmer than M and F and carried 1.4 mg/L more nitrates than F. F carried 10.8 mg/L and 11.8 mg/L more silica than M and P. M showed intermediate temperatures and silica concentrations, as well as 14.8 µS/cm and 8.9 µS/cm lower conductivities than P and F, respectively. Additionally, COD in M was 9.9 mg/L and 4.6 mg/L lower than P and F, respectively. We believe higher temperatures and lower silica in P are due to the loss of riparian forest and their role in buffering temperatures and recycling silicon. In addition, the existence of secondary forest (*guamil*) in M might explain the intermediate temperatures and silica concentrations. Our results highlight the contributions of forests to waterways and suggest potential water-quality depletion from the oil palm expansion in the EL.

Palabras claves: First-order streams, *Elaeis guineensis*, silica cycle, traditional agriculture, riparian forests, Northern Transversal Strip

Resumen

La red hídrica en la Ecorregión Lachuá (EL), Alta Verapaz, Guatemala, alberga una alta biodiversidad y abastece de agua a 44 comunidades mayas. Sin embargo, recientemente se ha visto amenazada por actividades industriales escasamente monitoreadas, incluido el creciente monocultivo de palma africana (*Elaeis guineensis* Jacq) del cual se desconocen sus impactos en la EL. Este estudio explora la calidad del agua de arroyos en plantaciones de palma africana (P), bosques primarios (B), y sistemas de potrero y milpa (M) en Lachuá. Durante 2015-2016, se tomaron muestras de 13 ríos (5 veces) para medir la temperatura del agua, pH, oxígeno disuelto (OD), conductividad, dureza, demanda química y bioquímica de oxígeno (DQO y DBO) y la concentración de sílice, nitratos, fosfatos, y amoníaco. Varios parámetros mostraron diferencias significativas. P fue 2.7 ºC y 1.8 ºC más calientes que M y F y portó 1.4 mg/L más nitrato que F. F portó 10.8 mg/L y 11.8 mg/L más sílice que M y P. M mostró temperaturas y concentraciones de sílice intermedias y conductividades 14.8 µS/cm y 8.9 µS/cm menores que P y F. La DQO en M fue 9.9 mg/L y 4.6 mg/L menor que P y F. El aumento de temperatura y la disminución de sílice en P podría deberse a la pérdida de bosques ribereños los cuales amortiguan la temperatura y reciclan el silicio. La presencia de bosque secundarios (guamil) en M podría explicar las temperaturas y las concentraciones de sílice intermedias resaltando la importancia de los bosques en la red hídrica. Se predice un posible deterioro en el agua resultado de la expansión de palma africana en la EL.

Keywords: Ríos de primer orden, *Elaeis guineensis*, ciclo del silicio, agricultura tradicional, bosques ribereños, Franja Transversal del Norte

Introduction

The Lachuá Ecoregion, located in the northern lowlands of the Alta Verapaz province in Guatemala (Figure 1), is an ecological zone of national and international importance. In addition to hosting the Lachuá Lake National Park, the ecoregion is renowned for its high biodiversity and global recognition as an Important Bird and Biodiversity Area (IBA), and by the Ramsar Convention as a Wetland of International Importance (Eisermann & Avendaño, 2007; Escuela de Biología de la Facultad de Ciencias Químicas y Farmacia de la Universidad de San Carlos de Guatemala, 2004). The ecoregion's water resources play a vital role in sustaining numerous species of mammals, amphibians, reptiles, insects, birds, and plants. The zone is part of the broader Usumacinta Biogeographical province, hosting many endemic fish species and at least 40 endangered fish species, including 22 protected by the Convention on International Trade in Endangred Spcies of Wild Fauna and Flora (CITES) (Granados, 2001). Additionally, more than 44 indigenous Q'eqchi' Mayan communities depend on the ecoregion's water supplies for essential livelihood activities like drinking, fishing, household uses, irrigation of crops, and other ecosystem services (benefits that people obtain from the ecosystem) (Dislich et al., 2017; Escuela de Biología de la Facultad de Ciencias Químicas y Farmacia de la Universidad de San Carlos de Guatemala, 2004).

As several studies have shown, land-use practices can dramatically influence the quality of nearby water systems. The presence of forests, for example, can improve water quality through root filtration and sequestration of pollutants (Fernandes et al., 2014). Correspondingly, land-use changes like the expansion of urban areas and monocrop agricultural systems are associated with declining water quality due to the increased flow of greywater, sediments, and agrochemicals (Comte et al., 2012; Kertész et al., 2019; Liberoff et al., 2019).

Land-use changes in the Lachuá Ecoregion have been profound in recent decades. Through aerial photographs analysis, Quezada et al. (2014) found that forest cover in the ecoregion declined by more than 55% between 1962 and 2011, with deforestation increasing substantially since the late 1980s. They attribute the loss of forest cover initially to the establishment of human settlements - which would include the formation of so-called 'model villages' to house and monitor displaced populations during the country's armed conflict (Taylor, 2007) – roads, annual crops, and, more recently, cattle pastures. However, the chaotic colonization processes also featured the industrial exploitation of natural resources (i.e., mining and oil extraction), which has continued into the post-war era (Avendaño et al., 2005; Secretaría de Planificación y Programación de la Presidencia [Segeplan], 2011).

The expansion of oil palm plantations (*Elaeis guineensis* L.) is among the most profound changes to land-use in the Lachuá Ecoregion in the 21st century (Gremial de Palmicultres de Guatemala [Grepalma], 2018; Solano, 2015). This monocrop arrived in Guatemala in the 1980s, where its cultivation was initially limited to a small number of farms located along the country's southern coast and piedmont. In the last two decades, however, the area cultivated with the crop has increased more than nine times its original size (Food and Agriculture Organization [FAO], s.f.), with nearly all of the expanded cultivation occurring in Guatemala's northern lowlands (Grepalma, 2019). For example, Alonso-Fradejas (2018) estimates that oil palm area expanded 17,340 ha annually between 2006 and 2014, out of which in 2005, 29% was forest, 14% staple agriculture, and 27% scrubland. Hervas (2019) documents similar trends in the Lachuá Ecoregion, where the introduction of approximately 520 ha of oil palm in one community since 2006 corresponded with the loss of ~380 ha of forest area by 2017. In this community, oil palm expansion initially occurred on land used for pasture but soon spread onto land used to cultivate other crops, especially forestland.

Despite the dramatic expansion of oil palm in the Lachuá Ecoregion, the environmental impacts of land-use change have not been investigated adequately. Studies elsewhere show that oil palm plantations are often associated with decreased water quality due to the large application of commercial fertilizers (Goh et al., 2003), herbicides (e.g., Glyphosate, Glufosinate-ammonium, Metsulfuron-methyl, +2, 4-D amide, and Triclopyr), insecticides (e.g. Butocarboxim, Chlorpyrifos, Cypermethrin, Deltamethrin, Gamma HCH, Lambda cyhalothrin, Methamidophos, Methidathion, Monocrothophos, Acephate) and fungicides (Captan, Cyproconazole, Dithiocarbamates, Difenoconazole) (Kuntom et al., 2007). Once these chemicals are applied, the rainfall transports their surplus into streams (Mercer et al., 2013; Wantzen, 2006). Ground cover clearance exacerbates this runoff (Department of Irrigation and Drainage, 1989). Industrial agriculture includes the mentioned practices, which has led to nutrient enrichment, eutrophication, and consequent ecological disruptions (Chappell et al., 2004; Sheil et al., 2009; State Environmental Conservation Department, 2000). This type of agriculture is associated with decreasing dissolved oxygen levels (i.e., 3.59-3.78 mg/L), which can be detrimental for fishes and macroinvertebrates (Sari et al., 2019). Streams running through this agriculture type also tend to be warmer (i.e., 3-7ºC) due to increased solar radiation and reduced evapotranspiration, resultant from the removal of riparian vegetation (Brauman et al., 2012; Carlson et al., 2014; Chellaiah & Yule, 2018), even several years after the establishment of the plantations (Avendaño et al., 2019; Carlson et al., 2014; Luke et al., 2017; Wilkinson et al., 2019). These disturbances are concerning as temperature directly influences various biological and chemical processes from dissolved oxygen concentration to metabolic rates and primary production (Australian New Zealand Educational Council [Anzec] & Agriculture and Resource Management Council of Australia and New Zealand [Armcanz], 2000; Dallas, 2009; Dallas & Ross-Gillespie, 2015). There is still a lack of studies regarding the environmental impacts of oil palm plantations on the Guatemalan river networks. Given the invaluable contributions of Lachuá's riparian environments to human settlements and biodiversity, it is imperative to understand how recent land-use changes in the ecoregion impact water quality. Furthermore, the study of surface water quality in karst environments, such as Lachuá, is critical to understanding groundwater and the complex hydrogeological context due to rapid infiltration schemes. The high connectivity and sub-surface interchange characterize these geological settings (Ford & Williams, 2013).

Alongside oil palm plantations, traditional agricultural practices are still present in the ecoregion, especially *milpas* and paddocks. The *milpa* is a multispecies agroforestry system, wherein maize (*Zea mays*) is combined with annual crops such as beans and squash, vertical crops such as sweet potatoes and other roots, and fruit crops such as bananas and plantains, followed by an eventual forest regeneration period or fallow. Maize is the staple crop that characterizes the milpa system in Mesoamerica (Ford & Nigh, 2016), and its cultivation requires clearing forests from a selected plot, up to twice per year, over 2-3 years. After that, the plot is typically fallowed for 2-3 years to avoid soil exhaustion. The Q'eqchi' population in Guatemala refers to secondary forest succession that emerges in these areas as *guamil*, consisting of herbs, bushes and trees. The *guamil* includes shrubs and generalist and fast-growing species such as *Cecropia peltata* and *Schyzollobium parahybum* (Ávila Santa Cruz et al., 2005). After the fallow period, farmers slash and burn the *guamil* to eliminate herbs and transform organic matter into soil nutrients (Hernández Bonilla, 2004; Monzón Miranda, 1999). Paddocks for livestock feeding (i.e., horses and cattle) are also present in the ecoregion (Solano, 2015). These areas are often covered with opportunistic vegetation like grasses, legumes, shrubs and trees that provide nutrients for the grazing animals (Proyecto Especial para la Seguridad Alimentaria [PESA], 2005) and serve as living fences. After grazed, paddocks are left resting and eventually become *guamiles* (PESA, 2005; Solano, 2015). These practices are cultural components of Lachuá Ecoregion's landscape and define a heterogeneous mosaic of non-extensive patches that contain several forest types at different succession stages (Ávila Santa Curz, 2004).

Our research aimed to understand how the diversity of land-uses influences the water quality of lotic ecosystems in the Lachuá Ecoregion. Specifically, we monitored and measured eleven different physical and chemical indicators of water quality at strategic points of the Lachuá Ecoregion hydrological network in order to assess the impact of three land-uses: (1) *Milpa*-paddocks-*guamil*, (2) oil palm monocultures, and (3) forested areas. For this purpose, we identified first-order streams whose catchments were surrounded separately by the indicated land-uses and assessed our chosen indicators at these locations every two months during one year (September 2015- July 2016).

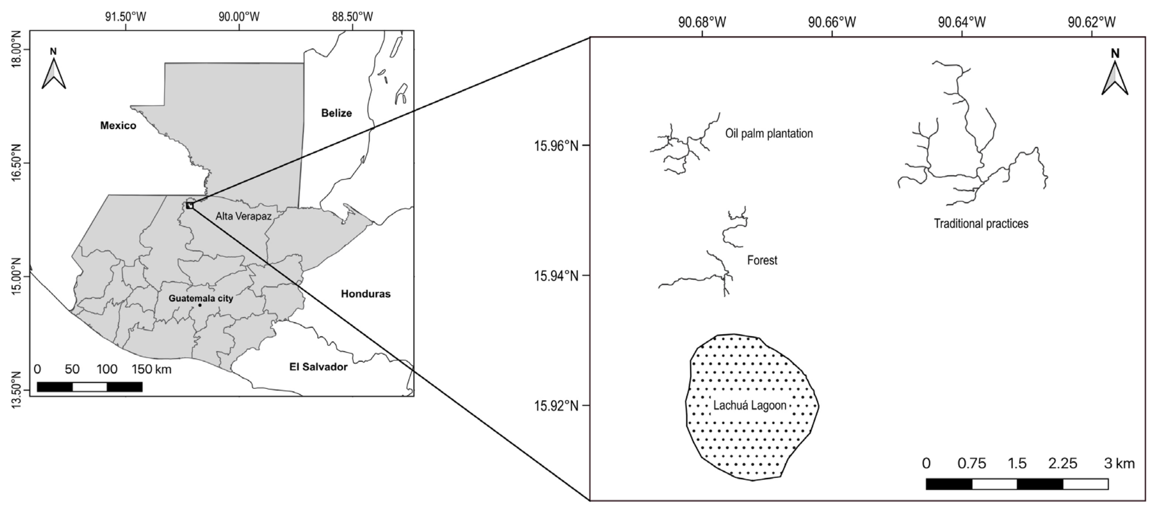
Materials and methods

Study area

We conducted our study in a small section of the Lachuá Ecoregion (15° 57' 30.40"N, 90° 38' 36. 29"W), located in the Department of Alta Verapaz in northeastern Guatemala (Figure 1). The Lachuá Ecoregion location at the northern lowlands of Guatemala frames it to the Chixoy, Icbolay, and Ixloc hydrologic basins that contain a variety of aquatic ecosystems, including wetlands, floodplains, lagoons, rivers, streams, and underwater connections characteristic of its karst hydrogeology (Avendaño et al., 2019; Escuela de Biología de la Facultad de Ciencias Químicas y Farmacia de la Universidad de San Carlos de Guatemala, 2004).

Figure 1

Location of the study streams at the Lachuá Ecoregion, Northern Transversal Strip in Alta Verapaz, Guatemala



The physiographic setting is contextualized by the Lacandón Fold Belt province and karstic Upper Cretaceous geology. In general, the ecoregion water tends to be hard (i.e., alkaline pH), with high conductivity as it contains particles of carbonates, silicates, sulphates, and other soluble salts, and high levels of dissolved oxygen (> 50%), except in slow-running waters (0.25 m/s). The elevation of the study area ranges between 160-210 m, associated with average mean temperatures of 25.3 °C, annual precipitations of 3,300 mm, with the highest rainfall occurring from June to October and only four months of relatively low rainfall, from February to May (Escuela de Biología de la Facultad de Ciencias Químicas y Farmacia de la Universidad de San Carlos de Guatemala, 2004). The complexity of the Lachua Ecoregion's hydrogeology and climatology demands detailed month-to-month monitoring for unveiling the influence of land use on water quality.

Treatments, geo-referencing, and mapping

The area under study includes the Lachuá Lake National Park (PNLL) and several agricultural and livestock practices zones. Inside the study area, we identified three land-use types (henceforth defined as treatments) to compare their effects on water quality. The first field experimental treatment (F) consisted of streams within forests of the PNLL (Figure 2). The PNLL is one of the last remnants of tropical rainforests of the Northern Transversal Strip in Guatemala. The park sustains a diverse ecosystem characterized by dense vegetation composed of 76 different plant families, notably Orchidaceae, Arecaceae, Fabaceae, Rubiaceae, Moraceae, Melastomataceae and Meliaceae (Castañeda Cerna, 1997).

The second treatment (M) consisted of streams surrounded by 'traditional' agricultural practices in the Lachuá Ecoregion. This treatment includes *milpa* where corn is cultivated in a polyculture system; paddocks, consisting of grassland intended for livestock grazing and often containing opportunistic vegetation and living fences; and *guamil* (Figure 3). Finally, the third treatment (P) represents a homogeneous land-use dominated by *Elaeis guineensis,* or oil palm, distanced approximately 15 m from the northern border of PNLL (Figure 4). We focused upon a single plantation with an area of approximately 90 ha, characterized by seven-year-old oil palms. This monocrop surrounds a small village (ca. 25 ha), separated from the PNLL by a 12 m-wide dirt road. The plantation has been fertilized chemically in the past years. However, during our study, the plantation owner applied vermicompost (late December 2015), an organic fertilizer (i.e., a by-product of earthworms) with a low environmental impact when compared to conventional chemicals (Doan et al., 2015).

To control for environmental and spatial variation, we sampled treatments in areas close to one another, avoiding as much as possible spatial autocorrelation (Ribeiro et al., 2013). This approach enabled us to measure differences across land-uses more accurately. There was no water catchment area from one type of treatment that overlapped with another. The distance between F and M was 10 km, 4 km between F and P, and 10 km between M and P.

We selected thirteen first-order streams (*sensu* Strahler, 1957) using Google Earth (C) satellite images from 2014, based on the predominant land use in the catchment area. Our experimental design resulted in five streams in F, four in M, and four in P. The catchment stream area was mapped based on a regional 12.5 m resolution Digital Elevation Model (DEM) employing Global Mapper (C).

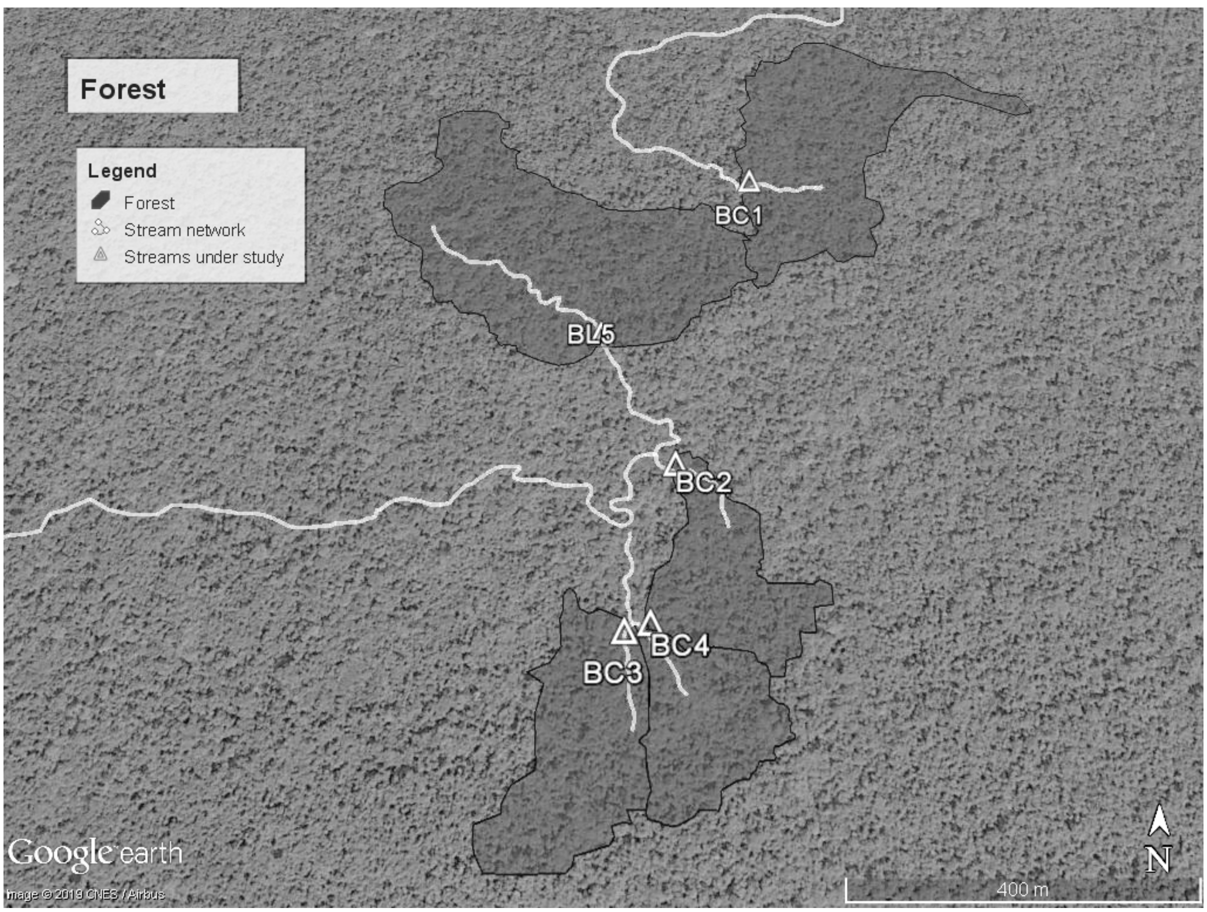
Field verification allowed us to map the waterways and choose strategic points for precise sampling. We chose first-order streams because a smaller catchment area (0.7 - 44 ha), compared to higher-order rivers (> 50 ha), would facilitate isolating the impacts of each land use type on water quality (Dodds & Oakes, 2008).

Water quality: Physical and chemical analysis

We defined an experimental unit consisting of three points (initial, mid-way, and final) spaced 50 m apart over a 100 m long tract for each stream (Figure

Figure 2

Streams from the Forest treatment (F) within the borders of the Lachuá National Park (PNLL)



Note. River codes: BC1, BC2, BC3, BC4, and BL5.

5). The sampling was carried out every two months between September 2015 and July 2016. Due to field logistic reasons, we only monitored oil palm and forest treatments in the first two sampling months (early September and late October 2015) and all three in the remaining samplings (January, March and July in 2016). In addition, we avoided sampling during the intense dry season due to the intermittent nature of some streams.

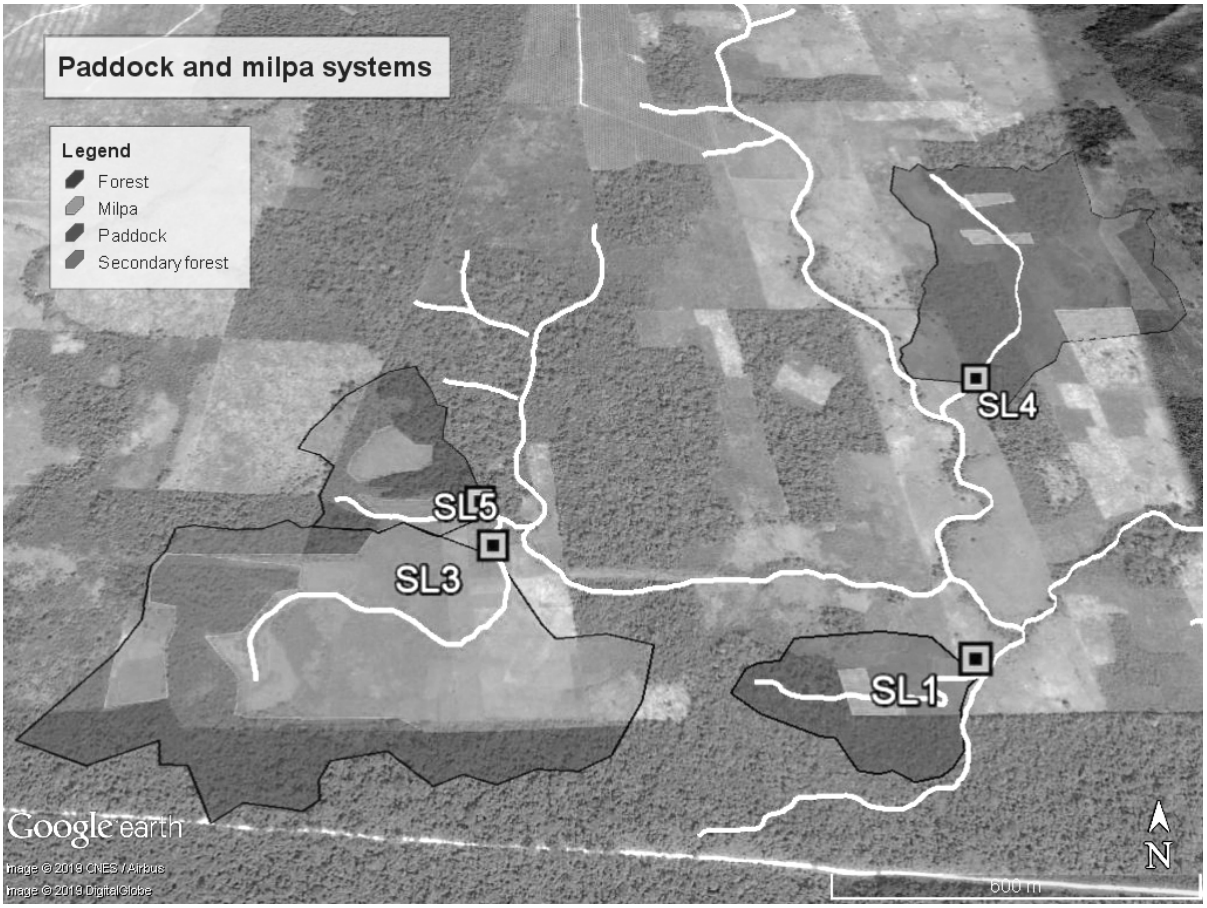
In total, we monitored and measured 11 water quality indicators: Dissolved oxygen (DO), pH, water temperature, electrical conductivity, hardness, chemical and biochemical oxygen demand (COD and BOD), and concentration of phosphates (PO_4), nitrates (NO_3), sulphates (SO_4) and silica (SiO_2). We measured DO, pH, and water temperature *in situ* at all three points of each sampling unit using a multiparameter HI9813-6N probe and an Extech DO210 oximeter. We measured the rest of the indicators *ex situ* at the Laboratory of Physicochemical and Microbiological Analysis (LAFYM) at San Carlos University in Guatemala City. We took water samples at the mid-way point of each unit in the field, stored them in plastic bags (Nasco Whirl-Park ©), and kept them at low temperatures for 3-4 days before delivering them to the laboratory for analysis.

Data analysis

To compare water quality among treatments, we analyzed the data using the packages ggplot2 (Wickham, 2016) and Rcmdr (Fox, 2016) in R studio (RStudio Team, 2016). When comparing more than

Figure 3

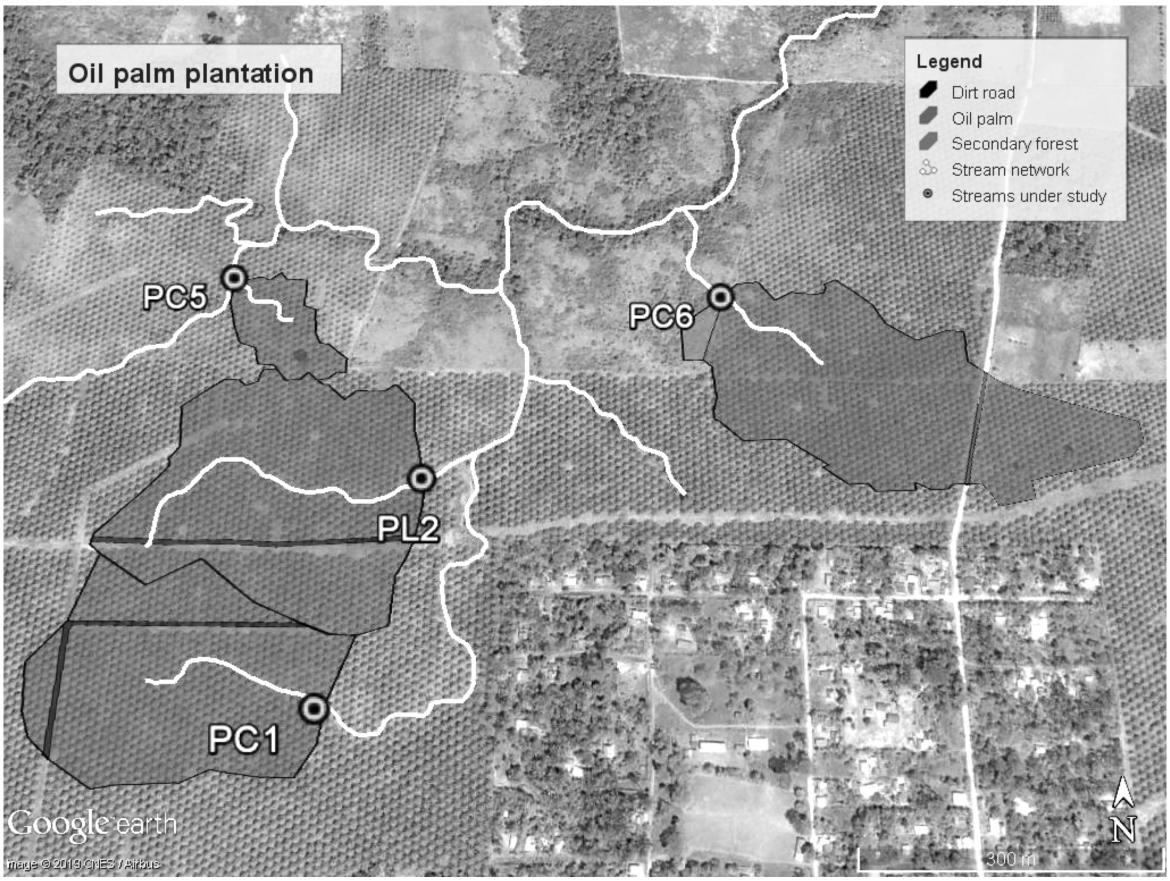
Streams from the Traditional Practices treatment (M), including milpa, paddock, and guamil land uses



Note. River codes: SL1, SL3, SL4, and SL5.

Figure 4

Streams from the oil palm treatment (P) employing vermicompost



Note. River codes: PC1, PL2, PC5, and PC6.

two treatments, we used the Kruskal Wallis (KW) hypothesis test (for non-normal data) and Analysis of Variance (ANOVA) (for normal data). When comparing only two treatments, we used the student t-test (for normal data) and KW. We compared five sampling months data for F and P, while M only the last three months. As the data exhibited a linear response, we used CANOCO (C) to perform a Redundancy Analysis (RDA) to determine the multivariate relationship between water quality and land use (ter Braak & Smilauer, 2012).

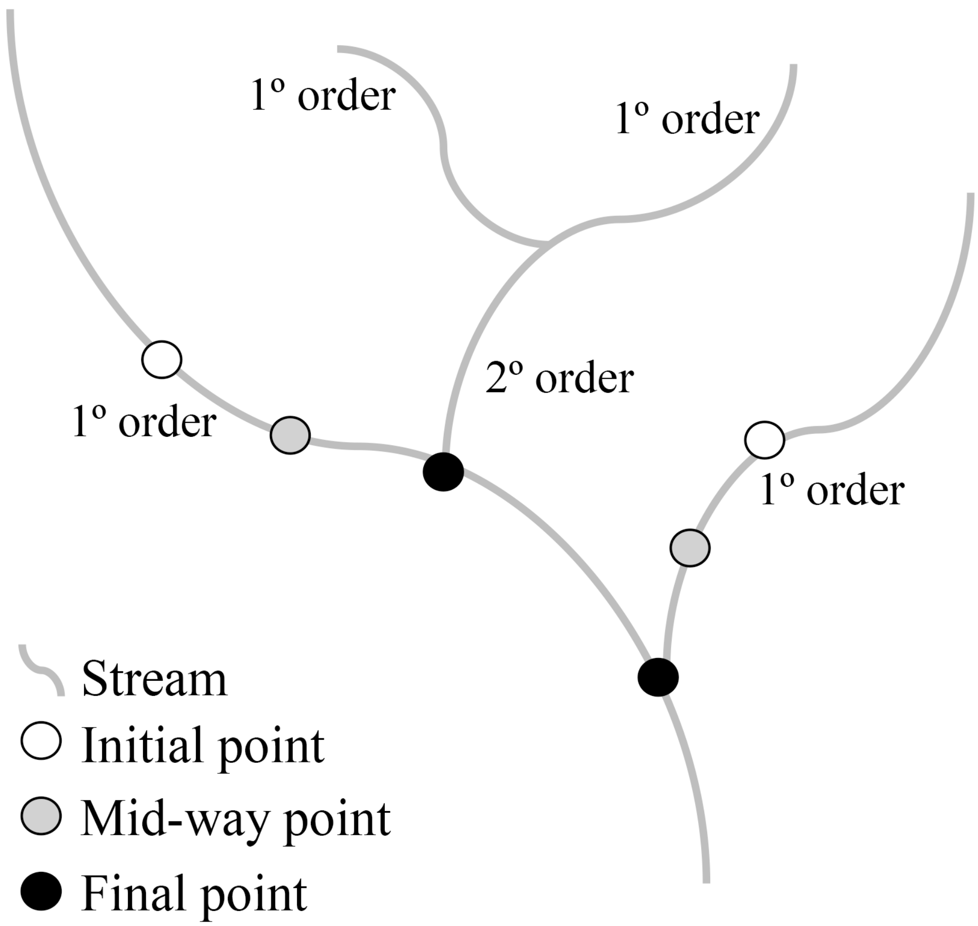
Results

Our results suggest that, relative to the other treatments, P is associated with generally poorer water quality, as reflected in statistically significant differences for five out of 12 of our chosen water quality indicators: Temperature, silica concentration (SiO_2), electrical conductivity, chemical oxygen demand (COD), and concentration of nitrates (NO_3) (Table 1). Following, we discuss our results by focusing on the parameters that showed significant differences between treatments to describe the possible consequences of expanding oil palm plantations in the Lachuá Ecoregion.

Temperature

P streams were significantly warmer ($p < .01$ in all months except January) than the streams of the other treatments. P streams were on average 1.8 ºC warmer than M streams. M streams exhibited inter-

Figure 5
Representation of the sampling units sensu Strahler (1957)



Note. Adapted From "Quantitative analysis of watershed geomorphology," A. N. Strahler, 1957,. Eos, Transactions, American Geophysical Union, 38(6), p. (https://doi.org/10.1029/TR038i006p00913)

mediate temperatures when contrasted with the rest of the treatments. F streams were 0.9 ºC cooler than M streams and 2.7 ºC cooler than P (Figure 6).

Silica concentration

The concentration of SiO_2 was significantly higher in F streams than in the M and P treatments (September, October, and March $p < .05$; January $p < .01$; and July $p < .1$). F streams carried 10.8 mg/L more silica than M streams, and 11.8 mg/L more than P streams. M streams carried on average more silica than P streams; however, this difference was not statistically significant (Figure 7).

Electrical conductivity

M streams presented significantly lower values in two of the three sampling months (January $p < .1$, March $p < .01$) in electrical conductivity. M streams were 14.8µS/cm less conductive than P streams and 8.9 µS/cm less conductive than F streams (Figure 8).

Table 1

Water quality physical and chemical parameters in study treatments across sampling months

Date	Land use	Temp °C		SiO2 mg/L		Cond uS/cm		COD mg/L		BOD mg/L		NO3 mg/L		PO4 mg/L		SO4 mg/L		OD mg/L		pH		Hardness mg/L Ca		Hardness mg/L Mg		NH4 mg/L	
		mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
Sep 2015	Oil palm	28.4	0.7	4.1	2.4	30.5	6.9	20.5	7.3	13.0	4.6	5.8	0.7	2.8	0.6	39.8	11.1	6.4	1.5	6.0	0.4	17.8	1.2	6.8	0.1	ND	ND
	Forest	25.9	0.6	14.6	5.4	28.7	6.7	13.2	9.4	9.6	7.1	3.2	0.7	2.4	0.4	27.6	14.0	6.6	1.9	5.9	0.2	16.3	0.6	6.7	0.4	ND	ND
Oct 2015	Oil palm	28.7	0.4	4.3	1.9	29.2	15.6	22.0	9.1	16.8	8.2	4.4	1.1	0.2	0.2	11.0	15.3	6.1	1.2	6.2	0.3	ND	ND	ND	ND	ND	ND
	Forest	25.6	0.2	8.7	1.7	34.9	16.2	24.6	20.4	13.9	15.7	2.4	0.4	0.3	0.4	5.2	3.8	6.3	0.7	5.7	0.2	ND	ND	ND	ND	ND	ND
Jan 2015	Oil palm	25.2	0.9	4.1	1.9	32.9	8.9	22.8	7.8	17.1	6.7	5.6	1.1	3.5	0.5	38.3	10.8	5.3	1.0	6.3	0.4	4.0	0.7	2.4	0.4	0.1	0.0
	Forest	24.2	0.2	19.8	5.3	26.7	4.8	13.4	7.8	9.8	7.5	4.1	0.7	3.1	0.4	32.6	11.7	6.6	1.4	6.0	0.2	5.3	1.1	3.2	0.7	0.1	0.1
	Milpa	24.8	1.3	4.3	0.4	15.4	3.3	12.0	4.1	7.8	6.6	6.0	1.0	4.0	0.6	44.3	22.4	6.1	1.7	6.0	0.6	8.0	3.5	4.9	2.1	0.1	0.0
Mar 2015	Oil palm	27.8	0.9	5.2	2.7	34.7	9.3	26.3	5.9	7.5	1.7	2.8	1.9	4.2	1.2	4.8	4.1	3.8	0.9	6.3	0.5	5.5	1.4	3.3	0.8	0.2	0.4
	Forest	23.3	0.2	16.5	5.7	24.9	6.0	14.4	6.2	8.4	3.0	7.9	6.8	4.0	0.5	9.4	6.9	6.6	1.2	6.0	0.1	5.9	2.8	3.6	1.8	0.0	0.0
	Milpa	23.8	0.6	4.6	1.0	15.1	0.9	13.0	1.8	9.8	1.0	5.1	1.2	4.4	0.8	5.0	1.8	3.5	1.3	6.1	0.6	6.7	3.8	4.0	2.3	0.0	0.0
Jul 2015	Oil palm	28.0	0.4	4.8	1.7	28.0	10.1	14.5	9.0	10.9	6.8	5.5	0.7	4.1	0.8	34.8	8.1	6.7	0.8	6.1	0.5	4.4	0.5	2.7	0.3	0.1	0.0
	Forest	25.5	0.4	13.1	6.4	26.1	4.1	13.8	7.2	10.4	5.4	6.0	1.7	3.9	0.5	28.2	10.5	6.2	1.8	5.7	0.1	6.1	0.9	3.7	0.6	0.1	0.0
	Milpa	28.1	1.0	6.8	1.1	23.7	4.7	11.3	1.5	8.4	1.1	6.3	0.4	4.2	0.9	33.0	6.6	5.5	0.7	5.8	0.4	7.6	3.8	4.6	2.3	0.1	0.0

Note. Cells in light gray represent slightly significant differences between treatments ($p < 0.1$) and dark gray highly significant ones ($p < .05$).

Chemical oxygen demand

P streams had significantly higher COD ($p < .01$) than F and M streams in March (Figure 9), while only significantly higher ($p < .1$) than M streams in July. Overall, P streams had a COD amount of 9.9 mg/L higher than M streams and 5.32 mg/L higher than F streams.

Nitrate Concentration

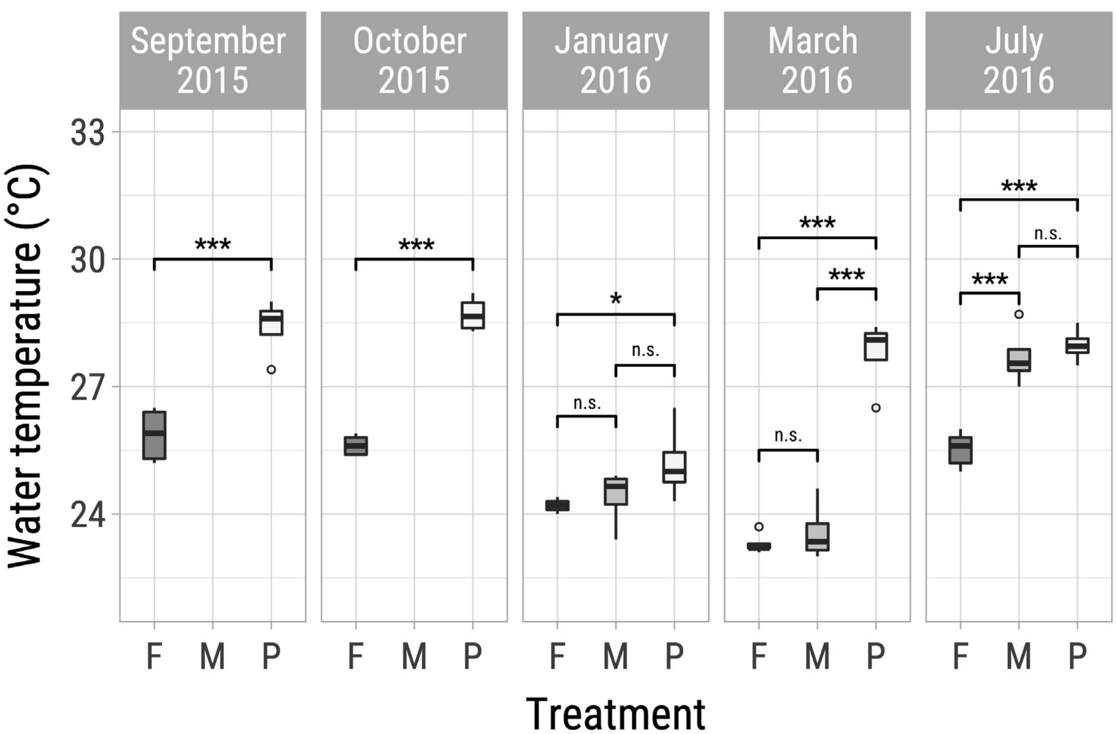
Concentrations of NO_3 were significantly lower ($p > .05$) in F streams than P in September, October, and January. F streams also had lower nitrate concentrations than milpa streams ($p < .1$) in January (Figure 10). There were no significant differences between the P and M streams. During the first three temporal units, P streams carried 1.4 mg/L more nitrates than F streams.

Multivariate relationship between water quality and land use

The RDA analysis indicated that 19% of the total variability was explained significantly ($p < .05$) by the water quality measurements, showing in the first axis a separation of F and P (55% of the variability). We observed a positive relationship between F, silica and DO and a negative one between F and NH_4. P exhibited a positive relationship with temperature, BOD and COD. M showed a positive relationship with hardness, phosphates, nitrates, and sulphates; and a negative one with conductivity (Figure 11).

Figure 6

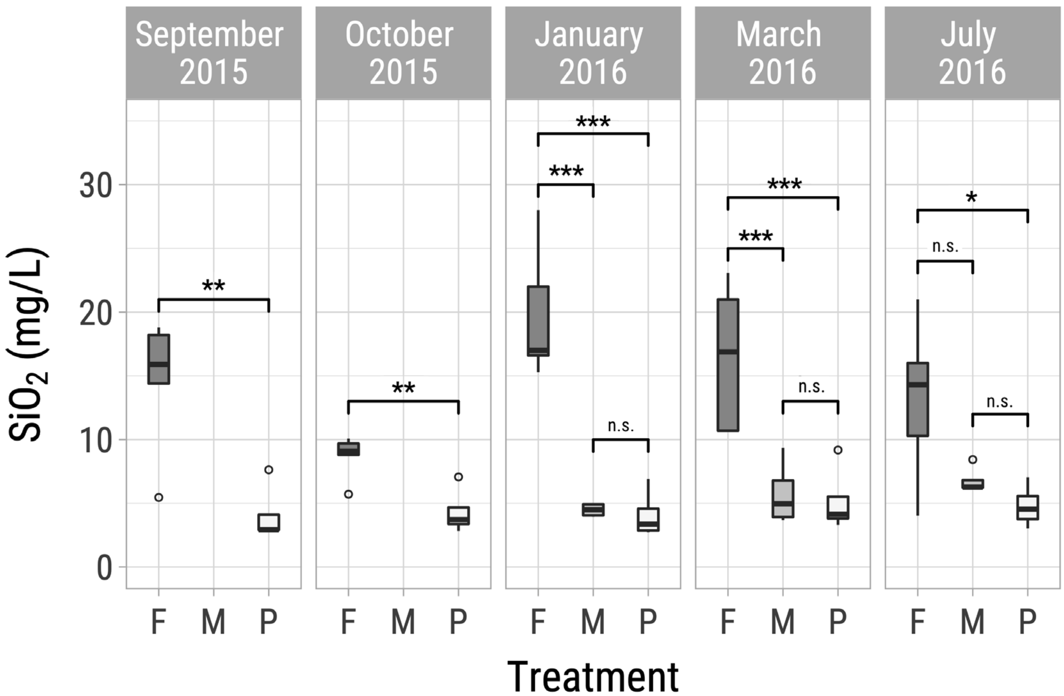
Water temperature from streams in forest (F), mixed non-extensive agriculture (M), and Oil palm (P). Mixed non-extensive streams (M) were not sampled during September and October 2015



Note. Asterisks indicate significance: *** = $p < .01$, ** = $p < .05$, * = $p < .10$. The first and third quartiles are represented by the box ends and the median as a thick line inside the box; empty circles represent outliers.

Figure 7

Silica concentration from streams in forest (F), mixed non-extensive agriculture (M), and Oil palm (P). Mixed non-extensive streams (M) were not sampled during September and October 2015



Note. Asterisks indicate significance: *** = $p < .01$, ** = $p < .05$, * = $p < .10$. The first and third quartiles are represented by the box ends and the median as a thick line inside the box; empty circles represent outliers.

Discussion

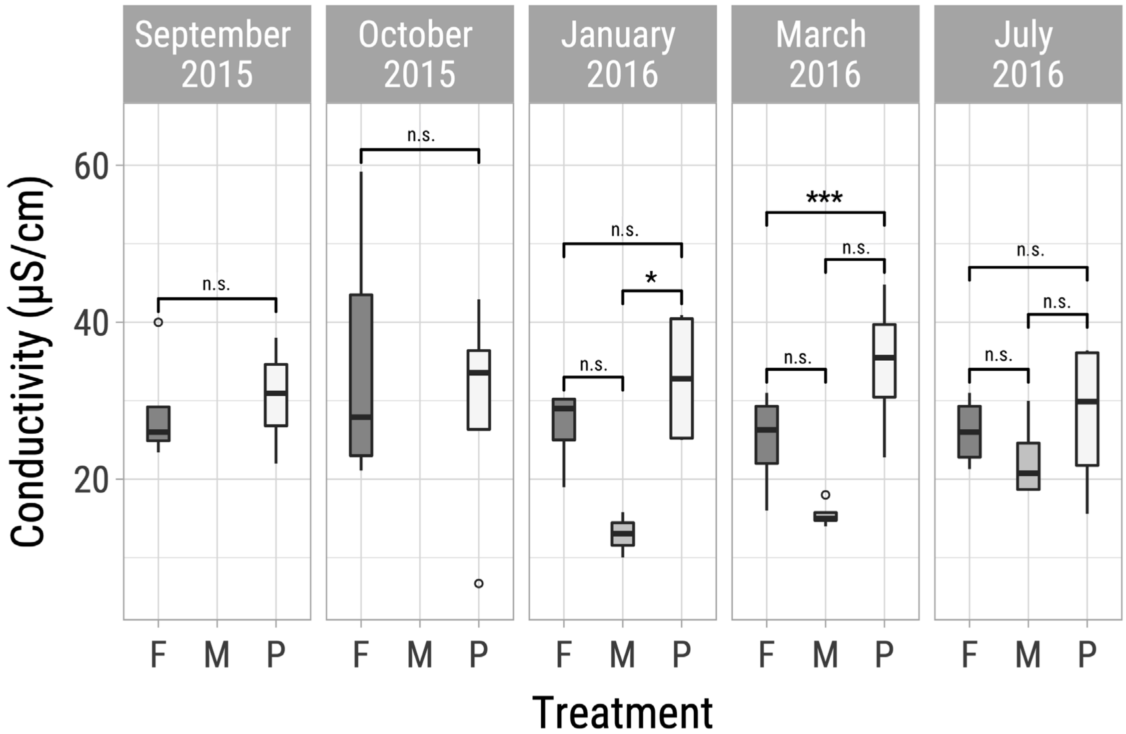
Our research complements studies that have examined the impacts of oil palm monocultures in other global scenarios by contrasting water quality measurements between these plantations, forests, and other land uses in specific regions. The majority of substantial differences range from pH, conductivity, total suspended solids, hardness, and concentration of nitrate and silica (Comte et al., 2012; Luke et al., 2017; Obidzinski et al., 2012). Our results revealed statistically significant differences ($p < .1$ & $p < .05$ in more than half of the months sampled) in five of the eleven properties we measured. As our findings agree with Comte et al. (2012) in Indonesian oil palm plantations, we can assert a more substantial validity when stating how P exhibit significant differences regarding conductivity, silica and nitrates concentrations when contrasted to other land uses. This suggests that increased nitrate and conductivity and decreased silica may be common impacts of the oil palm monocultures. Additionally, we found significant differences also in chemical oxygen demand and water temperature. The most important distinctions were found between treatments in water temperature and silica concentration, followed by nitrate concentration, conductivity, and chemical oxygen demand. Nevertheless, in our discussion, we debate the whole hydrological scenario to explore the influences of landscape variability on water quality in the Lachuá Ecoregion.

Temperature

P streams were significantly warmer than F streams in every sampling month. This difference

Figure 8

Water conductivity from streams in forest (F), mixed non-extensive agriculture (M), and Oil palm plantations (P). Mixed non-extensive streams (M) were not sampled during September and October 2015



Note. Asterisks indicate significance: *** = $p < .01$, ** = $p < .05$, * = $p < .10$. The first and third quartiles are represented by the box ends and the median as a thick line inside the box; empty circles represent outliers.

has an ecological implication, as water temperature influences biological and chemical processes such as metabolism rates, biological activity, primary production, and biotic composition due to differential tolerance and preferences among species (Anzecc & Armcanz, 2000; Dallas, 2009; Dallas & Ross-Gillespie, 2015). High stream temperatures can alter physical, chemical, and biological water properties (Dallas, 2009; Hawkins et al., 1997; Oyem et al., 2014). Overall, P streams were 2.7 ºC hotter than the F streams, which is remarkably similar to the difference of 3 °C reported by Carlson et al. (2014) between these two land-uses in Indonesia. Carlson et al. (2014) attributed this difference to the clear-cutting of riparian forest, which we also observed in our study area. The riparian forest provides shade that reduces direct solar radiation on soil and water. This type of forest reduces the fluctuation of air temperature in the canopy and understory, thus providing thermal regulation for stream water (Brauman et al., 2012; Gandaseca et al., 2015; Lorion & Kennedy, 2009; Studinski et al., 2012). Although the M treatment is also associated with loss of riparian forest, the dispersed presence of secondary forests (*guamil*) seems to buffer water temperature by preventing drastic increases.

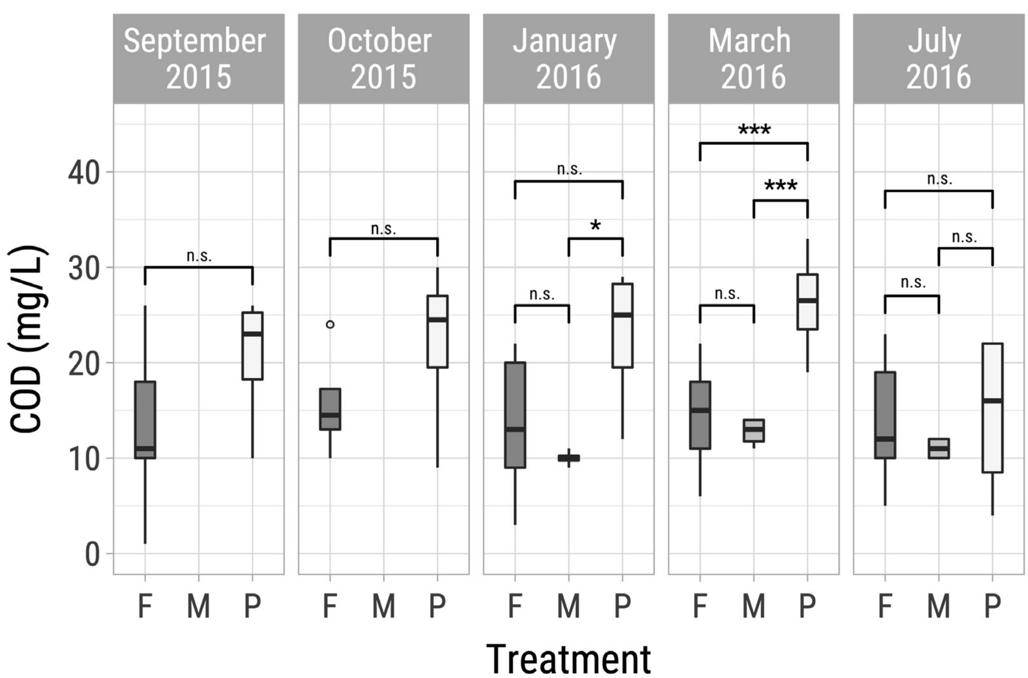
Increases in water temperature are generally associated with decreases in DO due to the inverse relationship between the solubility of gases and the temperature of the solvent (Morrill et al., 2005). However, we did not observe such a relationship (Figure 7) as other factors could affect the amount of oxygen in the water, including photosynthesis by diatoms, chlorophytes, and other algae.

Silica concentration

F streams showed significantly higher silica values than the other treatments. These findings are consistent with an earlier study by Fernandes et al., (2014), which noted an increase in silicon concentrations (although in silicate form) as the Mogi-Guaçu River at the Northeastern São Paulo State in Brazil. The authors attributed the higher silicon concentrations to the role of the forest in the recycling of this element. As plant tissues degrade in the woodlands, they reincorporate silicon into the soil in the form of phytoliths, which are then transported by surface runoff and groundwater leaching into rivers, lakes, and ultimately oceans (Farmer et al., 2005; Pokrovsky et al., 2005; Struyf & Conley, 2009; Wüst & Bustin, 2003). The significantly lower silica values in P and M might result from the lack of forest in the croplands and neighbouring riparian areas. The high uptake of this element by crops and following removal through harvesting provokes the impoverishment of the soil silica reservoir (Keller et al., 2012). Intensive agriculture then might relate to the general silicon decrease in the environment affecting its biogeochemical cycling. In our study area, M retains a more diverse vegetation structure and composition than P, as the former contains *guamil* and thus maintains silicon recycling more efficiently (Bartoli, 1983; Opalinska & Cowling, 2015). However, although M streams showed relatively higher silica concentrations than P streams, the difference was not statistically significant. Therefore, it is possible to suggest that reestablishing silicon transportation and recycling from mixed agriculture requires longer fallows because of their higher compatibility with the maintenance and restoration of such a biogeochemical cycle. Nonetheless, an increase in forest cover, especially in riparian zones, could replenish biogenic silicon reservoirs and

Figure 9

Chemical oxygen demand from streams in forest (F), mixed non-extensive agriculture (M), and Oil palm (P). Mixed non-extensive streams (M) were not sampled during September and October 2015



Note. Asterisks indicate significance: *** = $p < .01$, ** = $p < .05$, * = $p < .10$. The first and third quartiles are represented by the box ends and the median as a thick line inside the box; empty circles represent outliers.

maintain its biogeochemical cycling (Farmer et al., 2005; Fernandes et al., 2014) in mixed agriculture, and more importantly, in oil palm plantations.

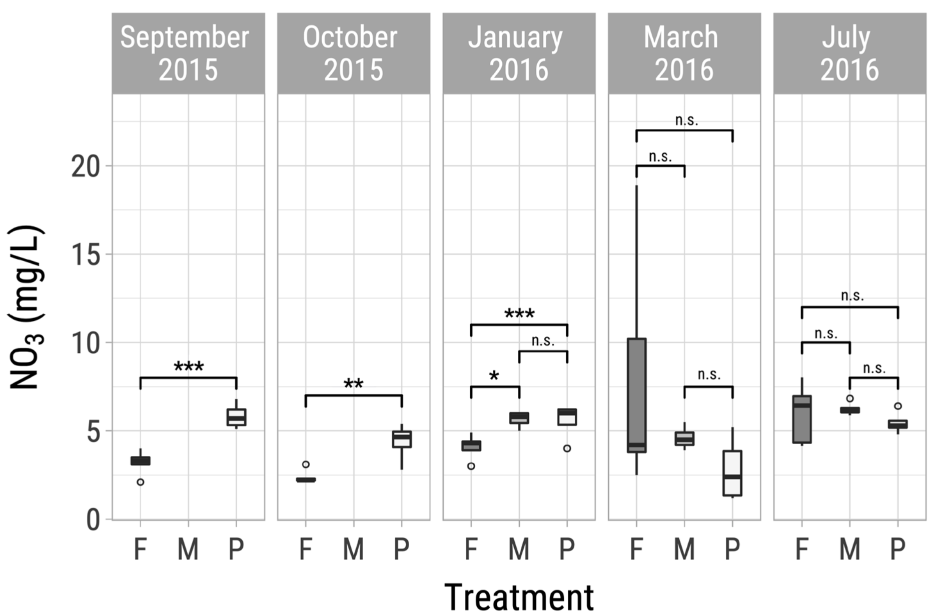
Our results are likely improving the understanding of how industrial agriculture, like oil palm monocrops, disrupt biogeochemical cycles. As rivers and streams play an essential role in silica transportation to the oceans, estimations indicate that they contribute as much as 80% of the silica entering oceans (Tréguer et al., 1995). In oceans, silica assimilation and integration represent 15% of marine biomass (Brzezinski, 2004; Street-Perrott & Barker, 2008). This biomass includes major primary producers, such as phytoplankton, responsible for producing approximately 80% of the planetary oxygen (Witman, 2017). Furthermore, silicon plays a vital role in climate dynamics because it interacts with carbon in the atmosphere, promoting carbon sequestration and oxygen release (Li et al., 2011; Song et al., 2012; Street-Perrott & Barker, 2008). As riparian forests continue diminishing at the local and regional scales, it affects both water quality and climatic processes that can result in global warming. Although our study's original goal does not have scope and representativity to determine the accuracy of this global scale statement, we are confident that more research is needed on this topic.

Electrical conductivity

The rivers in the Lachuá Ecoregion tend to show high conductivity (1000-1200 uS/cm) due to the high concentrations of carbonates, silicates, sulphates, and other soluble salts that characterize karstic regions (García & Méndez, 2014). Contrastingly, the studied streams showed considerably low conductivities (15-34 uS/cm), potentially as these are very small first and second order (*sensu* Strahler, 1957), therefore rainfall dependent. The M streams exhibited significantly lower conductivities when compared with P streams. On the one hand, this difference might be partly due to *guamil* and live fences in the M treatment, reducing soil erosion and decreasing electrolytes' flow. On the other hand, F streams showed higher conductivity than M streams possibly due to stronger fluvial-erosive

Figure 10

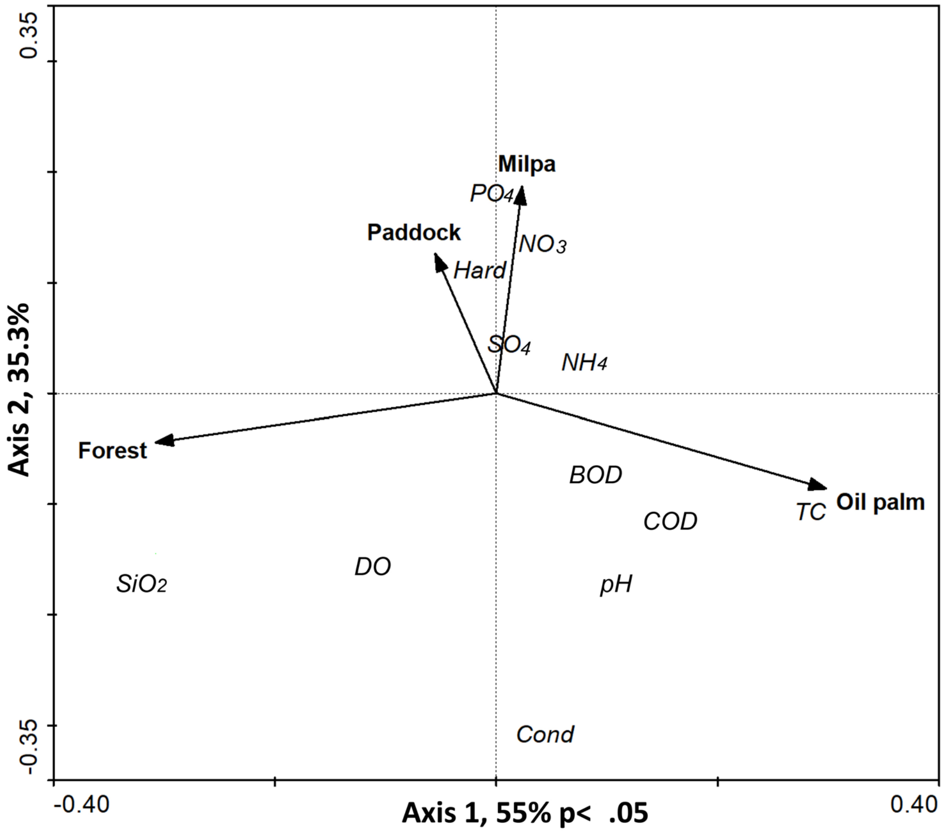
Nitrate concentration from streams in forest (F), mixed non-extensive agriculture (M), and Oil palm plantations (P). Mixed non-extensive streams (M) were not sampled during September and October 2015



Note. Asterisks indicate significance: *** = $p < .01$, ** = $p < .05$, * = $p < .10$. The first and third quartiles are represented by the box ends and the median as a thick line inside the box; empty circles represent outliers.

Figure 11

Redundancy analysis (RDA) showing the relationships between the study (land uses) and physical and chemical parameters



Note. The treatments explained 19% of the total variability ($p < .001$). Axis 1 explains 55%, and Axis 2 explains 35%. SiO_2 = Silica, DO = Dissolved oxygen, Cond = Electrical conductivity, BOD = Biological oxygen demand, COD = Chemical oxygen demand, TC= Temperature in degree Celsius, NH_4 = Ammonia, SO_4 = Sulfates, NO_3 = Nitrates, Hard = Hardness, PO_4 = Phosphates, pH = Potential of hydrogen.

processes because of their location in higher slope terrain (i.e., slightly steep dissected mountains) (Avendaño et al., 2005). In this context, M streams locations are flatter (i.e., middle to strong steep dissected hills). The fact that we did not find significant differences regarding conductivity among treatments might result from the interplay between slope and vegetative cover. The relatively denser vegetative cover on Lachuán forests may have helped reduce erosion on the relatively steeper land. Meanwhile, the relatively flatter terrain (i.e. plain hills) of oil palm plantations may have helped mitigate fluvial-erosive processes despite a much thinner vegetative cover.

Chemical oxygen demand

The higher COD in P streams is an indirect indicator of organic matter (Kosseva, 2013) that translates as low oxygen, critically affecting fishes and some macroinvertebrates due to increased anaerobic bacteria (Islam et al., 2019; Sari et al., 2019). In our study, the P streams COD median concentration was close to 25 mg L^{-1} every month except in July (Figure 11). While this exceeds the limit recommended by Malaysian officials regarding water quality (10-15 COD mg L^{-1}), it is considered acceptable by the Mexican National Water Commission (Comision Nacional del Agua, 2016), which results in overlapping water quality of P, F and M (COD of 10 and 15mg L^{-1}, respectively). Therefore, although COD might not be seen as a significant problem under these regulations, it is important to continue its monitoring. Barreto (2018) proposed that wastewater from oil palm plantations tailing ponds (with high COD and BOD) is one of the most plausible explanations behind the Pasion's River ecocide, which might have triggered oxygen depletion.

Nitrate Concentration

Even though there was no application of chemicals in P during our study (pers, comm. plantation owner), it showed significantly higher concentrations of nitrates than F streams during the first three sampling months. Although nitrate leaching might be higher in P than in F due to the failure of palms to fully occupy the available soil volume with their roots (Schroth et al., 2006), nitrate leaching is also high in croplands due to the use of fertilizers (Kurniawan et al., 2018). During our study's last two sampling months, P streams showed the lowest nitrate concentrations (although not statistically significant). This observation might be associated with other climatic variables such as precipitation, as the only sample taken under a precipitation event was in March in the F treatment. Considering the high solubility of nitrates, this might explain why there is a peak during that month in F (Figure 10). According to our RDA, there is a positive relationship between M, nitrates, phosphates and sulphates. This relationship has been observed in other studies due to fertilizer runoff in *milpa* fields (Camas Gómez et al., 2012) and cattle trampling and manure runoff in paddocks (Airaksinen et al., 2007; Wilson & Everard, 2018). Application of litter and other organic by-products to agricultural land is associated with a decreased nitrate runoff when contrasted with chemically-fertilized land (Harmel et al., 2009). Therefore, the oil palm plantation in our study likely exhibited lower impacts than conventional oil palm plantations, where chemical fertilization is standard practice. The oil palm plantation in our study is moderately sized, approximately 90 ha, which made us aware of the limitations in generalizing our findings at the Lachuá Ecoregion to the regional oil palm expansion effects across the Northern Transversal Strip.

Though relatively small in scale, our research suggests that the recent oil palm boom in the Guatemalan lowlands is likely to have a negative impact on water quality in the Lachuá Ecoregion. This situation is particularly worrisome given the tremendous importance of the region's hydrological network to supporting biological diversity and human livelihoods. One of our study highlights is establishing the presence of oil palm monocultures to higher water temperatures and decreasing silica transportation in streams. Furthermore, our study contrasts what happens in a moderately-sized plantation with an occasional vermicompost application instead of chemical fertilizers that might provoke more pronounced adverse environmental effects on water quality. Our study presents evidence of an exception, instead of the general trend in the Northern Guatemala Lowlands, where plantation administrators extensively apply harmful chemicals. Another breakthrough is that we found critical incipient evidence about the importance of riparian forests and secondary forests (included in the *guamil* system) to reduce land-use change impacts, including regulating water temperature and increasing silica transportation and recycling. Ultimately, this preliminary study points to the urgent need for more extensive research into large-scale oil palm plantations' effects on water quality in the Lachuá Ecoregion and other areas across the Northern Transversal Strip in Guatemala.

Acknowledgments

This research was partially funded by the Canada-Latin America and Caribbean Research Exchange Grant (LACREG) from the International Development Research Council (IDRC) and Universities in Canada. We want to thank the team at the LAFYM laboratory at San Carlos University of Guatemala, especially Lic. Ana Rodas and Ph.D. Rúben Velásquez, for their support in the laboratory analysis. We are also grateful for the support from the personnel at the Lachuá Lake National Park (administration and forest guards). Families Tox, Xo and Xat from the Lachuá Ecoregion communities are greatly thanked for their support in our study. Finally, we would like to thank Dr. Anastasia Hervas from the University of Toronto, who contributed significantly to the design of this study and the analysis of the data.

Contribution of authors

Drafting and revising the manuscript: OR, CA, RI
Conception and design of the study: OR, CA
Collecting of data: OR
Cleaning data, performing the analysis, and/or interpretation of data: OR, CA
Editing the manuscript critically for important intellectual content: OR, RI

Supplementary Materials

Data are within the paper

References

Airaksinen, S., Heiskanen, M.-L., & Heinonen-Tanski, H. (2007). Contamination of surface run-off water and soil in two horse paddocks. *Bioresource Technology*, *98*(9), 1762-1766. https://doi.org/10.1016/J.BIORTECH.2006.07.032

Alonso-Fradejas, A. (2018). *The rise of agro-extractive capitalism: Insights from Guatemala in the early 21st century*[Doctoral Thesis, Erasmus University]. http://hdl.handle.net/1765/110843

Australian New Zealand Educational Council & Agriculture and Resource Management Council of Australia and New Zealand. (2000). *Australian and New Zealand guidelines for fresh and marine water quality* (Vol. 1, The guidelines). https://www.sea.gob.cl//sites/default/files/migration_files/Normas_secundarias/Anexo_documental/Australia/Agua/AU-AG-01-NWQMS.pdf

Avendaño Mendoza, C, Avendaño Mendoza, C., Carías Sánchez, A. C., García Vettorazzi, M. J., Cajas Castillo, M. M., & De León Xic, K. J. (2005). *Dinámica del uso de la tierra y conservación de los recursos naturales en la región Lachúa* (FODECYT No. 20-2003). Consejo Nacional de Ciencia y Tecnología, Universidad de San Carlos de Guatemala, Facultad de Ciencias Químicas y farmacia, Escuela de Biología. http://glifos.senacyt.gob.gt/digital/fodecyt/fodecyt%202003.20.pdf

Avendaño, C., Hervas, A., & Rojas, O. (2019). *Effects of land use on water quality in first-order streams across tropical rainforest, milpa agriculture, and oil palm farms in the Lachuá Ecoregion, Guatemala: preliminary results* (Working Paper, November 15, 2019). Lachuá Socio-Ecological System Project.

Ávila Santa Cruz, R. C. (2004). *Estudio base para el programa de monitoreo de la vegetación en la zona de influencia del Parque Nacional Laguna Lachuá* [Tesis de licenciatura, Universidad de San Carlos de Guatemala]. http://biblioteca.usac.edu.gt/tesis/06/06_2221.pdf

Ávila Santa Cruz, R. C., Cajas C., J. O., Grajeda, A. L., Machuca C., O. H., & Benítez, L. (2005). *Aves y murciélagos como dispersores de semillas en tres etapas sucesionales de la Ecorregión Lachuá, Alta Verapaz, Guatemala* (Inf-2005-021) Universidad de San Carlos de Guatemala, Facultad de Ciencias Químicas y Farmacia.

Barreto, B. (27 noviembre, 2018). Guatemala: A tres años del ecocidio en el río La Pasión, el proceso judicial sigue detenido. *Mongabay*. https://es.mongabay.com/2018/11/palma-africana-en-guatemala/

Bartoli, F. (1983). The biogeochemical cycle of silicon in two temperate forest ecosystems. *Ecological Bulletins*, *35*, 469-476. https://doi.org/10.2307/20112881

Brauman, K. A., Freyberg, D. L., & Daily, G. C. (2012). Potential evapotranspiration from forest and pasture in the tropics: A case study in Kona, Hawai ‘i. *Journal of Hydrology*, *440-441*, 52-61. https://doi.org/https://doi.org/10.1016/j.jhydrol.2012.03.014

Brzezinski, M. A. (2004). The Si:C:N ratio of marine diatoms: Interspecific variability and the effect of some environmental variables. *Journal of Phycology*, *21*(3), 347-357. https://doi.org/10.1111/j.0022-3646.1985.00347.x

Camas Gómez, R., Turrent Fernández, A., Cortes Flores, J. I., Livera Muñóz, M., González Estrada, A., Villar Sánchez, B., López Martínez, J., Espinoza Paz, N., & Cadena Iñiguez, P. (2012). Erosión del suelo, escurrimiento y pérdida de nitrógeno y fósforo en laderas bajo diferentes sistemas de manejo en Chiapas, México. *Revista Mexicana de Ciencias Agrícolas*, *3*(2), 231-243.

Carlson, K. M., Curran, L. M., Ponette-González, A. G., Ratnasari, D., Ruspita, Lisnawati, N., Purwanto, Y., Brauman, K. A., & Raymond, P. A. (2014). Influence of watershed-climate interactions on stream temperature, sediment yield, and metabolism along a land use intensity gradient in Indonesian Borneo. *Journal of Geophysical Research: Biogeosciences*, *119*(6), 1110-1128. https://doi.org/10.1002/2013JG002516

Castañeda Cerna, C. A. (1997). Estudio florístico en el parque nacional Laguna Lachuá, Alta Verapaz, Guatemala [Tesis de licenciatura, Universidad de San Carlos de Guatemala]. http://biblioteca.usac.edu.gt/tesis/01/01_1668.pdf

Chappell, N. A., Tych, W., Yusop, Z., Rahim, N. A., & Kasran, B. (2004). Spatially significant effects of selective tropical forestry on water, nutrient and sediment flows: A modelling-supported review. In M. Bonell & L. Bruijnzeel (Eds.), *Forests, Water and People in the Humid Tropics: Past, Present and Future Hydrological Research for Integrated Land and Water Management* (pp. 513-532). Cambridge University Press. https://doi.org/10.1017/CBO9780511535666.027

Chellaiah, D., & Yule, C. M. (2018). Riparian buffers mitigate impacts of oil palm plantations on aquatic macroinvertebrate community structure in tropical streams of Borneo. *Ecological Indicators*, *95*, 53-62. https://doi.org/10.1016/j.ecolind.2018.07.025

Comte, I., Colin, F., Whalen, J. K., Grünberger, O., & Caliman, J.-P. (2012). Agricultural Practices in Oil Palm Plantations and Their Impact on Hydrological Changes, Nutrient Fluxes and Water Quality in Indonesia: A Review. *Advances in Agronomy*, *116*, 71-124. https://doi.org/10.1016/B978-0-12-394277-7.00003-8

Comisión Nacional del Agua. (2016). *Monitoreo de la calidad del agua en México*. https://www.gob.mx/conagua/documentos/monitoreo-de-la-calidad-del-agua-en-mexico

Dallas, H. (2009). *The effect of water temperature on aquatic organisms: a review of knowledge and methods for assessing biotic responses to temperature* (WRC Report KV, 213-09). Water Research Commission Report

Dallas, H., & Ross-Gillespie, V. (2015). Review: Sublethal effects of temperature on freshwater organisms, with special reference to aquatic insects. *Water SA*, *41*(5), 712-726. https://doi.org/10.4314/wsa.v41i5.15

Department of Irrigation and Drainage. (1989). *Tekam Experimental Basin Final Report*. https://jps.gov.my/index.php/pages/view/1300

Dislich, C., Keyel, A. C., Salecker, J., Kisel, Y., Meyer, K. M., Auliya, M., Barnes, A. D., Corre, M. D., Darras, K., Faust, H., Hess, B., Klasen, S., Knohl, A., Kreft, H., Meijide, A., Nurdiansyah, F., Otten, F., Pe'er, G., Steinebach, S., … Wiegand, K. (2017). A review of the ecosystem functions in oil palm plantations, using forests as a reference system. *Biological Reviews*, *92*(3), 1539-1569. https://doi.org/10.1111/brv.12295

Doan, T. T., Henry-des-Tureaux, T., Rumpel, C., Janeau, J.-L., & Jouquet, P. (2015). Impact of compost, vermicompost and biochar on soil fertility, maize yield and soil erosion in Northern Vietnam: A three year mesocosm experiment. *Science of The Total Environment*, *514*, 147-154. https://doi.org/10.1016/J.SCITOTENV.2015.02.005

Dodds, W. K., & Oakes, R. M. (2008). Headwater Influences on Downstream Water Quality. *Environmental Management*, *41*(3), 367-377. https://doi.org/10.1007/s00267-007-9033-y

Eisermann, K., & Avendaño, C. (2007). *Áreas propuestas para la designación como IBA (Área importante para la conservación de aves) en Guatemala, con una priorización para la conservación adentro de las IBAs y una evaluación de las IBAs para aves migratorias Neárticas-Neotropicales*. Sociedad Guatemalteca de Ornitología.

Escuela de Biología de la Facultad de Ciencias Químicas y Farmacia de la Universidad de San Carlos de Guatemala (Comp.). (2004). Ficha Informativa de los Humedales de Ramsar (FIR). In *Wetlands:Water life and culture*. https://conap.gob.gt/wp-content/uploads/2019/09/1623-Ecoregión-Lachua.pdf

Food and Agriculture Organization. (s.f.). *FAOSTAT Online Statistical Service*. http://www.fao.org/faostat/en/#data/QC

Farmer, V. C., Delbos, E., & Miller, J. D. (2005). The role of phytolith formation and dissolution in controlling concentrations of silica in soil solutions and streams. *Geoderma*, *127*(1-2), 71-79. https://doi.org/10.1016/J.GEODERMA.2004.11.014

Fernandes, J. de F., de Souza, A. L. T., & Tanaka, M. O. (2014). Can the structure of a riparian forest remnant influence stream water quality? A tropical case study. *Hydrobiologia*, *724*(1), 175-185. https://doi.org/https://doi.org/10.1007/s10750-013-1732-1

Ford, A., & Nigh, R. (2016). *The Maya forest garden: Eight millennia ofsSustainable cultivation of the tropical woodlands*. Routledge.

Ford, D., & Williams, P. D. (2013). *Karst hydrogeology and geomorphology*. John Wiley & Sons.

Fox, J. (2016). *Using the R commander: A point-and-click interface for R*. Chapman & Hall. https://socialsciences.mcmaster.ca/jfox/Books/RCommander/.

Gandaseca, S., Rosli, N., Hanafiidris, M., Haruna, O. A., & Mustapha, A. (2015). Effects of converting tropical peat swamp forest into oil palm plantation on water quality. *American Journal of Applied Sciences*, *12*(8), 525-532. https://doi.org/10.3844/ajassp.2015.525.532

García, P., & Méndez, C. (2014). Análisis de la distribución de macroinvertebrados acuáticos a escala detallada en la ecorregion Lachuá, Cobán, Alta Verapaz. *Revista Científica*, *19*(1), 37-46.

Goh, K.-J., Härdter, R., & Fairhurst, T. (2003). Fertilizing for maximum return. *Oil Palm: Management for Large and Sustainable Yields*, 279-306.

Granados, P. (2001). *Ictiofauna de la Laguna Lachuá, Parque Nacional Laguna Lachuá, Cobán, Alta Verapaz*. Universidad de San Carlos de Guatemala.

Gremial de Palmicultores de Guatemala. (2018). *I Anuario Estadístico*. content/uploads/2018/07/GREPALMA_Ints_Anuario_Estadistico.pdf

Gremial de Palmicultores de Guatemala.(2019). *Agroindustria sostenible de aceite de palma en Guatemala*. *Anuario estadístico 2018-2019*. https://www.grepalma.org/wp-content/uploads/2020/04/Anuario_estadistico_2018_2019.pdf

Harmel, R. D., Smith, D. R., Haney, R. L., & Dozier, M. (2009). Nitrogen and phosphorus runoff from cropland and pasture fields fertilized with poultry litter. *Journal of Soil and Water Conservation*, *64*(6), 400-412. https://doi.org/10.2489/jswc.64.6.400

Hawkins, C. P., Hogue, J. N., Decker, L. M., & Feminella, J. W. (1997). Channel morphology, water temperature, and assemblage structure of stream insects. *Journal of the North American Benthological Society*, *16*(4), 728-749. https://doi.org/10.2307/1468167

Hernández Bonilla, S. M. (2004). *Estudio Etnoecológico de las Actividades Agropecuarias, Cacería y Extractivas en dos comunidades Rocja Pontilá y San Benito I de la Ecorregión Lachuá. Fac. de CC. QQ y Farmacia, Universidad de San Carlos* [Tesis de licenciatura, Universidad de San Carlos de Guatemala]. http://biblioteca.usac.edu.gt/tesis/06/06_2294.pdf

Hervas, A. (2019). Land, development and contract farming on the Guatemalan oil palm frontier. *The Journal of Peasant Studies*, *46*(1), 115-141. https://doi.org/ 10.1080/03066150.2017.1351435

Islam, M. M. M., Shafi, S., Bandh, S. A., & Shameem, N. (2019). Impact of environmental changes and human activities on bacterial diversity of lakes. In John Wiley & Sons (Ed.), *Freshwater Microbiology: Perspectives of Bacterial Dynamics in Lake Ecosystems* (pp. 105-136). Academic Press. https://doi.org/10.1016/B978-0-12-817495-1.00003-7

Keller, C., Guntzer, F., Barboni, D., Labreuche, J., & Meunier, J.-D. (2012). Impact of agriculture on the Si biogeochemical cycle: Input from phytolith studies. *Comptes Rendus Geoscience*, *344*(11-12), 739-746. https://doi.org/10.1016/J.CRTE.2012.10.004

Kertész, Á., Nagy, L. A., & Balázs, B. (2019). Effect of land use change on ecosystem services in Lake Balaton Catchment. *Land Use Policy*, *80*, 430-438. https://doi.org/10.1016/j.landusepol.2018.04.005

Kosseva, M. R. (2013). Sources, Characterization, and Composition of Food Industry Wastes. In *Food Industry Wastes* (pp. 37-60). Elsevier. https://doi.org/10.1016/B978-0-12-391921-2.00003-2

Kuntom, A., Yew Ai, T., Kamaruddin, N., & Chee Beng, Y. (2007). Pesticide Application in the Oil Palm Plantation.

Kurniawan, S., Corre, M. D., Matson, A. L., Schulte-Bisping, H., Utami, S. R., Van Straaten, O., & Veldkamp, E. (2018). Conversion of tropical forests to smallholder rubber and oil palm plantations impacts nutrient leaching losses and nutrient retention efficiency in highly weathered soils. *Biogeosciences*, *15*(16), 5131-5154. https://doi.org/10.5194/BG-15-5131-2018

Li, D. D., Lerman, A., & Mackenzie, F. T. (2011). Human perturbations on the global biogeochemical cycles of coupled Si–C and responses of terrestrial processes and the coastal ocean. *Applied Geochemistry*, *26*, S289-S291.

Liberoff, A. L., Flaherty, S., Hualde, P., García Asorey, M. I., Fogel, M. L., & Pascual, M. A. (2019). Assessing land use and land cover influence on surface water quality using a parametric weighted distance function. *Limnologica*, *74*, 28-37. https://doi.org/10.1016/J.LIMNO.2018.10.003

Lorion, C. M., & Kennedy, B. P. (2009). Relationships between deforestation, riparian forest buffers and benthic macroinvertebrates in neotropical headwater streams. *Freshwater Biology*, *54*(1), 165-180. https://doi.org/10.1111/j.1365-2427.2008.02092.x

Luke, S. H., Barclay, H., Bidin, K., Chey, V. K., Ewers, R. M., Foster, W. A., Nainar, A., Pfeifer, M., Reynolds, G., Turner, E. C., Walsh, R. P. D., & Aldridge, D. C. (2017). The effects of catchment and riparian forest quality on stream environmental conditions across a tropical rainforest and oil palm landscape in Malaysian Borneo. *Ecohydrology*, *10*(4), Article e1827. https://doi.org/10.1002/eco.1827

Mercer, E. V., Mercer, T. G., & Sayok, A. K. (2013). Effects of forest conversions to oil palm plantations on freshwater macroinvertebrates: A case study from Sarawak, Malaysia. *Journal of Land Use Science*, *9*(3), 260-277. https://doi.org/10.1080/1747423X.2013.786149

Monzón Miranda, R. M. (1999). *Estudio general de los recursos agua, suelo y del uso de la tierra del parque nacional Laguna Lachuá y su zona de influencia, Cobán, Alta Verapaz* [Tesis de licenciatura, Universidad de San Carlos de San Carlos de Guatemala]. http://biblioteca.usac.edu.gt/tesis/01/01_1834.pdf

Morrill, J. C., Bales, R. C., & Conklin, M. H. (2005). Estimating Stream Temperature from Air Temperature: Implications for Future Water Quality. *Journal of Environmental Engineering*, *131*(1), 139-146. https://doi.org/10.1061/(ASCE)0733-9372(2005)131:1(139)

Obidzinski, K., Andriani, R., Komarudin, H., & Andrianto, A. (2012). Environmental and social impacts of oil palm plantations and their implications for biofuel production in Indonesia. *Ecology and Society*, *17*(1), Article 25. https://doi.org/http://dx.doi.org/10.5751/ES-04775-170125

Opalinska, B., & Cowling, S. A. (2015). Modelling the movement of biogenic silica from terrestrial vegetation to riverine systems within the continental USA. *Ecological Modelling*, *312*, 104-113. https://doi.org/10.1016/J.ECOLMODEL.2015.05.012

Oyem, H. H., Oyem, I. M., & Ezeweali, D. (2014). Temperature, pH, electrical conductivity, total dissolved solids and chemical oxygen demand of groundwater in Boji-BojiAgbor/Owa area and immediate suburbs. *Research Journal of Environmental Sciences*, *8*(8), 444-450. https://doi.org/10.3923/rjes.2014.444.450

Pokrovsky, O. S., Schott, J., Kudryavtzev, D. I., & Dupré, B. (2005). Basalt weathering in Central Siberia under permafrost conditions. *Geochimica et Cosmochimica Acta*, *69*(24), 5659-5680. https://doi.org/10.1016/J.GCA.2005.07.018

Proyecto Especial para la Seguridad Alimentaria. (2005). *La regeneración natural en áreas de cultivo* (Manejo de Sistemas Agroforestales 2). http://www.fao.org/3/a-at777s.pdf

Quezada, M. L., Arroyo-Rodríguez, V., Pérez-Silva, E., & Aide, T. M. (2014). Land cover changes in the Lachuá region, Guatemala: patterns, proximate causes, and underlying driving forces over the last 50 years. *Regional Environmental Change*, *14*(3), 1139-1149. https://doi.org/10.1007/s10113-013-0548-x

Ribeiro, M. C., Pinho, P., Llop, E., Branquinho, C., Sousa, A. J., & Pereira, M. J. (2013). Multivariate geostatistical methods for analysis of relationships between ecological indicators and environmental factors at multiple spatial scales. *Ecological Indicators*, *29*, 339-347. https://doi.org/10.1016/J.ECOLIND.2013.01.011

RStudio. (2016). *RStudio: Integrated Development Environment for R* (1.1.383) [Conjunto de datos].

Sari, F. I. P., Mahardika, R. G., & Roanisca, O. (2019). Water Quality Testing Due to Oil Palm Plantation Activities in Bangka Regency. *IOP Conference Series: Earth and Environmental Science*, *353*(1), 12019. https://doi.org/10.1088/1755-1315/353/1/012019

Schroth, G., Rodrigues, M. R. L., & D'Angelo, S. A. (2006). Spatial patterns of nitrogen mineralization, fertilizer distribution and roots explain nitrate leaching from mature Amazonian oil palm plantation. *Soil Use and Management*, *16*(3), 222-229. https://doi.org/10.1111/j.1475-2743.2000.tb00197.x

Secretaría de Planificación y Programación de la Presidencia. (2011). *Plan de desarrollo integral, Franja Transversal del Norte, tomo 1.* https://www.segeplan.gob.gt/nportal/index.php/biblioteca-documental/biblioteca-documentos/file/483-franja-transversal-del-norte-diagnostico-territorial-tomo-1

Sheil, D., Casson, A., Meijaard, E., Van Noordwijk, M., Gaskell, J., Sunderland-Groves, J., Wertz, K., & Kanninen, M. (2009). *The impacts and opportunities of oil palm in Southeast Asia: What do we know and what do we need to know?*

Solano, L. (2015). Palma africana y empresas se expanden aceleradamente a lo largo de la FTN. *Enfoque, 7*(36). http://www.albedrio.org/htm/otrosdocs/comunicados/EnfoqueNo.36-PalmaafricanaFTN-2015.pdf

Song, Z., Wang, H., Strong, P. J., Li, Z., & Jiang, P. (2012). Plant impact on the coupled terrestrial biogeochemical cycles of silicon and carbon: Implications for biogeochemical carbon sequestration. *Earth-Science Reviews*, *115*(4), 319-331. https://doi.org/10.1016/J.EARSCIREV.2012.09.006

State Environmental Conservation Department. (2000). *Environmental Impact Assessment (EIA) Guidelines for oil palm plantation development Third Draft* (Technical Report no.2, No. 4)

Strahler, A. N. (1957). Quantitative analysis of watershed geomorphology. *Eos, Transactions, American Geophysical Union*, *38*(6), 913-920. https://doi.org/10.1029/TR038i006p00913

Street-Perrott, F. A., & Barker, P. A. (2008). Biogenic silica: A neglected component of the coupled global continental biogeochemical cycles of carbon and silicon. *Earth Surface Processes and Landforms*, *33*(9), 1436-1457. https://doi.org/10.1002/esp.1712

Struyf, E., & Conley, D. J. (2009). Silica: An essential nutrient in wetland biogeochemistry. *Frontiers in Ecology and the Environment*, *7*(2), 88-94. https://doi.org/10.1890/070126

Studinski, J. M., Hartman, K. J., Niles, J. M., & Keyser, P. (2012). The effects of riparian forest disturbance on stream temperature, sedimentation, and morphology. *Hydrobiologia*, *686*(1), 107-117. https://doi.org/10.1007/s10750-012-1002-7

Taylor, M. J. (2007). Militarism and the environment in Guatemala. *GeoJournal, 2007*, *69*(3), 181-198. https://doi.org/10.1007/S10708-007-9108-6

ter Braak, C. J. F., & Smilauer, P. (2012). *Canoco reference manual and user's guide: Software for ordination, version 5.0*. Microcomputer Power.

Tréguer, P., Nelson, D. M., Van Bennekom, A. J., DeMaster, D. J., Leynaert, A., & Quéguiner, B. (1995). The silica balance in the world ocean: A reestimate. *Science*, *268*(5209), 375-379. https://doi.org/10.1126/science.268.5209.375

Wantzen, K. M. (2006). Physical pollution: Effects of gully erosion on benthic invertebrates in a tropical clear-water stream. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *16*(7), 733-749. https://doi.org/10.1002/aqc.813

Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis* (Vol. 10, pp. 973-978). Springer-Verlag. https://ggplot2.tidyverse.org.

Wilkinson, C. L., Yeo, D. C. J., Tan, H. H., Fikri, A. H., & Ewers, R. M. (2019). Resilience of tropical, freshwater fish (Nematabramis everetti) populations to severe drought over a land-use gradient in Borneo. *Environmental Research Letters*, *14*(4), Article 45008. https://doi.org/10.1088/1748-9326/ab0128

Wilson, J. L., & Everard, M. (2018). Real-time consequences of riparian cattle trampling for mobilization of sediment, nutrients and bacteria in a British lowland river. *International Journal of River Basin Management*, *16*(2), 231-244. https://doi.org/10.1080/15715124.2017.1402778

Witman, S. (2017). World's Biggest Oxygen Producers Living in Swirling Ocean Waters. *Eos, 98*. https://doi.org/10.1029/2017eo081067

Wüst, R. A. J., & Bustin, R. M. (2003). Opaline and Al–Si phytoliths from a tropical mire system of West Malaysia: Abundance, habit, elemental composition, preservation and significance. *Chemical Geology*, *200*(3-4), 267-292. https://doi.org/10.1016/S0009-2541(03)00196-7