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Changes in periphyton communities with land use in tropical mountain streams in Loja (Ecuador)

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ABSTRACT

Changes in periphyton communities with land use in tropical mountain streams in Loja (Ecuador)

Riparian vegetation is vital to the ecological integrity of stream ecosystems, regulating nutrient and sediment flow, stabilizing riverbanks, and moderating microclimate, all factors that influence primary production and periphyton communities. However, in tropical mountain regions, the ecological impacts of riparian degradation remain poorly documented. This study assessed how differences in land use and riparian cover affect environmental conditions, periphyton abundance, diversity, and diatom community composition in seven tropical mountain streams in southern Ecuador. Streams were sampled in forested, open (deforested), and degraded zones across a gradient of human disturbance. Water temperature and nutrient concentrations, particularly phosphates and nitrates/nitrites, were consistently higher in open and degraded sites. These conditions were not associated with greater periphyton abundance or diversity but with an increased prevalence of cyanobacteria, likely due to elevated light availability and temperature. Diatoms dominated the periphyton across all sites, with *Gomphonema minutum*, *G. parvulum*, and *Achnanthidium minutissimum* as the most abundant species. Diatom community composition in different land-use zones within the same stream was often as distinct as that observed between separate streams, underscoring the influence of fine-scale environmental variation over broader spatial patterns. The most degraded sites exhibited the most divergent diatom assemblages, reinforcing their value as sensitive indicators of ecological change. These findings highlight the need for conservation strategies that prioritize riparian vegetation protection, nutrient load reduction, and habitat heterogeneity. Diatom-based monitoring should be integrated into long-term ecological assessments to guide restoration efforts in increasingly threatened Andean stream ecosystems.

KEY WORDS: periphyton communities, riparian vegetation, diatoms, tropical mountain streams, land use change

RESUMEN

Cambios en las comunidades de perifiton según el uso del suelo en arroyos de montaña tropicales de Loja (Ecuador)

La vegetación ribereña es vital para la integridad ecológica de los ecosistemas fluviales, ya que regula el flujo de nutrientes y sedimentos, estabiliza las riberas y modera el microclima, todos ellos factores que influyen en la producción primaria y en las comunidades de perifiton. Sin embargo, en las regiones montañosas tropicales, los impactos ecológicos de la degradación ribereña siguen estando poco documentados. Este estudio evaluó cómo las diferencias en el uso del suelo y la cobertura ribereña afectan las condiciones ambientales, la abundancia y diversidad del perifiton, así como la composición de la comunidad de diatomeas en siete arroyos de montaña tropical en el sur de Ecuador. Se muestrearon arroyos en zonas boscosas, abiertas (deforestadas) y degradadas a lo largo de un gradiente de perturbación antrópica. La temperatura del agua y las concentraciones de nutrientes, particularmente fosfatos y nitratos/nitritos, fueron consistentemente más altas en sitios abiertos y degradados. Estas condiciones no estuvieron asociadas con una mayor abundancia o diversidad del perifiton, sino con una mayor prevalencia de cianobacterias, probablemente debido a una mayor disponibilidad de luz y temperaturas elevadas. Las diatomeas dominaron el perifiton en todos los sitios, siendo Gomphonema minutum, G. parvulum *y* Achnanthidium minutissimum *las especies más abundantes. La composición de las comunidades de diatomeas en diferentes zonas de uso del suelo dentro del mismo arroyo fue tan distinta como la observada entre arroyos separados, lo que resalta la influencia de variaciones ambientales a escala fina por encima de patrones espaciales más amplios. Los sitios más degradados presentaron los ensamblajes de diatomeas más divergentes, lo que refuerza su valor como indicadores sensibles del cambio ecológico. Estos hallazgos destacan la necesidad de estrategias de conservación que prioricen la protección de la vegetación ribereña, la reducción de la carga de nutrientes y la heterogeneidad del hábitat. El monitoreo basado en diatomeas debería integrarse en evaluaciones ecológicas de largo plazo para orientar los esfuerzos de restauración en ecosistemas fluviales andinos cada vez más amenazados.*

PALABRAS CLAVE: *comunidades de perifiton, vegetación ribereña, diatomeas, arroyos de montaña tropicales, cambio en el uso del suelo.*

INTRODUCTION

Lotic ecosystems are key components of the global hydrological cycle. Rivers and streams in good ecological condition deliver a wide array of ecosystem services that support human health, societal well-being and economic development (Davies & Jackson, 2006). These systems also help buffer natural hazards by regulating floods, controlling surface runoff, and mitigating climate change impacts (Gastezzi-Arias et al., 2016). Yet, beyond their natural variability (Vannote et al., 1980), lotic systems are increasingly impacted by anthropogenic pressures, particularly pollution and eutrophication. Domestic wastewater, industrial discharges, and excessive agrochemical use are all factors that degrade water quality, disrupt biotic communities, and impair essential ecological functions.

Riparian zones are biologically rich and ecologically dynamic transitional areas between terrestrial and aquatic ecosystems (Rood et al., 2020). Though the formal study of riparian ecology gained momentum only in the 1990s, the importance of riparian buffers in nutrient retention, habitat connectivity, and hydrological regulation has long been recognized. Research since the 1980s has documented the ecological consequences of grazing, damming, and river diversion, while recent work has emphasized the fluvial processes necessary for the regeneration of riparian plant communities. These areas are now central to restoration initiatives aimed at reestablishing natural flow regimes and mitigating the spread of invasive species, often through integrated biological control strategies.

Riparian vegetation strongly influences riverine water quality and habitat structure. The decomposition of plant material releases nutrients and organic matter, while oxidation processes help shape the chemical environment (Tabacchi et al., 2000). Herbaceous cover stabilizes banks and modulates sediment and nutrient fluxes (Allan, 2004), and tree canopies create microclimates that affect primary production (Broadmeadow & Nisbet, 2004). Forested riparian corridors support key ecological interactions involving soils, hydrology, and biotic communities (Klapproth & Johnson, 2009). However, land use changes, including deforestation, agriculture, and urbanization can significantly impact aquatic ecosystems and their resident species (Harding et al., 1998; Rios & Bailey, 2006; Vázquez et al., 2011). These impacts are particularly evident in periphyton communities, which shift in composition and biomass in response to increased light, altered flow, and nutrient inputs (Granados-Sánchez et al., 2006; Schiller et al., 2007; Samanez et al., 2014).

Diatoms are a diverse dominant group of microalgae, playing a central role in primary production, especially in wadeable streams (Pinto et al., 2016; Sabater et al., 2009). Their high sensitivity to water chemistry, particularly nutrient concentrations, pH, salinity, and contaminants, makes them reliable bioindicators of environmental change (Blanco et al., 2011; Uscanga, 2016). In tropical rivers, flow variability is a key driver of diatom community dynamics (Donato-Rondón, 2008). Owing to their well-characterized environmental tolerances, diatoms are widely used in biomonitoring programs to assess ecological status and detect early signs of ecosystem degradation (Bere & Tundisi, 2010; Munguía et al., 2007; Smol & Stoermer, 2010; Shibabaw et al., 2021).

This study aimed to evaluate whether changes in riparian vegetation are associated with shifts in periphyton abundance, diversity and community composition in tropical mountain streams of southern Ecuador (Loja). The study streams, three of which lie within a protected watershed that supplies water to roughly 270 000 people (Table S1, supplementary information, available at https://www.limnetica.com/en/limnetica), differ in land use and degradation levels. Based on surrounding vegetation, stream sections were categorized as either forested (i.e., close to intact riparian vegetation with minimal disturbance) or open (i.e., major replacement of natural riparian vegetation by pastures or crops). Some sites represented degraded zones, marked by clear and visible human disturbance such as livestock activity, infrastructure, and waste dumping. Given the sensitivity of diatoms to environmental changes, we hypothesized that open areas would show early signs of ecological degradation, both in water quality and diatom community structure, similar to those in degraded sites. The use of diatom communities as early indicators may provide valuable insights into the ecological integrity of stream ecosystems and support efforts to manage and protect water resources critical to both ecosystem and human health.

METHODS

Study area

The study was conducted in seven small Andean streams located near the city of Loja in southern Ecuador. This region has a temperate equatorial climate, with average temperatures ranging from 12 to 16°C (Zarate, 2011). The streams are situated at an elevation of approximately 2020 meters above sea level and belong to two small hydrographic systems in Loja Province: the Zamora and Northern Malacatos basins. These streams form part of the upper sub-basin of the Zamora River, which originates in the Cajanuma mountains and flows into the Santiago River, one of the tributaries of the Amazon River basin. Among the studies streams, El Carmen, Mónica, and Volcán are used for drinking water supply. El Carmen, in

Table 1. Sources and information collected for producing maps of the seven watersheds: Ministry of the Environment of Ecuador (MAE), National Internal Boundaries Committee (CONALI) and National Territorial Information System. *Fuentes e información recopilada para la elaboración de mapas de las siete cuencas hidrográficas: Ministerio del Ambiente del Ecuador (MAE), Comité Nacional de Límites Internos (CONALI) y Sistema Nacional de Información Territorial.*

Cartographic resource	Source	Scale	Year
Hydrography	SigTierras	1:25 000	2015
MDT (Digital Model of the Territory)	SigTierras	1:25 000	2015
Aerial images	SigTierras	1:5 000	2012
Land Use Coverage	SigTierras	1:25 000	2018
Sampling Points	Research team	1:10 000	2017
National System of Protected Areas	MAE	1: 100 000	2017
Political Administrative Division	National Internal Boundaries Committee (CONALI)	1:50 000	2017

particular, provides water to approximately 60% of Loja´s population (INEC, 2021). During the rainy season, these streams collectively discharge around 300 liters of water per second; however, this flow decreases to 180-200 liters per second during the dry season (El Telégrafo, 2013).

Maps for this study were created using freely accessible data provided by the Military Geographic Institute. (IGM, 2017), including hydrographic information and digital elevation models (Table 1). Field data collected during sampling were cross-referenced with digital cartography at various scales (1:100 000; 1:50 000; 1:25 000, 1:5 000) as well as with aerial photography. This integration allowed for the generation of accurate and detailed spatial information for each study area. Base maps and vegetation cover maps were developed using the coordinate system defined by the Military Geographic Institute (IGM, 2017), with the following geospatial parameters: Horizontal Datum: WGS84; Reference Zone: Zone 17 South; Cartographic Projection: Universal Transverse Mercator (UTM). Land cover categories and vegetation structure were classified using Geographic Information System (GIS) techniques. All spatial data processing and map generation were carried out using ArcGis version 10.5.

Sampling design

Fieldwork was conducted in collaboration with the Department of Agriculture and Renewable Natural Resources at the National University of Loja. In November 2016, water samples were collected from seven streams in the vicinity of Loja: El Carmen, San Simón, Mónica, Volcán, Violeta, Tenería and Shucos (Fig. 1).

For the El Carmen, San Simón, Mónica, and Vol-

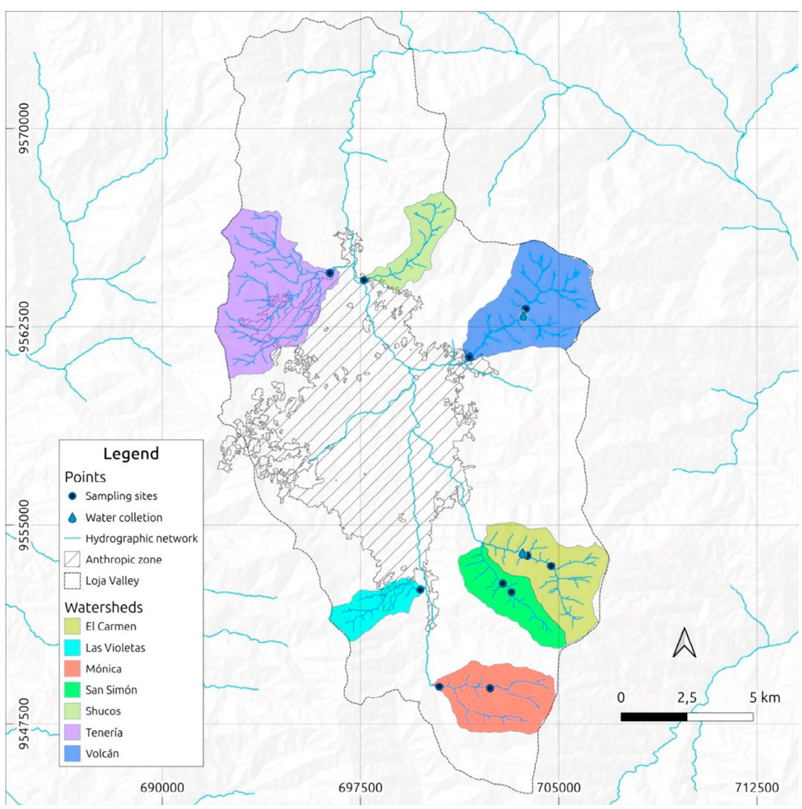

Figure 1. Map of the seven streams included in this study near the city of Loja (Ecuador). Blue dots represent sampling locations in each stream. Blue waterdrop symbols represent the location of water treatment plants. The hatched area represents the city of Loja. *Mapa de los siete arroyos incluidos en este estudio cerca de la ciudad de Loja (Ecuador). Los puntos azules representan las ubicaciones de muestreo en cada arroyo. Los símbolos de gotas de agua azules indican la ubicación de las plantas de tratamiento de agua. El área sombreada representa la ciudad de Loja.*

cán streams (i.e., four streams), two distinct zones were identified within each watershed using vegetation cover maps and posterior NDVI analysis. The forested zone was defined as a 100-meter continuous stretch of dense natural vegetation, with average NDVI values above 0.6, extending at least 5 meters on both sides of the stream. In contrast, the open zone was characterized by average NDVI values below 0.3 and showing clear signs of vegetation removal or land-use change (e.g., agriculture or livestock activity, Fig. 2). Thus, forested and open zone classification was supported by visual in situ characterization, interpretation of satellite imagery and consistent NDVI thresholds to ensure an objective and replicable approach across all sites. Within each watershed, we selected two adjacent, or as close as possible, forested and open zones for sampling. This design minimized variation due to elevation, climate, and stream characteristics, allowing for a more controlled comparison of land-use effects on stream conditions.

For the other three streams (Shucos, Tenería, and Violeta), data collecting and sampling was limited to degraded areas due to the absence of extended, continuous forest cover, which prevented the identification of comparable forested zones as in the other watersheds. These streams were therefore used as reference sites representing predominantly degraded conditions within the study area. In all cases, a 100-meter transect was established following the direction of river flow. Each transect was divided into five 20-meter sections for data collection and sampling. Thus, each zone of a stream was sampled five times.

Water sampling

Water samples for periphyton community analysis were collected at each replicate point within the sampling zones (every 20 meters) using acid-washed 100 ml plastic bottles and preserved with glutaraldehyde (1 ml, in a final concentration of 2.5%). Standard collection and processing methods were followed (Danielson, 2009; Fetscher et al., 2009; Mayama et al., 2022). At each site, five small rocks were retrieved from the riverbed, and a composite sample was obtained by scraping a circular area of 2.9 cm^2 per

Figure 2. Examples of Open (left) and Forested (right) zones in the Mónica stream. *Ejemplos de zonas abiertas (izquierda) y boscosas (derecha) en la quebrada Mónica.*

rock, using 20 ml of water for rinsing. Diatom abundance, initially calculated as cells/mL from subsample counts, was converted to cells/cm² by multiplying the concentration by the suspension volume (20 mL) and dividing by the total area sampled (14.5 cm²). At each sub-sample point, a portable multiparameter probe (HQ40D Hach) was used to measure water temperature, pH, dissolved oxygen, and conductivity. Additionally, 10 ml water samples were preserved with 0.5 ml of sulfuric acid (final concentration of less than 5%) for subsequent nutrient analyses. Nutrients analyses conducted in the laboratory included measurements of total phosphates (μg/L) and nitrites/nitrates (μg/L), using an AQ2 discrete analyzer. These analyses followed EPA methods 365.1, version 2 and 353.2, version 2 (1993), respectively. To measure streamflow, the salt tracer method was employed, a technique suitable for small streams with variable velocities and turbulence (Roa, 2011). This method is independent of the river´s cross-sectional area and sampling distance. A soluble salt was used to increase electrical conductivity (EC), serving as a tracer to monitor water movement. The method involved introducing a known quantity of salt dissolved in water at a specific point in the stream. Conductivity was then measured 40 meters downstream (the dissolution distance) to detect changes in electrical conductivity (EC). There is a direct linear relationship between the increase in EC and the concentration of dissolved salt (for EC <1000 μS/cm), allowing EC measurements to be converted into the amount of salt passing through the stream per unit of time. By plotting conductivity against time, the area under the curve was calculated and used to determine streamflow (Q in L/s) using the following formula:

$$Q = \frac{V}{k * \sum[EC(t) - EC_{bg}]\Delta t}$$

with: $EC(t)$ = measured conductivity at time t in μS/cm, EC_{bg} = measured background conductivity in μS/cm, V = volume of salt injected in mg, and k = conversion factor in $\frac{mg \frac{\mu S}{cm}}{l}$.

Periphyton community analysis

In the laboratory, the entire periphyton community was analyzed to quantify total abundance and two community indices: species richness and Shannon diversity (Somarriba, 1999). Quantitative analysis of periphyton was performed using the Palmer-Maloney counting method (Palmer & Maloney, 1954). All colonies and filaments were disaggregated into individual cells for further analysis. For each sampling site, a minimum of 100 algal cells were counted. All algal groups were identified to the lowest possible taxonomic level. Cell density was calculated based on the number of cells per unit per sample, accounting for any dilution or concentration steps during sample preparation (American Public Health Association, 1998; Ministério da Saúde, 2015).

Diatom identification

Diatom identification required the removal of organic matter from frustules through an oxidation process using strong acids, followed by the preparation of permanent slides in a high refractive index resin (Charles et al., 2002; Manoylov, 2015; Samanez et al., 2014). Sample preparation was conducted at the Laboratory of the Department of Biological and Environmental Sciences, Georgia College and State University (USA), between fall 2018 to spring 2019. Following digestion with nitric acid and subsequent neutralization, cleaned diatom material was mounted onto slides using Naphrax™ (Brunel Microscopes Inc., United Kingdom), a resin with a high refractive index suitable for diatom microscopy. Diatom enumeration aimed for a standard count of 600 valves per sample. In nearly all cases, this target was reached under consistent scanning effort. However, in two low-density samples (San Simón and Mónica Forested zones), the entire slide was scanned to count all available valves, which did not reach the 600-valve target. No additional targeted searches for rare taxa were conducted beyond this procedure. For all statistical analyses, only the identified valves within the standard count (or the full count in low-density samples) were used to ensure comparability across samples. Enumerations and identifications were conducted using a Leica DM2500 microscope equipped with a Leica DFC295 camera, at 1000x magnification (Leica Microsystems, Wetzlar, Germany) at Georgia College and State University. Diatom identification was based on a range of taxonomic keys, including Lange-Bertalot et al. (2003, 2011), Lange-Bertalot & Metzeltin (1996), Patrick (1966); Patrick & Reimer (1975), Krammer et al. (1986), Krammer & Lange-Bertalot (1988, 1991, 2000), and Núñez et al. (2008). To estimate total cell density, the volume of each transect was assumed to be 8 mm^3. For each sample, regardless of whether it came from Degraded, Forested or Open zones, five sub-samples were analyzed, with three transects examined per sub-sample. This resulted in a total analyzed volume of 120 mm^3 per stream.

Data analyses

Data from four streams, El Carmen, Mónica, San Simón and Volcán were used to compare the open and forested sections, while data from three streams: Tenería, Violeta and Shucos, represented the highly degraded watersheds and were used as reference. The variables included in this comparison were: total phosphates, nitrates/nitrites, water temperature, conductivity, pH, dissolved oxygen, water flow, total periphyton abundance, periphyton species richness and Shannon index based on species abundances. Additionally, for each stream, periphyton community composition was determined at the phylum level, expressed as the relative contribution of each phylum to total abundance. The contribution of each algal phylum to total abundance was assessed across all streams and within each zone type (forested, open, or degraded). To explore potential relationships between environmental variables, a correlation-based Principal Component Analysis (PCA) was conducted on the seven environmental variables (conductivity, oxygen concentration, pH, flow, water temperature, total phosphates, and nitrates/nitrites). For the PCA, the environmental variables were averaged for each stream and each zone, resulting in 11 datapoints. The PCA enabled us to reduce the dimensionality of the dataset, identify major environmental gradients across sites, and facilitate the interpretation of patterns in water quality conditions. It also allowed us to compare how different land-use types (forested vs. open zones) are associated with variations in environmental variables.

A cluster analysis was conducted to evaluate and compare the similarity in diatom community composition across different streams and zone types. Due to the loss of algal samples during transportation, diatom data from the Shucos and San Simón streams were excluded to avoid bias from incomplete data. The analysis was performed using hierarchical clustering with Ward's linkage method and squared Euclidean distances, which minimizes within-cluster variance. Prior to clustering, diatom relative abundance data were standardized (Z-scores) to ensure equal weighting of all taxa and account for differences in scale. This approach assumes that clustering patterns are influenced by relative rather than absolute dif-

Table 2. Overview of the seven environmental variables across three zones, with results from the Linear Mixed Model comparing only Forested and Open zones. Degraded zones are presented for reference but were excluded from statistical analyses. *Resumen de las siete variables ambientales en las tres zonas, con los resultados del Modelo Lineal Mixto que compara únicamente las zonas forestadas y abiertas. Las zonas degradadas se presentan como referencia, pero fueron excluidas de los análisis estadísticos.*

Environmental Variable	Zone Effect ($F_{1,3}$)	p-value	Mean Forested	Mean Open	Mean Degraded
Total Phosphates (µg/L)	8.45	0.006	17.68	21.23	90.46
Nitrates/Nitrites (µg/L)	180.26	<0.0001	44.15	61	41.2
Water Temperature (°C)	222.99	<0.0001	13.9	16.5	16.88
Conductivity (µS/cm)	245.57	<0.0001	23.87	38.94	9.29
pH	1.98	0.168	6.1	6.24	8.4
Dissolved Oxygen (mg/L)	56	<0.0001	7.9	7.5	7.73
Water Flow (L/s)	1.93	0.174	104.29	100.78	7.15

ferences in community composition. The number of clusters was determined through visual inspection of the dendrogram and biological relevance of groupings. The resulting clusters were used to assess similarity among stream zones based on diatom assemblages.

All statistical analyses were performed using JMP version 18 (SAS Institute Inc., Cary, NC, USA).

RESULTS

Environmental conditions across stream zones

Linear mixed-effects model (LMM) analyses revealed significant differences in some environmental conditions between forested and open stream zones. Total phosphate concentrations were significantly higher in open zones (21.23 µg/L) than in forested zones (17.68 µg/L; $F_{1,3}$ = 8.45, p = 0.0063, n = 40). Nitrate/nitrite levels also differed significantly, with higher values in open zones (61 µg/L) compared to forested zones (44.15 µg/L; $F_{1,3}$ = 180.26, p < 0.0001, n = 40). Similarly, water temperature was significantly elevated in open zones (16.5 °C) relative to forested ones (13.9 °C; $F_{1,3}$ = 223.00, p < 0.0001), and conductivity was higher in open zones (38.94 µS/cm) than in forested zones (23.87 µS/cm; $F_{1,3}$ = 245.57, p < 0.0001, n = 40). Dissolved oxygen was significantly higher in forested zones (7.9 mg/L) than in open zones (7.5 mg/L; $F_{1,3}$ = 56.00, p < 0.0001, n = 40). In contrast, pH and water flow did not differ significantly between forested and open zones (p = 0.1682 and p = 0.1736, respectively). Environmental values from degraded sites (not included in the statistical comparisons) are reported as a reference to illustrate broader environmental variation. Degraded zones showed notably higher total phosphates (90.46 µg/L) and pH (8.4), as well as much lower water flow (7.15 L/s) and conductivity (9.29 µS/cm) than either forested or open zones (Table 3).

Periphyton community metrics

Periphyton community metrics did not differ significantly between forested and open stream zones based on linear mixed-effects models. Cell abundance tended to be higher in open zones (mean = 13 223 cells/cm^2) than in forested zones (mean = 7929 cells/cm^2), but this difference was not statistically significant ($F_{1,3}$ = 2.65, p = 0.11, n = 40). Similarly, species richness was slightly higher in open zones (mean = 9.35) than in forested zones (mean = 8.45), though the effect was also non-significant ($F_{1,3}$ = 1.88, p = 0.18, n = 40). Shannon diversity showed no difference between zones ($F_{1,3}$ = 0.001, p = 0.97, n = 40), with nearly identical means (0.706 in forested vs. 0.704 in open zones). Although degraded sites were not included in the statistical comparison, their values provide a reference for broader context. Degraded sites exhibited substantially higher cell abundance (23 239 cells/cm^2) and species richness (16 species), suggesting possible eutrophication or altered community dynamics in more disturbed environments. Shannon diversity in degraded sites (0.763) was comparable to that of forested and open zones.

Table 3. Overview of the three variables related to periphyton community composition across three zones, with results from the Linear Mixed Model comparing only Forested and Open zones. Degraded zones are presented for reference but were excluded from statistical analyses. *Resumen de las tres variables relacionadas a la composición de las comunidades de perifiton en las tres zonas, con los resultados del Modelo Lineal Mixto que compara únicamente las zonas forestadas y abiertas. Las zonas degradadas se presentan como referencia, pero fueron excluidas de los análisis estadísticos.*

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Environmental patterns: PCA

Principal Component Analysis (PCA) was used to explore multivariate patterns in environmental variables across forested, open, and degraded stream zones (Fig. 3). The first two principal components explained a combined 80.7% of the total variance in the dataset (PC1: 49.1%, PC2: 31.6%). PC1 captured a gradient associated mainly with water flow (loading = +0.52), pH (−0.49), and total phosphates (−0.45), reflecting a hydrological and nutrient-enrichment axis. PC2 was primarily driven by temperature (+0.63) and nitrate/nitrite concentrations (+0.55), indicating a thermal and nutrient input gradient. Site scores on the PCA plot showed clear separation among zone types. Forested zones clustered in the lower right quadrant (high PC1, low PC2), associated with faster water flow, lower pH, and low nutrient concentrations, indicative of relatively intact conditions. Open zones were located in the upper right quadrant (high PC1, high PC2), maintaining moderate flow but exhibiting increased temperature and nitrate levels, likely due to canopy loss and higher exposure. Degraded zones appeared on the left side of the plot (low PC1, variable PC2), characterized by reduced flow and elevated phosphates and pH, with variable thermal and nutrient conditions. This distribution reflects more severely impacted environments. The PCA results suggest that forest cover and degradation are strongly associated with consistent shifts in environmental conditions, particularly those linked to flow dynamics, nutrient accumulation, and temperature.

Algal community composition across zones

Diatoms (Bacillariophyta) were the dominant algal group across all streams, accounting for 82% of cell counts (Fig. 4). Cyanobacteria were the

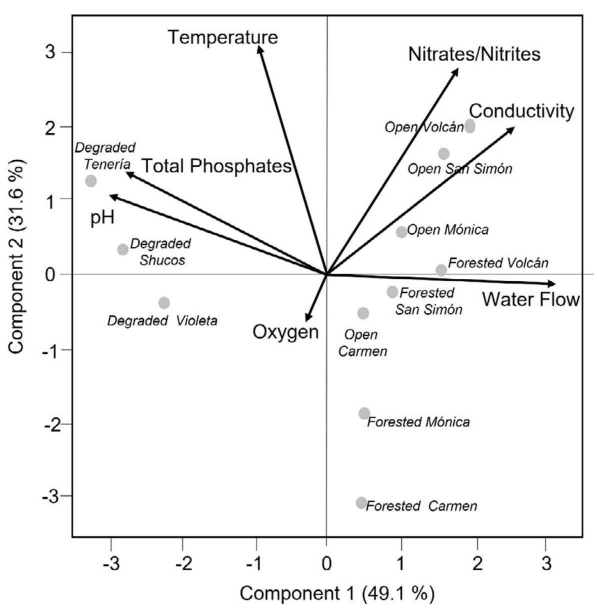

Figure 3. Biplot of the first two principal components showing environmental variation among Forested, Open, and Degraded zones across the seven streams. Arrows represent the direction and strength (loadings) of environmental variables contributing to each axis. Grey dots represent each zone type in a stream. Forested zones cluster in the lower right quadrant, associated with higher water flow and lower pH and total phosphates. Open zones appear in the upper right quadrant, associated with elevated temperature and nitrate concentrations. Degraded zones are located on the left side of the plot, characterized by reduced flow and nutrient accumulation. The separation among zone types indicates distinct environmental conditions linked to canopy cover and land degradation. *Biplot de los dos primeros componentes principales que muestra la variación ambiental entre zonas Boscosas, Abiertas y Degradadas en los siete arroyos. Las flechas representan la dirección y magnitud (cargas) de las variables ambientales que contribuyen a cada eje. Los puntos grises representan cada tipo de zona en un río. Las zonas boscosas se agrupan en el cuadrante inferior derecho, asociadas con mayor caudal y menores valores de pH y fosfatos totales. Las zonas abiertas se ubican en el cuadrante superior derecho, relacionadas con temperaturas más altas y mayores concentraciones de nitratos. Las zonas degradadas se encuentran en el lado izquierdo del gráfico, caracterizadas por menor caudal y acumulación de nutrientes. La separación entre tipos de zona indica condiciones ambientales distintas vinculadas a la cobertura vegetal y al grado de degradación del entorno*.

second most abundant group (12.4%), followed by Chlorophyta (4.1%) and Rhodophyta, represented by *Batrachospermum* sp. (1.8%). No colonial forms of Cyanobacteria or Chlorophyta were observed in this study. Substantial variation in algal phyla was found both among streams and among zone types. Some zones contained only a single phylum (i.e., Bacillariophyta), while none of the sampled zones included representatives of all four phyla simultaneously. The phyla composition varied notably across zone types, with the most pronounced differences occurring between open and degraded zones. Open zones exhibited a higher relative abundance of Cyanobacteria, exceeding 20 % in two streams (Mónica and San Simón). In contrast, the degraded and forested zones displayed overall similar phyla compositions, though forested zones uniquely contained Rhodophyta and Chlorophyta. Only diatoms and filamentous cyanobacteria were found in the degraded zones.

Diatom composition and community structure

Across all samples, 22 diatom genera and 48 species were identified (Table S1, Supplementary Information, available at https://www.limnetica.com/en/limnetica). The most species rich genera were *Navicula* (9 species), *Achnanthidium* (5 species), *Gomphonema* (5 species), and *Nitzschia* (5 species). Across the entire dataset, *Gomphonema* was the most abundant genus, accounting for 39% of all diatom cell counts, followed by *Achnanthidium* at 22.7%. In the Volcan open site, *Gomphonema* cells observed in girdle view reached a relative abundance of 68%. The most abundant species overall were *Gomphonema minutum* (average relative abundance: 30.2%, range 1-50%) and *Achnanthidium minutissimum* (average 14.1%, range 3-47%). The more widespread genera were *Achnanthidium* and *Gomphonema*, both present in all sampling sites. Among the most frequently observed species were *Gomphonema minutum*, *G. parvulum*, and *Achnanthidium minutissimum*, found in six streams, while *Achnanthidium subatomus* was present in five sites. The number of genera per site ranged from 3 to 10, and species richness per site ranged from 4 to 16. A total of 27 diatom species were recorded at only one site each, suggesting these taxa may have narrower ecological niches. The number of narrow-tolerance species ranged from 4 to 10 per stream and from 1 to 6 per zone. In the three streams with both forested and open zones, the number of narrow-tolerance taxa declined as natural

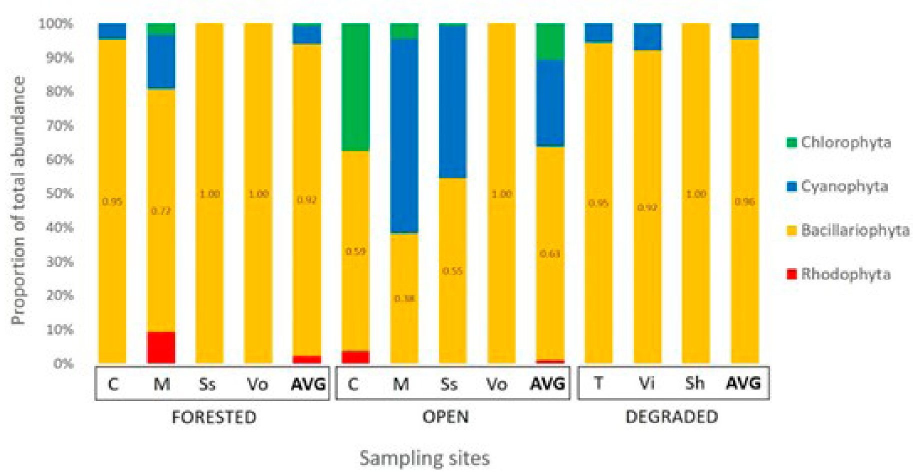

Figure 4. Phyla composition of the periphyton communities in different zones (Forested, Open and Degraded) and different streams, represented as their relative contribution to total abundance. (C = El Carmen, M = Mónica, Ss = San Simón, Vo = Volcán, T = Tenería, Vi = Violetas, Sh = Shucos). AVG represents the average composition in each zone. Numbers in the yellow bars represent the proportion of diatoms at each site. *Composición de los filos de las comunidades de perifiton en diferentes zonas (boscosas, abiertas y degradadas) y diferentes arroyos, representada como su contribución relativa a la abundancia total.*

riparian vegetation was replaced by pastures or crops. Variation in species richness and the relative contribution of species to total abundance resulted in generally low diversity, with Shannon index values ranging from very low (0.32) to low (0.96). Diatom cell abundance varied over two orders of magnitude, from approximately 35 854 to 365 435 cells/cm^2. A clear gradient was observed, with increasing cell abundances from forested to open and degraded zones.

Four diatom species were either exclusive to or notably more abundant in Violeta, a degraded site: *Geissleria decussis*, *Navicula germainii*, *Nitzschia recta* and *Planothidium lanceolatum*. Tenería (also a degraded stream) included four species, *Cocconeis placentula*, *Navicula lanceolata*, *Nitzschia frustulum* and *Rhoicosphenia abbreviata* that were either unique to or more abundant in this site. The forested zone of the El Carmen stream stood out due to the presence of three distinctive species: *Achnanthidium rivulare*, *Kobayasiella subtilissima* and *Planothidium* sp. The Volcán open site was differentiated by a strong dominance of *Gomphonema* sp. Meanwhile, the forested zone in Mónica showed high abundance of *Achnanthidium minutissimum* and the unique presence of *Bacillaria paradoxa* and *Nupela* sp. The remaining sites, Carmen open, Volcán forested and Mónica open, also hosted unique taxa, further supporting the influence of local habitat characteristics on diatom community composition.

Cluster and dissimilarity analysis

Cluster analysis based on diatom community composition revealed that the two degraded streams harbored communities most distinct from those of the other six sites, regardless of zone type (forested or open, Fig. 5a). In the resulting dendrogram, forested and open sites did not form separate groups but were intermixed, indicating that land cover alone did not fully explain community similarity patterns. The presence of

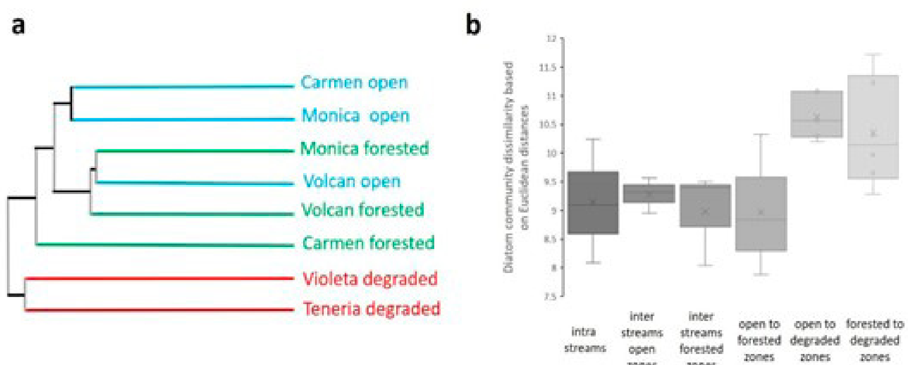

Figure 5. a) Cluster analysis of diatom community composition across the eight sampled sites. The two degraded sites (red) form a distinct cluster, while the remaining six sites (green: forested; blue: open) show no clear clustering pattern. Long terminal branches (colored) indicate a high degree of compositional uniqueness at each site, whereas short basal branches (grey) suggest a limited pool of shared species among sites. b) Comparison of Euclidean distances representing compositional dissimilarity in diatom communities across spatial groupings. Crosses denote mean values, horizontal lines indicate medians, bars represent standard deviations, and boxes depict 95% confidence intervals. Intra streams represent diatom communities from different zones within each stream (n = 3). Inter streams open zones represent communities from open sites in different streams (n = 3). Inter streams forested zones represent communities from forested sites in different streams (n = 3). Open to forested zones represents communities from the two zones across different streams (n = 6). *a) Análisis de clúster de la composición de la comunidad de los ocho sitios muestreados. Los dos sitios degradados (en rojo) forman un clúster separado. Las otras seis comunidades de diatomeas están mezcladas sin un patrón claro de agrupamiento. Las ramas terminales del árbol (en color) son relativamente largas, lo que sugiere que cada sitio tiene una considerable unicidad en su composición. Las ramas basales cortas (en gris) sugieren que el grupo de especies compartidas por los diferentes sitios es reducido. El azul representa sitios abiertos y el verde representa sitios boscosos. b) Comparación de las distancias euclidianas que separan los diferentes sitios según su composición de especies de diatomeas. Las cruces representan promedios, las líneas horizontales representan valores medianos y las barras representan desviaciones estándar. Las cajas representan intervalos de confianza del 95%. Las comunidades intra-arroyo representan comunidades de diatomeas de diferentes zonas dentro de cada arroyo (n = 3). Las zonas abiertas inter-arroyo representan comunidades de sitios abiertos en diferentes arroyos (n = 3). Las zonas boscosas inter-arroyo representan comunidades de sitios boscosos en diferentes arroyos (n = 3). Las zonas abiertas a boscosas representan comunidades de las dos zonas a través de diferentes arroyos (n = 6).*

long terminal branches (colored) in the cluster tree highlights the high degree of compositional uniqueness among the eight sites. In contrast, the short basal branches (grey) indicate a limited pool of shared species and relative abundances across sites. This suggests that most of the observed spatial variation in community composition is due to taxa being unique to individual sites.

The analysis of community dissimilarity, based on the Euclidean distances derived from the clustering analysis, revealed two findings (Fig. 5b). First, diatom communities from different zones within the same stream (intra-streams comparisons) are as compositionally different as communities from: 1) open zones across different streams (inter-stream open), 2) forested zones across different streams (inter-stream forested) and 3) open and forested zones across streams (cross-zone inter-stream). In other words, intra-stream dissimilarity was comparable in magnitude to inter-stream dissimilarity, suggesting strong site-specific effects on community composition. Second, the analysis showed that diatom communities from both forested and open zones were similarly dissimilar from those in the degraded sites. This indicates that degradation produces a distinct shift in community structure, regardless of the original land cover type of the less-impacted sites.

DISCUSSION

Periphyton assemblages, particularly diatoms, are highly sensitive to both chemical and physical changes in stream environments, making them valuable bioindicators of water quality. Diatoms can detect subtle ecological shifts that may be overlooked by traditional physico-chemical analyses. While widely applied in temperate regions (Hill et al., 2000; Kelly et al., 2009), the use of periphyton, and especially diatoms, in assessing tropical mountain streams remains limited. This knowledge gap is critical given the rapid degradation occurring in Andean ecosystems, driven by agriculture, livestock grazing, mining, infrastructure development, and climate change. In this context, our study aimed to determine whether differences in land cover influence physico-chemical conditions and, consequently, periphyton community composition in seven tropical mountain streams in Southern Ecuador.

Compared to forested stream sections, open zones adjacent to pastures or croplands exhibited modest but consistent changes in several environmental conditions. In particular, we observed increased total phosphate and nitrates/nitrite concentrations, higher water temperature and conductivity as well as a reduced oxygen concentration, patterns consistent with early signs of stream degradation. Some of these changes mirror findings from previous studies linking riparian vegetation removal to nutrient enrichment and warming (Halliday et al., 2016; Hession et al., 2003; Majdi et al., 2015; Mosisch et al., 2001; Schiller et al., 2007; Vázquez et al., 2011). However, the environmental divergence between forested and open zones was not consistent across all variables or streams. This suggests that, while riparian clearing may initiate degradation, its impact on water quality in these systems is still relatively limited, though potentially progressing. Monitoring such transitional stages is essential for early detection of ecological change. Principal Component Analysis (PCA) provided a broader picture of multivariate environmental gradients along land use categories. The first principal component (PC1) captured variation linked to water flow, pH, and phosphates, thus separating degraded zones from others, while the second (PC2) reflected temperature and nitrate/nitrite concentrations, differentiating forested and open zones. This indicates that while degraded sites are distinguished by altered hydrological and nutrient regimes, forested and open zones diverge along a separate gradient tied to nutrient enrichment and thermal conditions.

A major objective of this study was to expand our understanding of periphyton assemblage composition in tropical mountain streams. Diatoms dominated the periphyton communities in streams around Loja; however, substantial spatial variation was observed in community composition both within and among streams. At the phylum level, communities in degraded zones were more similar to those in forested zones than those in open zones. Open zones, in contrast, were characterized by a higher relative abundance of cyanobacteria and a reduced contribution of diatoms to total algal abundance. This pattern aligns with findings from a previous study in Mexican mountain streams, which reported the presence of cyanobacteria near pasture areas but not in forested zones (Vázquez et al., 2011). The increased prevalence of cyanobacteria in the open zones of two streams may be linked to elevated phosphate concentrations and higher water temperatures, conditions known to favor cyanobacterial growth (Huisman et al., 2018). The shift toward cyanobacteria dominance in these open zones could represent an ecological signal of water quality degradation associated with the removal of natural riparian forest in high-altitude tropical watersheds. In contrast, the degraded zones exhibited lower phylum-level diversity, with no records of chlorophytes or rhodophytes, further highlighting the simplified community structure in more severely impacted environments.

Overall, species belonging to the genera *Gomphonema* and *Achnanthidium* dominated the periphyton communities in the streams studied around Loja. These genera are known to be widespread in rivers and streams across a broad range of environmental conditions (Bona et al., 2008; Huisman et al., 2018; Mosisch et al., 2001). An additional 20 genera, comprising 37 diatom species, contributed to a high spatial variability observed among streams and between zones within streams. However, none of these taxa exceeded 14% of the total abundance at any site. Most were relatively rare, typically accounting for only 0.5% to 4% of total diatom abundance. Species richness per sampling site was relatively low, ranging from 4 to 16, a pattern consistent with findings from other studies on diatom communities in mountain streams (Vázquez et al., 2011). While the average number of species did not differ between forested and open zones, the number of unique taxa was lower in the open zones. This suggests that even small-scale changes in environmental conditions, over distances of just a few hundred meters, can influence species composition and favor taxa capable adapted to altered conditions. Unfortunately, the current dataset does not allow us to pinpoint which specific variables were driving these patterns, underscoring the need for further targeted research.

It is also important to consider that diatom communities may reflect past rather than current environmental conditions. Temporal lags in community response are common in benthic algae, particularly in ecosystems subject to recent or fluctuating disturbances. As such, some diatom assemblages observed in this study may have been shaped by legacy effects of historical land-use or water quality changes, rather than by present-day conditions alone. Because our study was based on a single sampling event, it may not fully capture the temporal dynamics of community-environment interactions. We therefore recommend that future research incorporate repeated temporal sampling to better understand the stability, resilience, and responsiveness of diatom communities over time.

The cluster analysis confirmed the compositional uniqueness of all study sites, with few species shared across all locations and several taxa found exclusively at individual sites. This supports the well-documented sensitivity of diatoms to localized environmental conditions, as observed in other studies of mountain streams (Bere et al., 2013; Bona et al., 2008; Jüttner et al., 2004; Ponader & Potapova, 2007; Vázquez et al., 2011). The analysis also reinforced that the diatom communities from the two degraded sites were the most distinct from those of the other six sites, regardless of land use classification (forested or open). Furthermore, the cluster analysis revealed that variation in community composition among different streams was comparable to the variation observed within individual streams. Diatom communities located only a few hundred meters apart within the same stream were often as compositionally different as those from entirely separate watersheds several kilometers away. This finding underscores the dominant role of local-scale processes, such as environmental filtering, species interactions, and microhabitat variability (e.g., substrate type, shading, grazing pressure), in shaping periphyton communities in tropical mountain streams near Loja. These results suggest that local habitat conditions may exert a stronger influence on diatom community composition than broader-scale environmental gradients or generalized effects of anthropogenic land use, as also noted by Jüttner et al. (2004).

An important limitation of this study is that data were collected during a single sampling event in November 2016, near the beginning of the rainy season in southern Ecuador. As such, the measured flow conditions may not be representative of the full range of hydrological variability that typically occurs across seasons or between years. In particular, flow regimes in tropical mountain streams can vary significantly between wet and dry seasons, influencing nutrient transport, temperature, sedimentation, and periphyton dynamics. Without seasonal or interannual data, it is difficult to assess whether the observed environmental patterns and community structures reflect stable conditions or transient responses to recent hydrological events. Future studies should incorporate repeated sampling across different seasons and years to better understand how flow variability affects stream ecosystems in this region.

This study examined the environmental and biological characteristics of seven tropical mountain streams in southern Ecuador, each associated with different land use types. Given the limited research on periphyton communities in these ecosystems, the findings provide valuable baseline on water quality and community structure in poorly studied tropical highland streams. The results highlight several ecological impacts of riparian vegetation degradation on stream ecosystems. First, the removal of native forest cover consistently led to increased water temperature. Second, nutrient concentrations, particularly phosphates and nitrates/nitrites, tended to rise in areas influenced by human activities. Third, cyanobacteria became more prevalent in open stream sections, likely due to higher light availability and elevated temperatures. Fourth, the number of endemic or unique diatom taxa was reduced in disturbed zones, suggesting a loss of ecological specialization. Despite these patterns, the dissimilarity in diatom community composition between forested and open zones within the same stream was comparable to the dissimilarity among different streams. This indicates that diatom assemblages are shaped primarily by local environmental conditions and the sensitivities of individual taxa, rather than by spatial scale or hydrological connectivity. In other words, two sites within the same stream, but subject to contrasting environmental conditions, can be as compositionally distinct as sites from entirely separate watersheds. Lastly, the most degraded sites, which showed the most altered physico-chemical profiles, also supported the most divergent diatom communities. This underscores the value of diatoms as sensitive indicators of ecological integrity and highlights the need for conservation and restoration efforts in tropical mountain streams under increasing anthropogenic pressure. Effective conservation and restoration in tropical mountain streams must therefore prioritize the protection of native riparian vegetation, control of nutrient inputs, and attention to fine-scale habitat conditions. As land-use pressures intensify across the Andes, long-term ecological monitoring using diatom-based approaches will be essential for tracking ecosystem health and guiding management interventions.

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DECLARATIONS

Conflict of interest

The authors declared that there is no conflict of interest.

Data availability

Data collected and analyzed are available from the authors upon reasonable request.

AUTHOR CONTRIBUTIONS

V.A.C.: Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing - original draft; K.M.: Investigation, Methodology, Supervision, Validation, Writing - review and editing; B.W.I.: Investigation, Supervision, Writing - review and editing; N.A.: Investigation, Validation, Writing - review and editing; P.V.: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Project administration, Resources, Software, Supervision, Validation, Writing - review and editing.

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