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Land-Use Dynamics and Water Quality in Andean Basins

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Abstract: Conventional agricultural practices, such as the use of agrochemicals, implementation of monocultures, and the expansion of crops in strategic ecosystems, have significant impacts in Andean basins, directly increasing nutrient inputs to waterways, and contributing to ecological fragility and socioeconomic vulnerability. This complex dynamic is related to land-use change and production activities that affect the provision of hydrological ecosystem services. This study presents an integrated analysis of socioecological interactions related to water quality in the Las Piedras River basin (LPRB), a water supply basin located in the Andean region of southwestern Colombia. The analysis was conducted over a five-year monitoring period to assess the spatiotemporal variation and correlation of water quality between streams and agricultural runoff water within the LPRB. Furthermore, water quality indices were calculated based on physicochemical and biological parameters to evaluate the impact of land-use/land-cover changes and agricultural activities within the basin. Results demonstrate that different types of actors, productive logics, mechanisms of use, and access to water within the basin affect water quality and uncertainty for water management, while facing socioecological conflicts between actors.

Keywords: water pollution; agriculture; drinking water; land use/land cover; monitoring

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1. Introduction

Basins are considered worldwide to be key environmental units regarding the provision of goods and ecosystem services (ES), which are vital for community development [1–4]. In the Andean region of South America, the widespread application of conventional agriculture (impacting natural resources and thus ES), exposes a contradiction of interests with which political decisions of human development are managed [5–7]. Sustainable development is a common narrative of decision makers but, in practice, basin development projects and policies tend to prioritize profit [8,9]. In Colombia, the implementation of conventional agriculture extends to strategic ecological zones such as the area between the Andean and páramo forests in the southwest region, which are key to hydrological regulation. Such areas represent the recharge and flow regulation zones that are crucial for national water supply [10,11]. The expansion of conventional agriculture in the region has been driven by an economic need, thereby increasing crop productivity, primarily with the use of agrochemicals [12–15]. As such, conventional agricultural production represents one of the main means of income for socioeconomically vulnerable communities in the region. However, conventional agriculture is simultaneously one of the main drivers of biodiversity loss, especially in the Upper Cauca River Basin (UCRB) in Colombia due to large areas of monocultures [16,17]. Deforestation and degradation rates are also increasing in the UCRB due to the cultivation of intensive and illegal crops [18–21].

Strategies to increase conventional crop production in the region encourage the use of unsustainable practices, such as deforestation, land-use change, intensive tilling on slopes, monocultures with bare soils, overuse of chemical inputs, and others. These practices deteriorate basins in a systematic way, affecting the quality of life of rural communities, as well as the water supply for urban areas [22,23]. To address this problem, the literature focuses independently on the physicochemical, bacteriological, or biological characteristics of water through the analysis of spatiotemporal variations in water quality [24,25], which are aligned with policies that aim at guaranteeing water supply in adequate quality and quantity as well as access to water, sanitation, and hygiene (WASH) for citizens around the world.

While the results from the literature on water quality provide information on the impacts that are generated, they are not often analyzed under an integral systems framework, leaving a gap in identifying the causes that trigger these effects [26]. For this reason, a systemic approach is necessary which addresses the complex relationships between community actors, the socioeconomic activities they carry out, and the ecosystem services demands within a basin. Under this view, the authors propose a socioecological networks (SENs) approach, which attempts to understand the views of communities from within the basin and the dynamics of their productive systems, as well as the relationships among social and ecological elements that determine water quality [27]. With a SEN, the information gathered can then be applied for more integrated water management strategies and policies.

There has been an increase in the number of publications worldwide which offer an integrated view connecting productive activities and water quality (WQ), particularly since 2017. For example, Almansa-Manrique (2018) [28], É.F.; Hairani, A. (2020) [29], and M. Lin Lawell, C.-Y.C. et al. (2018) [30] have used WQ data to analyze the relationships between water pollution, income, and political institutions [28–30]. Berrios, F. et al. (2018), Meza-Salazar, A.M. (2020), Mohamamad, A. and Jalal, K.C.A (2020) have studied the community structure and composition of macroinvertebrates in order to better understand the ecological state of rivers [31–33]. Mendieta-Mendoza, A. et al. (2020) and Torti, M.J. et al. (2020) studied the relationship between nitrogen and phosphates and their mobilization towards riverbeds [34,35]; Peluso, J. et al. (2020) analyzed WQ considering the concentrations of metals and pesticides [36] and Aguirre, M.A. et al. (2020) and Esse, C. et al. (2019) studied the effects of WQ recreational ecosystem services [37,38]. Additionally, there have been some initiatives and trends in an integrated land (cover) use-based management analysis to support decision making for sustainable land management and planning with the use of agent-based land-use models [39], changes in landscape patterns and ecosystem service value [40–42], and efforts to understand connections between land use and ES supply [43].

In the context of Colombia, only eight papers can be found that address different perspectives of WQ; however, this analysis is not from an integrated systems approach [32,37]. Therefore, there is a clear need to develop strategies that consider the integration of activities and components that trigger effects on WQ. Such strategies should also consider SENs [44], because productive activities are directly related with actors' perspectives and can contribute to increasing the sustainability and resilience of agricultural systems [45–47].

This study presents a comprehensive understanding of the socioecological dynamics related to water quality (WQ) in Andean basins of Colombia, where land-use changes and conventional agricultural practices affect the provision of hydrological ecosystem services, using a case study in the Las Piedras River basin, located in the UCRB. The impacts on WQ were analyzed by subzones to differentiate the productive practices that drive changes in the basin. This includes evaluating the effects on the physical, chemical, and biological aspects of aquatic ecosystems. In addition, interactions between soil, vegetation, and climate were considered focusing on the contribution of pollutants from productive activities. By studying these interactions, we aim to develop a better understanding of how socioecological factors contribute to fluctuations in water quality within Andean basins.

2. Materials and Methods

2.1. Study Area

The research presented in this paper focuses on the Las Piedras River Basin (LPRB), located within the municipalities of Popayán and Totoró in the department of Cauca in southwestern Colombia. The coordinates of the basin are between 76°31′22″ W–2°28′00″ N and 76°22′10″ W–2°24′23″ N, as shown in Figure 1, with an extension of 6626 hectares and a yearly mean temperature that varies from 8 °C in the upper areas of the basin to 18.4 °C in the lower areas. The climate is typically cold and temperate, with a bimodal rainfall regimen. The topography is mountainous with steep slopes in the middle and upper areas, contrasting with the flat and concave terrains in the lower areas. The altitude ranges from 1980–3820 m above sea level. The average annual rainfall in the lower area of the basin is 1768 mm, 1800–2000 mm in the middle area, and 2200 mm and above in the upper area. Towards the Paramo (high Andean ecosystem) zone, records exceed 2300 mm of average annual rainfall (Arrayanales weather station ID number 26015040). The dry period is typically during June, July, and August, the rainy period is during April and October to December, and the transition period, which presents the average rainfall, is during January to March and May and September. The soil is largely composed of volcanic ash and silty clay with a pH of 5.0–5.9, and high saturation of aluminum (up to 85%) leading to poor fertility [48]. With respect to water availability for local communities, there is no water treatment system within the LPRB.

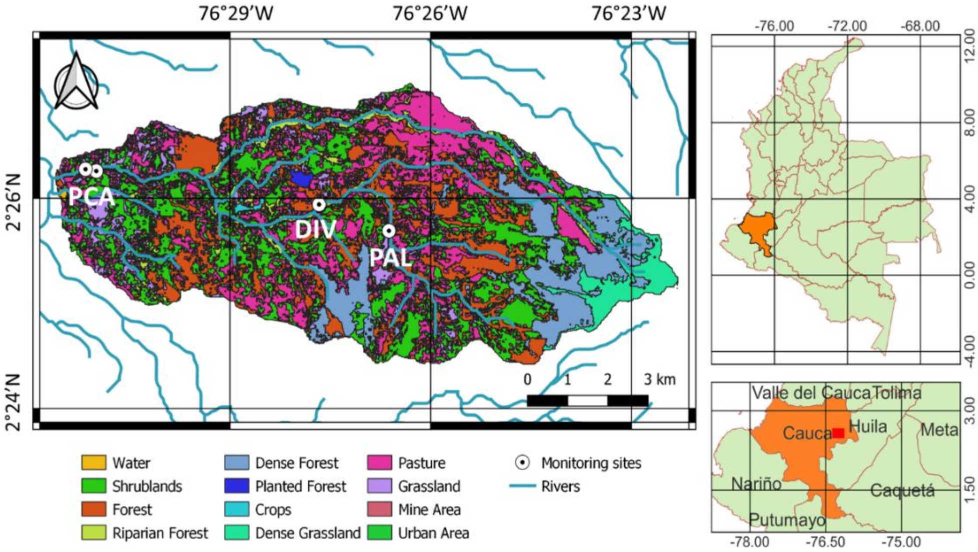


Figure 1. Map of the Las Piedras River Basin which showcases the most representative land use and land covers of the area.

The study period for the analysis of agricultural activities and their relation to WQ was 2013–2017 at monthly intervals and climatic periods, which were identified according to the multiannual variation. Physicochemical in situ samples were collected for the period 2013–2017 in order to analyze the land-cover (LC) changes observed from available remote sensing data in the area. A total of twelve LC classes were defined (see Figure 1), with the following breakdown of the LCs that mainly make up the LPRB (as per 2017): 20.1% dense forests (1329 ha), 20.7% open and fragmented forests (1370 ha), 23.5% natural grasses (1554 ha), and 35.6% pastures (2353 ha). To analyze WQ, three monitoring sites were selected. These points were selected based on the morphometric conditions, land use/land cover (LULC), productive activities, and to ensure representation of the three areas of the basin. The location of these points can be seen in Figure 1 and are represented by: (1) Puente Alto (PAL): 76°26′56″ W–2°25′29″ N at 2470 m.a.s.l; (2) Diviso (DIV):

76°27′50″ W–2°25′57″ N at 2290 m.a.s.l; and (3) Puente Carretera (PCA): 76°31′02″ W–2°26′36″ N at 1990 m.a.s.l.

2.2. Methods

To carry out the analysis of the relationship between productive activities and water quality in the Las Piedras River basin, three main steps were followed (Figure 2). During the first step, the 2017 LULC map was utilized to perform a spatiotemporal analysis to detect LULC changes over the five-year study period. Next, a characterization was carried out of the socioecological network (SEN) based on participatory workshops, in which the objective was to identify the relationships, interactions and conflicts between social actors through the agricultural and management activities that the participants prioritize in the LPRB. The last step joins together the findings from steps one and two to analyze the correlations and interactions between the agricultural activities, the LULC changes and the WQ itself. To this aim, WQ was analyzed at key points throughout the basin (PAL, DIV, and PCA). Further details can be found in the next section.

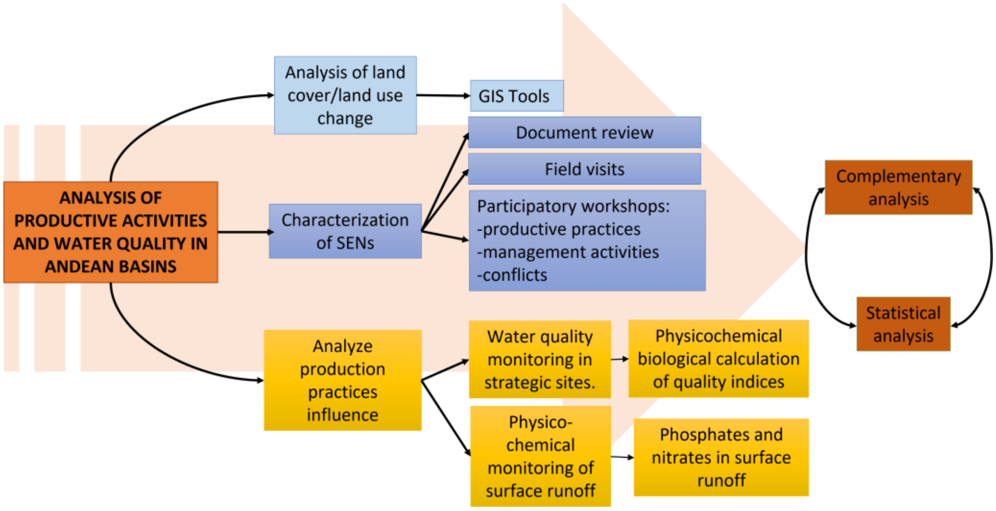


Figure 2. General block scheme of the steps followed to analyze the correlation between productive activities and water quality.

2.2.1. Land-Cover and Land-Use Change Analysis

The relationship between agricultural activities and WQ was determined by analyzing the LULC changes in LPRB. Landcovers were generated from optical remote sensing data (from Sentinel-2 and Landsat sensors) and LULC were analyzed from maps of 2008 (initial year) and 2017 (final year). Cloud-free images were not available for the entire study period as there is frequent cloud cover in the area. The LC maps were available almost yearly from existing projects AQARISC and RICCLISA. Figure 1 shows the LC map for 2017, where LCs have been grouped in different mosaics due to spatial resolution limitations from satellite data. Given the extension of the area, and the socioecological complexity of the Andean region, three sub-areas of the basin for studying the changes were considered: upper, middle, and lower. The upper area corresponds to that located between point PAL and the right limit of the basin in Figure 1. The middle area corresponds to that located between the points DIV and PAL in Figure 1. And the lower area corresponds to that located between the left limit of the basin and the point DIV in Figure 1.

Several methodologies can be found in the literature that take into account time as a variable in order to detect and quantify changes in landcover [49–53]. For the purposes of this paper, and considering the application at the local level, a methodology suggested by the Colombian Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM in Spanish) in its Environmental Information System for Colombia (SIAC in Spanish) [54] was used. IDEAM formulated a set of rules and indicators to be followed for the characterization of the ecosystems in Colombia, with a total of 149 indicators for 10 different areas [55–57]. The indicator used in this research falls in the biodiversity area, forests, and LC uses. More specifically, in the losses in biodiversity and LCs (indicator number 35), corresponding to multitemporal changes in areas such as páramos and forests, among others. Indicator 35 helps to estimate changes in LC area for a given period using LULC maps. For this research, classification maps dating from 2008 were obtained following a supervised approach and by using Landsat images (at 30 m spatial resolution) [58]. A more detailed map (10 m spatial resolution) was obtained for 2017 from Sentinel-2 sensor [59]. Sentinel-2 was launched in 2015, but data for Colombia is only available starting from early 2017. Thus, no earlier data was available to perform a detailed analysis for the entire period studied in this research. Information from both Landsat and Sentinel-2 sensors was used as input for indicator 35. Validation of the classifications was carried out with in situ data collected during field work, in collaboration with community leaders in the LPRB. The entire LPRB and surrounding areas were visited during the field work outings. Additionally, Ground Control Points (GCPs) and geo-referenced photos were collected with the goal of validating classification maps. Validation was complemented through social cartography workshops, in which small farmer organizations participated by following the methodology proposed by Sarmiento López et al. (2011) [60]. Final classifications accuracy was (on average) around 93% with a kappa factor of 0.92.

Three variables can be calculated from this indicator: (1) the area, (2) the rate, and (3) the mean annual change. The change in the areas (Δ_A) of each LC corresponds to the difference between these areas for the initial reference year (2008) and the final year (2017). Whereas the rate of change is calculated as the percentage of the area of change w.r.t. the initial area. Finally, the mean annual change is estimated as a simple arithmetic average. If Δ_A is negative, then there has been a loss of LC for the considered period. Whereas if Δ_A is positive, it means there has been a gain of LC for the considered period. Patterns of change were analyzed and characterized according to the three variables described above, with special attention paid to agricultural areas, considering their distinct WQ impact due to runoff.

2.2.2. Characterization of SENs

The characterization of agricultural activities as part of the SEN of the basin was carried out by means of participatory workshops with community members and key actors of the LPRB. Some of the information for the characterization was obtained through specific projects: (1) "Optimization of business schemes for the aqueduct and sewerage company of Popayán 2014" (which takes water from the LPRB) and (2) "AQUARISC-vulnerability and risk in supply systems 2016" [61,62]. These workshops were used to characterize the use and management of LCs, in particular LCs used for agricultural activities. Utilizing the characterization results from the previous workshops, four subsequent workshops were carried out in 2017 to characterize agricultural activities with LPRB communities. One workshop was held with stakeholders of each sub-area of the basin (upper, middle, lower) to gather more context-specific information. The final workshop was held that involved stakeholders from the three sub-areas of the basin to validate the consolidated information among all the participants. Table 1 shows an example of the questionnaire used during the agricultural activity characterization workshops (some examples of possible answers are provided). All the information was collected in two sessions during the workshop by (i) working by sub-groups and (ii) a plenary discussion of the different sub-groups and agreement of final answers.

Through the workshops, weather conditions of neutral years were identified among El Niño–Southern Oscillation (ENSO) phases considering a 10-year analysis period (2009–2019), as part of the SEN characterization. Local knowledge regarding historical events was also gathered during the workshops to identify key milestones (i.e., recall specific events, occurrences, or situations that may be associated with a particular). This strategy was used since no detailed information was available from weather stations in the LPRB. Once the neutral years were identified, the specific variations for each month of the year were evaluated. This helped to determine rainy and dry months, in contrast to the multi-year variation as well as the climatic patterns in the area. The next step was to identify the main agricultural activities carried out in each sub-area throughout the year, indicating the management practices (i.e., sowing, fertilizing, harvesting) and the impact generated in relation to the climatic condition (i.e., losses, pests, disease). Additionally, descriptions of the agricultural practices were provided by participants including the following: size of cultivated area, size of area dedicated to livestock, type of fertilizers used, management of soil acidity, soil preparation and planting techniques, rotation, pest management, products for direct consumption, and products for commercialization. All this information, together with climate information, was used to build an agricultural activities calendar [63,64].

To highlight the interactions of SENs, a plenary discussion was facilitated during the workshops to examine how the various actors of the LPRB utilize and engage with ecosystem services (ES) in the basin The significance of these ES for each key actor and their corresponding approaches to guarantee water availability for community needs (urban and rural) were analyzed based on their perspectives and the official planning documents (developed by law for each territory in Colombia).

Table 1. Template of the questionnaires used during workshops for characterizing productive activities of LPRB (month by month).

Studied Year and Associated Historical Event												
MONTH	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Weather Conditions	Semi-arid, wet, rainy, dry, windy, hail, others.											
AGRICULTURAL ACTIVITIES	**TASKS**											
1. Dual purpose livestock	Preparation of the land, sowing grass, milk production, maintenance of beef cattle and paddocks, others.											
2. Artisanal fish farming (e.g., trout)	Harvest once weight reaches 250–300 g, commercialization in organic markets, pond maintenance, fish stocking, others.											
3. Horticultural crops (e.g., corn, beans, blackberries, peas)	Land preparation, planting, weeding, fertilizing, pest control, harvesting, seed saving, others.											
4. Dairy products	Permanent production and commercialization											
5. Minor species (e.g., hens, guinea pigs, chickens)	Shelter maintenance, purchasing young of breeding, feeding, monitoring health, commercialization, others.											

2.2.3. Water Quality Analysis in the LPRB

To determine the relationship between agricultural activities, LULC and WQ in the LPRB, an analysis of water quality was carried out in the following steps: (a) WQ monitoring in strategic sites using physicochemical and biological parameters, (b) application of water quality assessment indices, and (c) analysis of surface runoff water.

Water Quality Monitoring in Strategic Sites

In this study, physicochemical and biological parameters were considered and measured over three strategic sites (see Figure 1) for water quality monitoring. The WQ was assessed based on correlation of the above parameters along with the variables that they measure through different indices [65–67]:

- Physicochemical parameters for water monitoring

Water samples for physicochemical analysis (three replicates) were collected manually, each in a 1 L amber glass container, which were subsequently labeled and refrigerated. Twelve samples per year (one per month) were collected over a five-year period, for a total of 60 samples. The collections were carried out in the morning, first in the upper area of the basin (PAL), then the middle area (DIV), and ending in the lower area (PCA). The monitoring campaign was designed to be able to map the rainy, dry and transition seasons, in accordance with the climatic variations in the area.

Samples were sent to a certified laboratory to analyze the following variables: pH, nitrates (NO_3^-), phosphates (PO_4^{3-}), biological oxygen demand (BOD_5), dissolved oxygen, Total Dissolved Solids (TDS), turbidity, and temperature. In situ measurements were taken with a HACH 40D probe multi-parametric equipment;

- Biological parameters for water monitoring

To calculate biological indices of WQ, two parameters were considered: fecal coliforms and epicontinental aquatic macroinvertebrates (EAM). To analyze fecal coliforms, the membrane filtration method was used, which is a valid method according to Colombian regulations (Ministry of Housing, Decree 2115 of 2007). Sterile jars of 100 mL were used to collect and keep the samples refrigerated. Three replicates per sub-area were collected. Processing time was no longer than eight hours from the time of collection to time of processing in the laboratory. The structure and composition of EAM in the basin was measured by collecting samples using both manual and net methods. Both parameters were sampled over a five-year period with 12 samples per year (one per month).

Water Quality Assessment Indices

Physicochemical and biological parameters were correlated according to the water quality index (WQI) and pollution index (PWI) [68]. These indices evidence the pollution processes associated with high nutrients and ion concentrations. The effect on the EAM communities, because of organic pollution, is also indicated. For the physicochemical parameters, the variables analyzed were those in the National Sanitation Foundation index (NSF) [68]: pH, nitrates (mg/L), phosphates (mg/L), biological oxygen demand (BOD-mg/L), dissolved oxygen (mg/L), total dissolved solids (TDS-mg/L), turbidity (NTU), and temperature (°C).

For the biological parameters, the fecal coliform (CFU/100 mL) and the composition of the EAM community was studied through taxonomic classification at the family level. The qualitative biotic index biological monitoring working part (BMWP) was applied for the analysis. BMWP considers the presence or absence of the different aquatic macroinvertebrates' families. To this aim, a score is assigned that determines the tolerance level to organic pollution. The most sensitive families received a score of 10 [69], while the most tolerant ones received a score of 1. Other indices used for the analysis were the ICOMO and ICOSUS. These indices consider the parameters BOD_5 (mg/L), fecal coliforms (CFU/100 mL), dissolved oxygen (mg/L), and TDS (see water quality classification table from [69] for more details).

Surface Water Runoff Analysis

For the analysis of surface water runoff near areas of agricultural production, runoff was collected after applying a localized rain simulator, designed by Lobato-Vargas [70]. This tool simulates rain analysis, under controlled conditions and requires to be set up to produce "fast, reliable, efficient, replaceable, and cost-effective data" [71]. The simulator emulates rain droplets of about 2.75 mm in diameter, by means of hypodermic needle-like nozzles ($n = 24$), distributed in an area of 0.42 m × 0.33 m, with terminal velocities of around 4.0 m/s, and rain kinetic energy of 17.9 J/mm/m [71]. The simulated rain intensity was calibrated. A calibration, according to climatic conditions and historical rainfall distribution in the region and the methodology proposed for Andean soils [70,72], was carried out. A time period of 30 min was chosen for the tests [73], which were performed in the morning at the same time at each sampling site. A soil sample was collected before the simulation to analyze initial humidity conditions.

This tool was used on the areas surrounding the riverbed, more specifically on the three testing points shown in Figure 1 as PAL, DIV, and PCA. Differences in climatic seasons: rainy (R), dry (D), and transitions (T), were also considered. Once the simulator was set up, it can be used to collect samples of runoff that consider the different nutrients going through the soil (particularly nitrates and phosphates) and coming from surrounding areas with different agricultural activities. These samples were taken to the laboratory and analyzed with a spectrophotometer to measure nitrates and phosphates concentrations (in mg/L) [74].

Experimental Design and Correlation Analysis

After obtaining the previously mentioned variables, a statistical analysis was carried out to understand the correlation between agricultural activities and WQ. The statistical analysis was performed using the XLSTAT and the Past paleontological statistics software (Past v.1.44), which included a data analysis with Kruskall–Wallis and Mann–Whitney tests [75] and unifactorial ANOVA [76] gathering significant differences ($p < 0.05$) between the different variables, sites, and climatic periods. A multivariate analysis was also carried out in order to integrate the main parameters.

3. Results

The results are presented in the same order as the Section 2.2 by directly applying the process developed in Figure 2.

3.1. Land Cover and Land-Use Change Analysis

The predominant LCs in the LPRB are natural grass (1674 ha) and pastures (1658 ha), followed by open and fragmented forest (1361 ha) (see Figure 1). The proportion of other relevant LCs (due to their natural regulatory role in the water cycle) are limited, with bushes covering 545 ha, riparian forest 253 ha, dense forest 777 ha and páramos 224 ha. Land use for livestock activities (1658 ha) greatly surpasses the area of land use for crop cultivation (88 ha) and productive forests (18 ha). Even though all types of LCs have an impact on WQ, the most pertinent type for the area are those related to agriculture (mosaics). It is important to clarify that while urban areas may have a larger impact on WQ than agricultural areas, they are not considered here because the vast majority of the LPRB is rural, except for a small urban zone surrounding the PAC monitoring point in the lower part of the basin.

It was found that agricultural coverage decreased with the altitudinal gradient in the basin. For the upper area, there was an increase in agricultural areas coverage of about 2.6%, going from 0.8% in 2008 to 2.1% in 2017; an increase of 1.5% in the middle area from 5.7% in 2008 to 8.4% in 2017; while the lower area endured the least transformation (1.3%), going from 16.1% coverage in 2008 to 21.3% in 2017. Despite the small change in the lower area of the basin, it continues to be the area with the largest coverage of agricultural land use. The most critical transformation corresponds to the upper area of the basin, where dense forest and páramos have been replaced by agriculture mosaics as is shown in Figure 3.

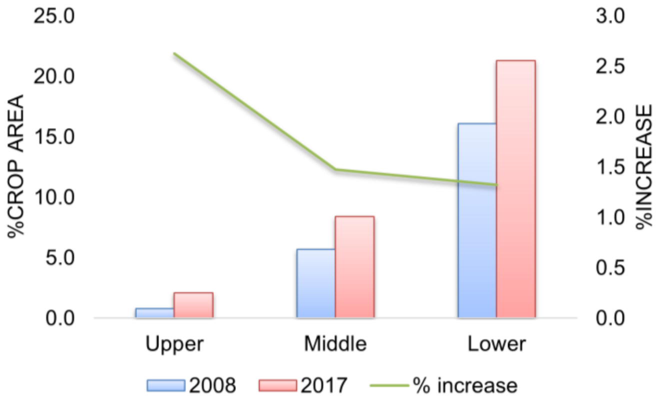


Figure 3. Agricultural areas (mosaics) variation in LPRB for the analyzed period (2008–2017).

3.2. Characterization of SENs

As with LULC analysis, agricultural activities were also characterized according to topographic gradient throughout the LPRB in the upper, middle, and lower areas. A calendar was produced for each area of the basin that represents the main agricultural activities carried out in the LPRB for a neutral ENSO year, according to workshop participants from the basin.

3.2.1. Agricultural Activities in the Upper Area of the LPRB

In the upper area of the basin, participants identified dual-purpose livestock, artisanal fish farming (trout), horticulture (corn, beans, blackberries), and rearing of minor species (hens, guinea pigs, chickens) as the main agricultural activities being carried out (Figure 4). The LULC analysis confirmed that the main agricultural activity of this area is indeed livestock production. The cultivated area corresponded to 30.8 ha, 23.14 ha of crops, pastures, and natural spaces mosaic, and 7.66 ha of pastures and crops mosaic.

These activities provide subsistence for inhabitants as well as generate income. Meat and eggs are obtained from poultry farming, both for subsistence and local trade, whereas vegetables are used mainly for household subsistence. Commercialization of agricultural products as well as value-added products such as yogurt are important sources of income for families in the area working within a small-scale economy model.

Participants documented that organic and chemical fertilizers, as well as pesticide use during agricultural production. Since the soil is acidic, ash is used to neutralize pH to allow for better production. It was determined that the soil is worked in a purely manual manner; crops are not often rotated, and production is kept at a small scale because of the steep topography and lack of arable land. Recently (since 2018), the area of trout production was expanded in the Sardinas sector, greatly impacting the WQ of the upper area. The management of natural LCs was performed by isolating the areas with posts, usually located in the riverbed's adjacent areas, or by natural succession. No reforestation processes were carried out in the area.

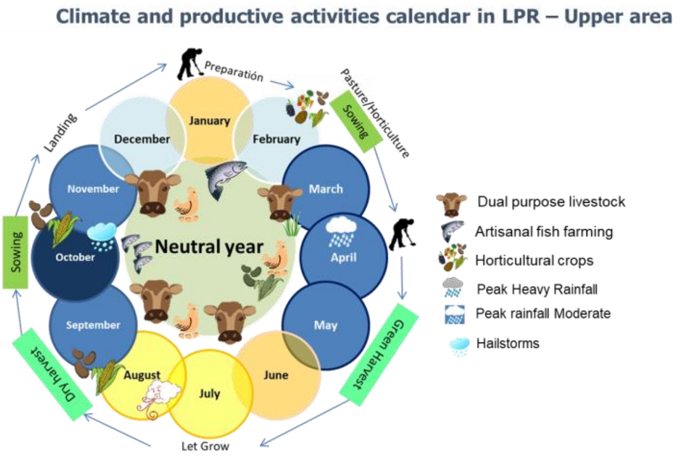


Figure 4. Productive activities calendar for the upper area of LPR basin on a neutral year (i.e., under normal weather conditions).

3.2.2. Agricultural Activities in the Middle Area of LPRB

In the middle area, participants identified the production of cabuya, coffee, corn, legumes, root vegetables, leafy greens, bananas, and fruit trees (blackberry, lulo, tomato, orange) as the main agricultural activities. It was determined that vegetables are used mainly for subsistence purposes as the community in this area does not often carry out transformation of value-added products (Figure 5). As in the upper area, the inhabitants of the middle area subsist on a model of a small-scale economy. This corresponds to the LULC analysis to an extent in that 8.07 ha is classified as cultivated area 0.56 ha of crops, pastures, and natural spaces mosaics, 8.52 ha is classified as mosaic pastures and crops mosaic, and 8.99 ha planted forest pine. This indicates that the communities living within this area are not those who are carrying out livestock and/or pine tree production.

Due to the low fertility conditions of the soils, both organic and chemical fertilizers are applied in the area. Like the upper area, the soil acidity is corrected with the ancestral use of ash to "heat the soil". Soil preparation is mostly manual, and mechanical activities performed by animals are less frequent. Crop rotation is not frequently practiced due to lack of arable land, but agricultural activities were alternated with livestock, allowing the soil to rest by planting crops that require shorter growth period. A total of three harvests per year were produced over 3 years per land parcel. Corn, tomato, coriander, peas, beans, grapes, flowers, banana, mango, and avocado are mostly produced for commercial purposes. The management and protection of natural LCs was carried out through reforestation following natural succession patterns and planting native and exotic vegetation species. There also exists extraction of forest material, farms with livestock and with natural protection areas.

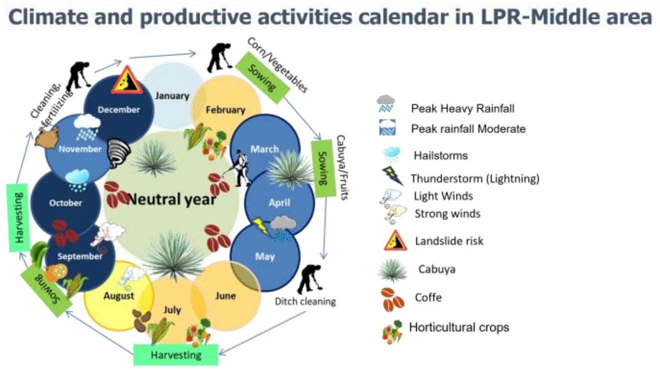


Figure 5. Productive activities calendar for the middle area of LPRB on a neutral year (i.e., under normal weather conditions).

3.2.3. Agricultural Activities in the Lower Area of the LPRB

In the lower area of the basin, participants identified similar agricultural activities as those in the middle area including corn, beans, vegetables, peas, and coffee planted during normal weather conditions (neutral year). However, for a rainy period, coffee, cassava, and banana are not as successful as vegetable crops (e.g., peas and beans), due to their resistance to humidity and cold (Figure 6). In this area there were no transformation processes for the value-added products identified and most of the crops were sold in markets in the city of Popayán. In recent years, producers in the area have been participating in organic markets, strengthening relationships with institutions and increasing direct access to consumers, which reduces the role of intermediaries and increases farmers' profits.

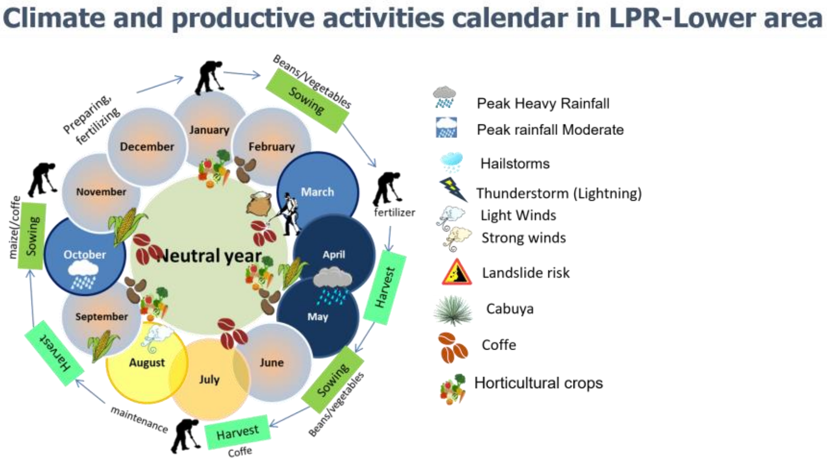


Figure 6. Productive activities calendar for the lower area of LPR basin on a neutral year (i.e., under normal weather conditions).

It was found that among the anthropic LCs present in the area, there were livestock pastures (44.79 ha) and eucalyptus planted forest (44.7 ha). The cultivated area was 187.42 ha, of which 123.13 ha were crops, pastures, and natural spaces mosaic, and 64.29 ha were pastures and crops mosaic. Unlike the other areas in the basin, organic fertilizers are applied more often than chemical ones, and many producers make their own organic fertilizer and pest control. It was determined that crop rotation is practiced based on the idea that fertilizers remain in the soil from previous crops and will benefit the next cycle. As such, it was thought that this was the reason why it was possible to sow grass and to harvest food all year round. Permanent crops such as coffee and avocado, semi-permanent (vegetables), and temporary crops (blackberry) are also cultivated in the area. The products were divided between household subsistence and market purposes, but only the surpluses were destined for the latter. The management of natural soils is performed by planting forest, living fences or post fences, and isolation of water sources and native forest reserves. Reforestation is carried out with the support of local institutions.

3.2.4. Socioecological Dynamics Network

The socioecological dynamics of the LPRB are complex due to the diverse range of actors involved in the use, management, and administration of ecosystem services to guarantee water supply for the city of Popayán. Basin actors include the following: (i) indigenous communities; (ii) small peasant communities with associated farmers as well as independent farmers; and (iii) community and governmental institutions. They all have different perspectives and interests on the LPRB that have implications regarding its management. These interactions produce both socioecological conflicts as well as sustainability opportunities. Figure 7 illustrates these interactions and conflicts that arise among actors. It also highlights the gap between local governance and institutional articulation, indicating the need for a more integrated approach.

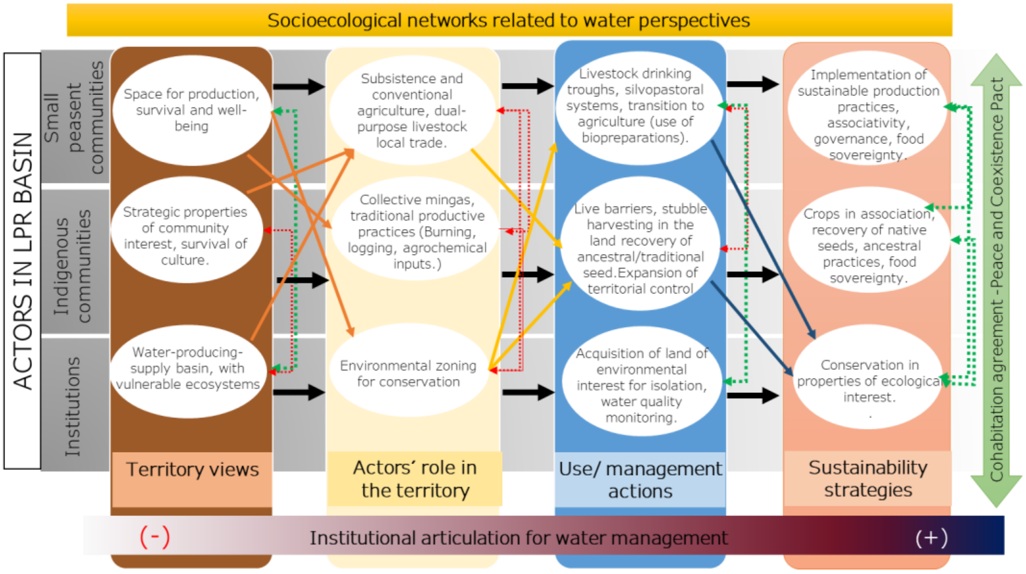


Figure 7. Socioecological networks related to water perspectives in LPRB.

Different levels of community-institutional articulation are shown in Figure 7, according to the four components presented by each type of actor: visions of the territory, the role of each actor, use and management actions, and sustainability strategies. Both articulations and conflicts were observed among actors across the four components. For example, the difference in the vision of the LPRB between indigenous communities as a living space, and for institutions, as a space for water availability and production activities. Regarding roles within the territory, the differences among actors are marked, and conflicts arise due to the overlapping of actions developed to isolate strategic areas by the institutions, versus the development of unsustainable agricultural practices.

However, there are also synergies among actors, particularly regarding management actions. These synergies have ultimately led to the conservation of ES supply and towards community wellbeing including maintaining a peaceful relationship among the basin actors. However, the different visions and actions of the actors have also led to scenarios of socioecological conflicts in the basin, as depicted in Figure 7.

Figure 7 shows the interactions corresponding to action flow (black line), conflicts (red dotted line), synergies (green dotted line), direct interactions between the dimensions analyzed: visions of the territory (brown line), actors' role in the territory (yellow line), and use and management actions (blue line).

3.3. Water Quality Analysis in the LPRB

3.3.1. Water Quality Monitoring in Strategic Sites

1. Physicochemical parameters

When analyzing the data variation, according to the monitored years, important changes were observed for the oxygen saturation percentage ($\%O_2$-$p = 0.036$) and TDS ($p < 0.0001$), associated with the years with the lowest rainfall record. Regarding the monitoring sites, the data differed for the pH ($p = 0.005$), $\%O_2$ ($p = 0.042$), and TDS ($p = 0.039$), especially in the PCA monitoring area. The physicochemical quality data measured by months, presented a normal distribution (Kolmogorov-Smirnov). The space–time variation showed that the conductivity and TDS variables ($p < 0.0001$), registered high values in the transition periods from dry to rainy (August and September), in the years 2015 and 2016. The dissolved oxygen ($p < 0.0001$), registered the lowest value in the year 2014, in the dry season (June), while the turbidity ($p = 0.006$), was very high in 2016, during the month of May. The average differences between the monitoring sites were significant. This was even more clear when comparing the middle area (DIV) to the lower area (PCA), for conductivity and TDS. In contrast, the biggest differences between the lower and higher areas (PAL) were found in the turbidity. Detailed ranges for each variable can be found in Table 2. It is important to remark that such dataset is unique for the study area but as the LPRB represents is representative of a typical Andean basin, this data is a significant contribution for the study of Andean hydrological basins.

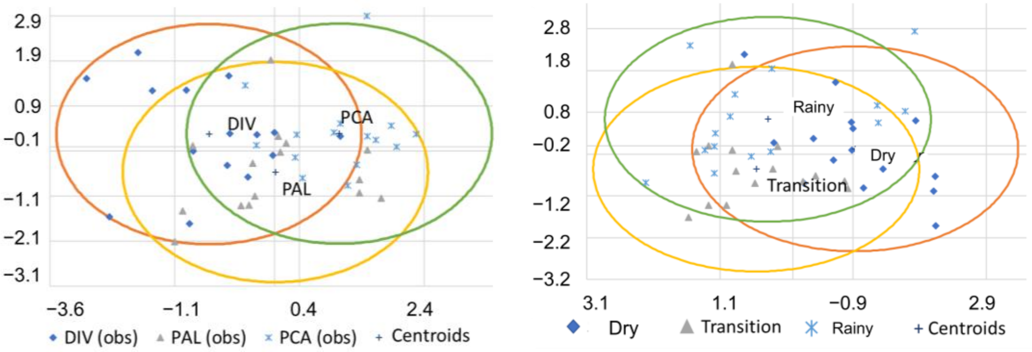
Table 2. Water quality characteristics according to physicochemical parameters.

Parameter	Minimum	Maximum	Mean	Typical Deviation	Standard Limits for Human Consumption *
Temperature (°C)	15.130	18.820	16.620	0.873	25
Conductivity ($\mu S.cm^{-1}$)	33.800	120.900	65.721	12.750	1
TDS (mg/L)	16.900	66.200	32.296	6.906	≤100
O (mg/L)	6.200	10.200	7.900	0.683	>7
%O	95.000	107.567	100.644	1.969	>70
pH	6.760	7.980	7.311	0.246	6.5–8.5
Nitrates (mg/L)	0.350	3.490	1.834	0.665	0.2
Turbidity (NTU)	0.200	10.000	2.389	1.374	5
Phosphates (mg/L)	0.060	0.990	0.338	0.173	0.5

* According to the Colombian regulation norm 1575/2005.

Both parametric (PO_4^{3-}, NO_3^-, pH, %O, TDS, turbidity, and temperature) and non-parametric (BOD_5) variables were identified through variation analysis. The samples were independently analyzed, according to their distribution, using the Kruskall–Wallis test (Bonferroni level of statistical significance) and the unifactorial ANOVA test (comparisons with Tuckey and multiple ones with Dunnet's T3). This analysis allowed to identify if there was a relationship between the physicochemical variables and the factors of interest: year (2013–2017), climatic period (R, D, T), and site (PAL, DIV, PCA). A significant difference was identified between the factors and variables, as described. For the year factor there were significant differences for the pH ($p < 0.045$), %O ($p < 0.036$), and TDS ($p < 0.001$), for the climatic period factor, the PO_4^{3-} ($p < 0.042$), pH ($p < 0.005$), %O ($p < 0.0042$), and TDS ($p < 0.0039$), and regarding the site factor, the BOD_5, and NO_3^- ($p < 0.0001$) parameters.

A further study was carried out by means of discriminant analysis of physicochemical parameters of surface water runoff (see Figure 8) with Wilks' Lambda test. The discriminant analysis allowed for a grouping by sampling sites, differentiating between the PAL site and the middle and lower areas ($p = 0.001$), with a total variance of 100% (F1 and F2), as shown in Figure 8a. Climatic periods were grouped together, and results indicate a significant variation for the transition period, which increased the uncertainty for local communities when planning of agricultural activities (see Figure 8b). Details about different physicochemical parameters are offered in the next section, while the data measured on the stream, with a monthly sampling, can be seen in Table 2.



(**a**) (**b**)

Figure 8. Discriminant analysis of physicochemical parameters stream water for (**a**) the three monitoring sites: DIV, PAL, and PCA and (**b**) the three climatic periods: R, T, and D.

Nitrates: Larger values of NO_3^- concentration corresponded to the PCA monitoring point during the rainy period in 2014 and the transition one period in 2016. There was not a significant NO_3^- concentration across the three monitoring points. However, a variant of NO_3^- exists that depends on factors such as climatic condition, year, and monitoring point. This reflected the different nitrogen cycle stages, as well as the capacity of plants and algae to assimilate NO_3^- or the capacity to reincorporate ammonium NH_4^+ and nitrites NO_2^- to the atmosphere [77].

Phosphates: Variations in PO_4^{3-} concentration were present in the PAL and PCA monitoring points, for the rainy and dry periods in 2014, 2016, and 2017. Those concentrations exceeded the limits established in Colombian regulatory norms for WQ (0.5 mg/L).

Turbidity: The increase in turbidity was most noted during the dry and transition periods were, especially at the PCA monitoring point where the maximum value was registered (10 NTU). This was due to the input of sediments and alien material as the riparian vegetation cover towards this zone decreased, enhancing the effects of precipitation with the presence of suspended material and organic particles. Water turbidity for human consumption should range between 1 NTU to 5 NTU [78].

Oxygen: Due to the hydrodynamic conditions of the LPRB, oxygen saturation and concentration, temperature, and atmospheric pressure were considered good, favoring both nitrogen compounds oxidation and organic matter degradation. The PCA monitoring point presented the maximum value of precipitation during the rainy period. This value was related to an excess of primary producers [79], in particular the discharge from fish farms which operate in the middle area of the basin.

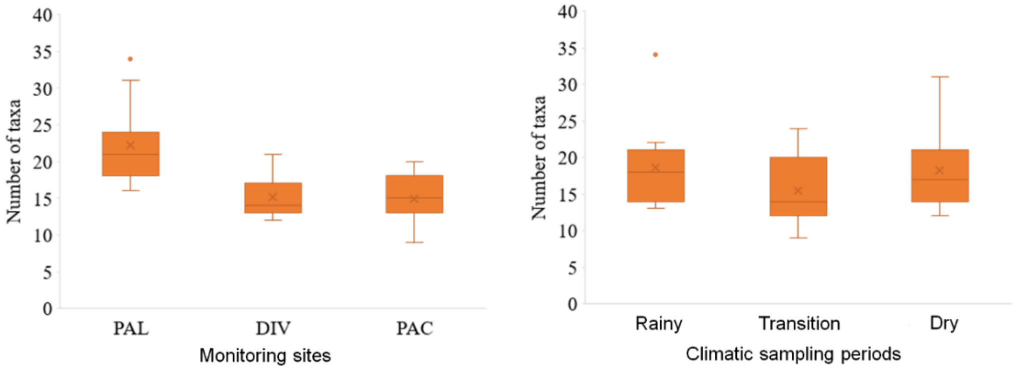
Biological Oxygen Demand: BOD_5 concentration was generally high across the LPRB, with values higher than 10 mg/L in all the monitoring points. The lower area was the most affected during the dry period. This condition indicates that the enzymatic reduction does not denature the biological compounds rapidly, evidencing processes of WQ alteration. Likewise, the increase that occurred in other periods of the year denoted accumulation of suspended material from the dragging of sediments by rain and agricultural activities in the lower area.

Hydrogen potential: The slightly alkaline conditions of the Las Piedras River present a statistically significant variation between the monitored sites and years. These variations are due to the presence of phosphate and sulphate anions, sourced from the agricultural activities occurring due to the presence of crops near the riverbed (as **determined** from LULC analysis). The oxidation of the organic matter present in the system played an important role since it allows the presence of pollutants which are tolerated **by** macroinvertebrates. However, the reported pH values are within the optimal range.

2. Biological parameters

Fecal Coliforms: This group of bacteria is present in the LPRB with quantities ranging between 31.60 CFU/100 mL and 313 CFU/100 mL. The maximum records were reported in the middle (DIV) and lower (PCA) areas, during the transition period (313 CFU/100 mL). The data reported for this variable indicates that there was livestock activity as well as sewage discharge from agricultural domestic activities close to the river and its tributaries. In the middle area, which had the highest CFU/100 mL values, livestock activities were developed without technification or forestry strategies, where cows have direct access to streams. In addition to the geomorphological characteristics of the middle and lower areas, there was a higher population density, which together with the lack of basic sanitation, increased the sewage pollution.

Epicontinental Aquatic Macroinvertebrates (EAM): A total of 8017 specimens were collected, then organized in 6 classes, 19 orders, 56 families, and 89 species (see Figure 9). There was a heterogeneity of habitats and food supply that favored the appearance of stenotypic species (*Atopsyche*, *Tricorythodes*, *Elmoparnus*, *Chimarra*, *Corydalus*, *Limnocoris*). However, the presence of other groups of organisms, with wide ranges of distribution (*Thraulodes*, *Anchytarsus*, *Hidropsyche*, *Helicopsyche*, *Rhagovelia*), as well as the physicochemical conditions of the water, were indications of biological quality alteration. Due to the availability of organic matter in the area, organisms typical of eutrophic waters were also found (*Chironomidae*, *Muscidae*, *Tipulidae*). EAM distribution is represented in Figure 9 where both monitoring sites and climatic periods are considered. From these plots a larger diversity can be found in the upper area together with the dry period.

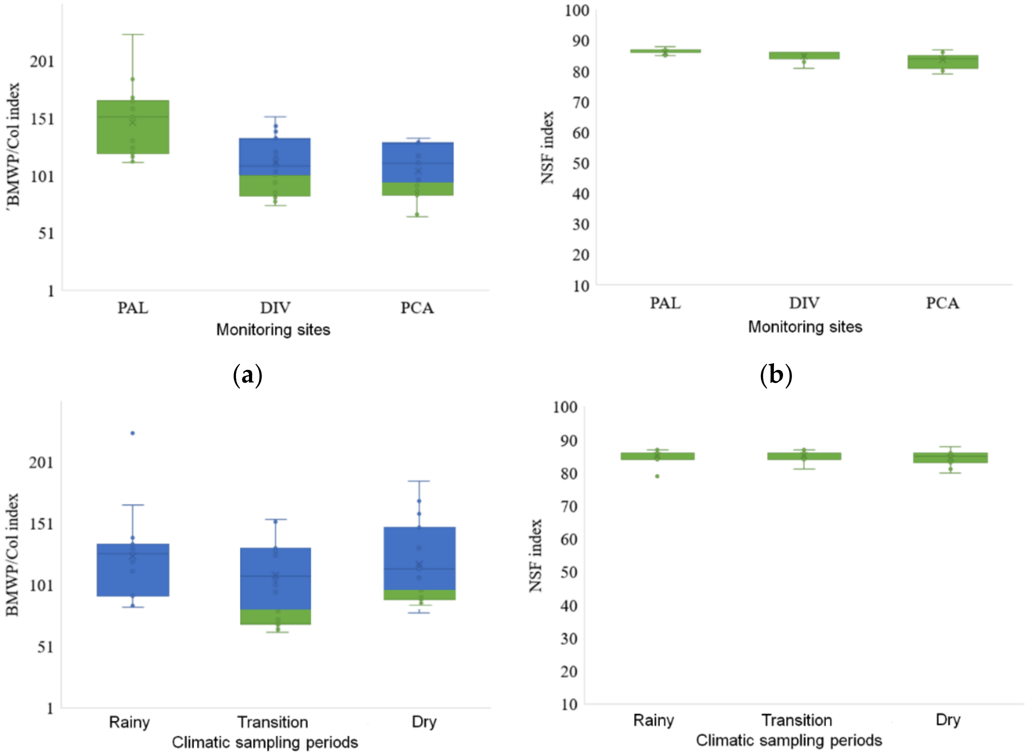


(**a**) (**b**)

Figure 9. EAM in the LPRB basin for (**a**) the three monitoring sites and (**b**) the different climatic periods.

3. Water quality indices

The WQI and PWI indices evidence the pollution processes associated with high concentration of nutrients and ions. The effect on the EAM communities, because of organic pollution, is also indicated. According to the BMWP/Col biotic index, the WQ in the LPRB varies from acceptable to good (see Figure 10a), with the situation in PAL being the best. This is also the case for the NSF (see Figure 10b), where PAL shows an acceptable condition with the presence of organisms that are tolerant to the contamination. In the case of ICOMO and ICOSUS (Figure 10c,d), degradation processes can be seen for the PAL and PCA monitoring points, during the dry periods. Contamination by TDS was also found in the DIV point during all the climatic period analyzed.



(**a**) (**b**)

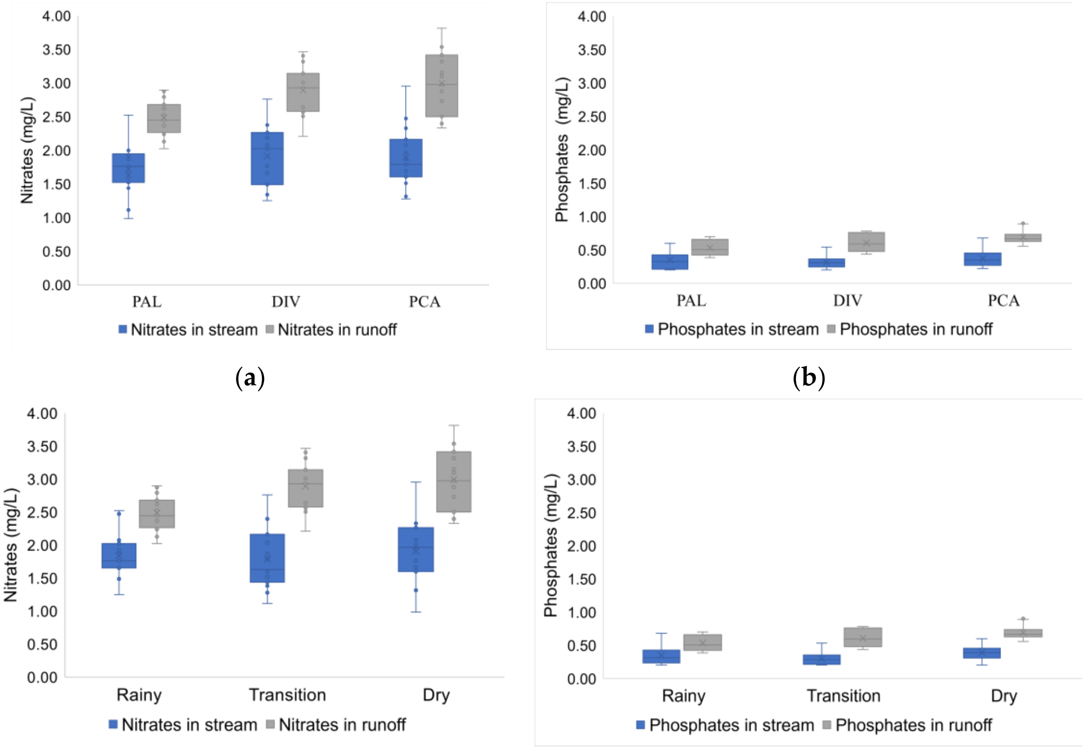
(**c**) (**d**)

Figure 10. WQI variation in the different monitoring points: (**a**) BMWP/Col and (**b**) NSF; and different climatic periods: (**c**) BMWP/Col and (**d**) NSF.

Considering the relationship between the WQ indices and the physicochemical and biological parameters, a statistical correlation was applied that allowed to identify the association level between them. According to this analysis, it was possible to identify the key variables that negatively affected the WQ. In the physicochemical characteristics, the phosphates, pH, and BOD_5 decreased the NSF index, modifying the nitrogen cycle toward the lower area of the basin, where the water intake for Popayán's aqueduct is located. The biological characteristics, on the other hand, were affected by the increase in TDS, which favors the presence of eurytopic macroinvertebrates. These two characteristics are mainly affected by the different agricultural activities that imply the use of agrochemicals (see Figures 3–6).

3.3.2. Surface Runoff Characterization

In order to perform the surface runoff characterization, comparisons of nitrates and phosphates were considered for all monitoring points (see Figure 11a,b) and climatic periods (see Figure 11c,d). In general, it was found that concentrations of nitrates and phosphates were higher in runoff water than in streams. This was clearer in the middle and upper areas, where agricultural activities close to the riverbed were more frequent, introducing more contaminants to the water and reducing its availability for human consumption. Due to the lack of planning around fertilizer application during the transition climate period, nitrates and phosphates were deposited into the river more rapidly than other climatic periods (Figure 11c,d).



(**a**) (**b**)

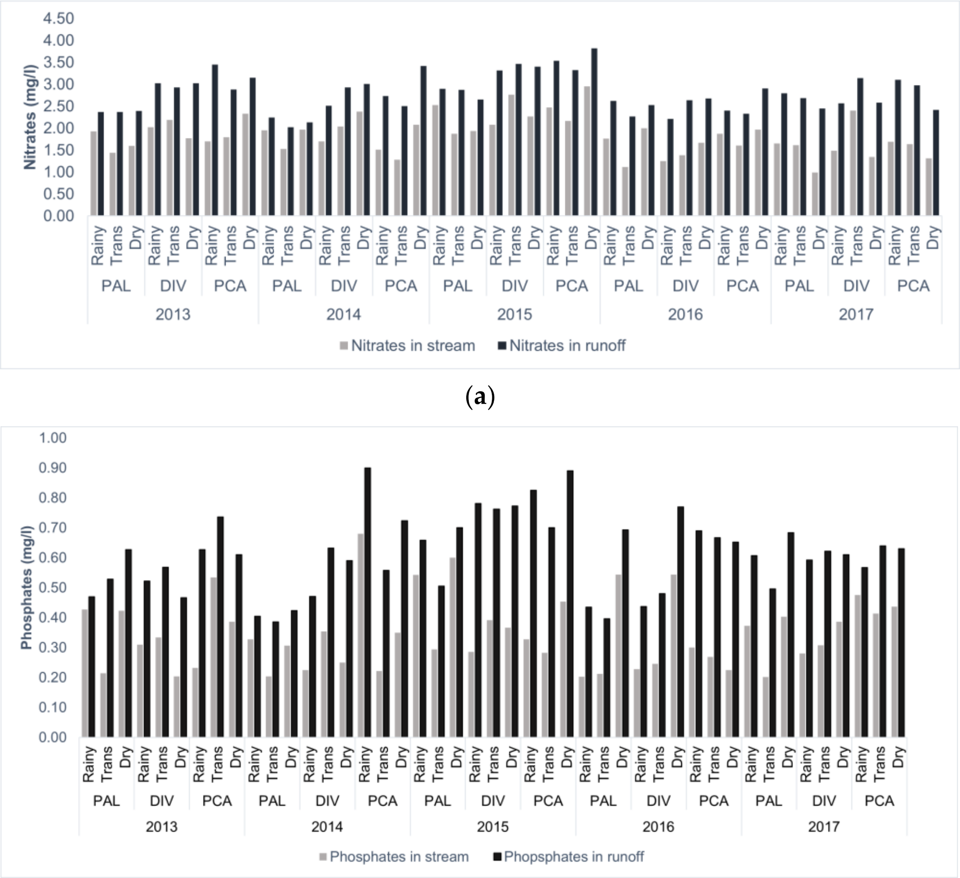
(**c**) (**d**)

Figure 11. Physicochemical parameters variation in both surface runoff and streams for the LPRB: (**a**) nitrates in different monitoring points; (**b**) phosphates in different monitoring points; (**c**) nitrates in different climatic periods; and (**d**) phosphates in different climatic periods.

According to the ANOVA unifactorial analysis, there exist statistically significant differences across the monitored years. To give an example, for 2015, PO_4^{3-} presented a p = 0.007 and NO_3^- presented a p = 0.018. Whereas for 2016, PO_4^{3-} presented a p = 0.004 and NO_3^- presented a p = 0.050. Figure 12 shows the detailed results of nitrates (a) and phosphates (b) distribution in surface runoff and stream for the LPRB over the 2013–2017 period, the three climatic periods (rainy, transition, and dry) and the three monitoring points (PAL, DIV, and PCA). As such, it is possible to see how the concentration of both parameters was higher in the surface runoff water than in streams. This seems to be always the case across the whole basin and climatic periods.

The discriminant statistical analysis with respect to the monitoring sites and the climatic periods was performed with a 95% confidence interval (see Figure 13). This analysis showed that with respect to the climatic periods, there was a difference between the upper and middle areas with a p = 0.037 in the rainy vs. dry period. For the DIV point, there was a difference in rainy vs. transition period with a p = 0.016, and in rainy vs. dry with a p = 0.018. On the contrary, there was no difference for the lower area. With respect to the monitoring sites, it was found that there was a difference between upper and lower areas (PAL vs. PCA with p = 0.04). This shows how concentrations of nutrients in the upper area came from different sources than those of the middle and lower areas. Transition and dry periods had a huge impact in the PO_4^{3-} concentration that increased towards the lower areas (≤2000 m.a.s.l.), where most of the cultivated areas can be found. The

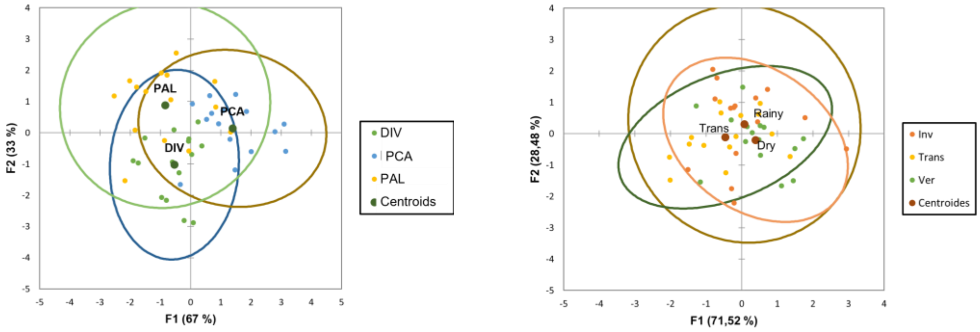
Spearman correlation tests (see Figure 14) allowed us to identify both positive and negative associations between the analyzed variables. From these tests the following was found: (i) a directly proportional relationship between NO_3^- and PO_4^{3-}; (ii) a direct relationship between the measured nutrients in stream and runoff water; (iii) an inverse correlation between NO_3^- and PO_4^{3-} and the water indices measured on stream and runoff water; and (iv) a negative correlation between the monitoring sites and the NSF and BMWP/Col. The correlations values can be seen in Supplementary Materials (Tables S1 and S2).



(**a**)

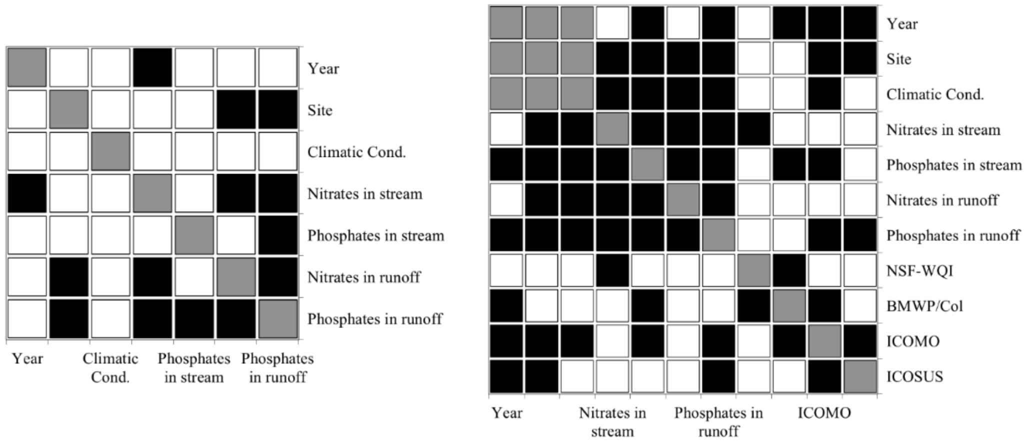
(**b**)

Figure 12. Physicochemical parameters measured in surface runoff and streams for the LPRB over the 2013–2017 period, the three climatic periods (R, T, and D), and the three monitoring points (PAL, DIV, and PCA): (**a**) nitrates and (**b**) phosphates.



(**a**) (**b**)

Figure 13. Discriminant analysis of physicochemical parameters on surface runoff water for: (**a**) the three monitoring sites: DIV, PAL, and PCA and (**b**) the three climatic periods: R, T, and D.



(**a**) (**b**)

Figure 14. Correlation between variables in the surface runoff and stream (**a**) between measured variables and (**b**) water quality indexes variables. Colors indicate different correlation values: Black: 1.0; Gray: 0.5; and White: 0.0.

4. Discussion

In Colombia, conventional agriculture exists mainly due to political and social situations, including the privatization of land ownership, inequity, and poverty. This makes rural agricultural production the most affordable livelihood for economically vulnerable communities. Rural Andean basins are characterized by the interactions between water, agricultural practices, and human consumption needs [48,80]. As such, the Andean region a great number of smallholder farms (64%) have developed, intensifying conventional agricultural activities in order to meet the socioeconomic needs of local communities. The effects of this dynamic have been amplified towards the upper areas of the basins due to the existence of strategic ecosystems, and practices such as logging, burning, and deforestation limit the availability of water for local communities [81]. In the LPRB, conventional agriculture activities refer to the use of agrochemical inputs, cultivating adjacent to streams or on the slopes (increasing the surface runoff of nutrients), and direct access of livestock to the riverbed. Local communities have developed informal water supply systems to meet the growing water demands of conventional agriculture activities to secure their livelihood. In this context, the dynamics of the LPRB respond to the socioeconomic interactions of the actors in the upper, middle, and lower areas. As such, the availability of hydrological ecosystem services for urban and rural communities are directly related to deforestation and other LULC changes, as the main drivers of change in the Andean region.

In this sense, an important condition in the LPRB is the land-use change and the loss of regulating vegetation such as dense forests (especially the páramo). The situation in the upper area, where the area of productive LC has tripled during the analysed period (0.8% to 2.1%), is critical because together with the increasing population within the basin (0.84% annual rate) and the urban population downstream (2.5% annual rate [48]) the water demand will continue to rise. The heterogeneity of the LPRB (where both indigenous and small famers live) is expressed in the production practices developed in the basin, which are related to WQ and water management. Furthermore, agricultural and livestock activities were differentiated in the three sub-areas, depending on altitude, slope type, and soil fertility. Thus, in the upper area, livestock (dual-purpose livestock), fish farming, and the rearing of minor species were predominant. In the middle and lower areas, agriculture was the main activity, with crops such as corn, coffee, cabuya, and horticulture [48,80].

The analysis of the agricultural calendars allowed for the identification of the differences in the productive activities and techniques, as well as the problems present in the areas, carried out by the community present in the LPRB. A common characteristic of the agricultural activities in the area is that crops are mainly grown for families (contributing to food sovereignty), and without water supply systems, they are highly dependent on the rainy season to carry out their work. Producers do not often follow technical recommendations, leading to the overapplication of agrochemicals. and were not articulated in local market dynamics.

The communities in the middle area of the basin adjust their agricultural work according to the rainfall (excess and deficit). Land preparation and planting take place during the first quarter of the year and from September to November. By modifying the work according to the local climate, producers can maintain their crops year round by using irrigation, canals, organic fertilizer, and agrochemical inputs (fumigation and nutrition), which gives better results in scenarios of water surplus. In the middle and lower areas of the LPRB, cabuya or fique crops were also planted, with recurrent slash-and-burn practices. In the lower area, despite differentiating types of crops according to the climatic requirements throughout the year (dry, rainy, and transition), land work and maintenance actions were reduced during months of water excess and deficit. Fertilization and soil preparation (liming and hilling) were also carried out in relation to rainfall; chemical fertilizers were used, but organic fertilizers prepared by local producers were preferred for soil nutrition.

One of the major findings of this study is regarding WQ in the LPRB, as it is one of the main supply basins for the city of Popayán. It was found that despite the impacts of conventional agriculture activities in the basin, the WQ still meets the conditions set by the aqueduct of Popayán to be used for domestic consumption after mandatory disinfection and treatment (especially due to high concentrations of phosphorus and nitrates). However, in contrast, rural communities of the LPRB are without a water treatment system and address their (multipurpose) water needs with less safe methods, such as direct distribution systems or open channels. This situation increases their exposure to water borne diseases, especially due to the presence of phosphates. These compounds tend to elevate correspondingly with changes in climatic conditions—a factor that is intimately linked with fluctuations in pH levels and TDS on a multiannual scale.

In the LPRB, the main source of phosphates was the agricultural and fisheries activities in areas near the riverbed, as supported by the LC analysis that showed high presence of crops in the lower area of the basin (near PCA point). Statistical results from ANOVA tests that show a recent nutrient increase flowing into streams, and when looked at in conjunction with the agricultural productive calendars, it can be inferred that the continued use of agrochemical inputs is linked to soil fertility loss and generate runoff that affects WQ of surrounding waterways.

Nitrogen concentrations in the basin are related to productive activities such as livestock, the use of fertilizers, and discharge of domestic sewage. It is important to indicate that the increase in the concentration of nitrates also limits the use of water for human consumption, even under disinfection processes and especially because communities in the basin use the water from rural water supply systems directly, without potabilization processes. Furthermore, the flow of nitrates to the main river was increased by the surface runoff water, cultivation on slopes, and conventional agricultural practices, also causing risk of flooding [72,82].

In addition, the increase in the dragging of suspended particles and organic matter, due to the construction of roads towards the upper area of the basin and the extraction of quarry material along the riverbank leaves bare and eroded soils [72]. Such soils are easily dragged by surface runoff that increases due to the steep terrain in the upper and middle areas ($\geq$50%). This condition is important for the management of agricultural areas established in the riparian strips given that runoff mobilizes nutrients, eroded soil, and organic matter towards the main channel. Thus, limiting the water supply for human consumption and increasing the costs of the water potabilization process, which is then transferred to users in urban areas.

The results of the biological quality indices indicate a gradual process of degradation of the aquatic ecosystem in the LPRB. In the upper area there was high diversity due to the conservation zones of páramo and dense forests upstream of the monitoring point, which decreases along the river in the middle and lower areas. In relation to the climatic conditions, greater diversity was found in dry periods because of more stabilized concentration of organic matter and TDS, which increase during rainy periods. This pattern reflects an interdependent relationship between these organisms' habitats and local climatic conditions which affected different sections of this river system distinctly. This is evidenced by the presence of macroinvertebrates families which are tolerant to low oxygen concentrations and abundant organic matter, (related to the expansion of agricultural LC), which results in low diversity and high dominance of species.

The understanding of the interconnections between the biological characteristics, physicochemical parameters, and the changes in land use, helps to understand in an integral way the transformations generated in the LPRB's trophic dynamics and WQ. In this sense, it is especially important to articulate actions for the sustainable management of riparian areas, to decrease the use of chemical inputs, and to limit the access of livestock to the riverbed.

With respect to the interactions from a SENs framework, it is noted that the dynamics in the LPRB have led to the emergence of socioecological conflicts over water, as well as to planning processes that have materialized in actions of land-use conversion, environmental zoning, and bio-economic productive strategies. Regarding the historical context of the basin, it is important to highlight the Peace and Coexistence Pact of 2002, in which four fundamental actors of the LPRB in the management dynamics of the basin and allowed to solve internal conflicts. These have contributed to consolidation of internal governance processes, although there remain considerable challenges of inter-institutional articulation and maintaining the Peace and Coexistence Pact amid new sociocultural dynamics in the region, including the participation of new community and productive organisations. It is precisely in this last point that there is an opportunity to generate water management actions that are flexible to the dynamics that the basin has undergone, and that should be integrated into the actions that are part of the Pact for Peace and Coexistence, in order to continue strengthening collective community actions and institutional support in the conservation, revitalization, and conversion of strategic hydrological zones to guarantee water supply both to the inhabitants of the basin and to downstream users.

5. Conclusions

An integrated analysis of how agricultural activities affect water quality in an Andean basin in southwest Colombia has been presented. To the best of the authors' knowledge, this is the first time that a comprehensive understanding of socioecological dynamics related to WQ in Andean basins in Colombia has been presented at this level. In this context, it was found that the deterioration of water quality is directly related to (i) unsustainable agricultural practices including the over application of agrochemical, (ii) changes in LULC affecting regulatory ecosystems such as dense Andean forests and páramos, (iii) climate variability that causes difficult in agricultural planning and can ruin crop production, and (iv) increase in water pollution and continuous transportation of soil and nutrients to the river. Each of these conditions generates direct impacts on water quality and ecosystem services in Andean basins, as well as for the rural and urban communities who depend on them. The disparity in access to water for human consumption between urban and rural areas further exacerbates the urban–rural divide. This division is largely influenced by the varied mechanisms through which water is provided to these different areas and the difficulties for articulating distinct actors involved in water use and management. This situation increases the socioenvironmental vulnerability of the communities that depend on the supply of natural resources in their territories for their survival.

In the case of the Las Piedras River basin, it was also found that regional climate variability triggers the concentration of contaminants flowing to the river, which also affects the agricultural practices planning and hinders the organization of productive calendars. With respect to water quality, it is important to consider the increase in nutrients that limit the availability of water for human consumption (nitrogen and phosphates), as well as the presence of total and fecal coliform bacteria in the LPRB, such conditions resulted from agricultural and livestock production processes, generating soil compaction and increased surface runoff during rainfall. This is exacerbated by the poor sanitation infrastructure in the LPRB, causing sediments, biological waste, and agrochemicals to enter the river as runoff, also impacting ecological conditions in the basin. As future developments, we would like to consider the modelling of diffuse contaminants coming from secondary productive activities developed in the basin that also changes the WQ. This analysis can be performed in a complementary way to hydrological modelling, allowing the identification of additional processes that contribute to the water contamination and make the controlling process more difficult.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su152215965/s1, Table S1. Correlation values -Spearman correlation test. Table S2. Correlation values -Spearman correlation test.

Author Contributions: D.M.R.-O., conceptualized the manuscript, oversaw data curation, formal analysis, and investigation, worked on the methodology, software, and visualization of results, wrote the original draft, and reviewed and edited the final version; Y.T.S.-C., conceptualized the manuscript, oversaw data curation and formal analysis, worked in the methodology, software, and visualization of results, wrote the original draft, and reviewed and edited the final version; R.M., performed the final formal analysis and reviewed and edited the final version; and A.F.-C., conceptualized the manuscript, oversaw funding acquisition and project administration and supervision, and reviewed and edited the final version. All authors contributed to the article and approved the submitted version. All authors have read and agreed to the published version of the manuscript.

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