

GEOGRAPHY, ENVIRONMENTAL SCIENCE & DISASTER MANAGEMENT

Neighborhood-Scale Urban
Forest Structure and Health

Tourism in the Bioceanic
Road Corridor

Community Forest
Concessions in Guatemala

Ecological Collapse and
Hypereutrophication in
Lake

Discovering Thoughts, Inventing Future

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PREFACE

The Global Journal of Human-Social Science (GJHSS) is pleased to present this issue, bringing together a curated collection of high-quality research papers that explore diverse dimensions of human society, culture, and the social world.

This issue features research spanning topics including arts & humanities, sociology, history, anthropology, economics, political science, linguistics, education, and interdisciplinary social inquiry. Each paper has undergone a rigorous double-blind peer-review process to ensure scholarly rigor and originality.

We would like to express our sincere gratitude to the authors for entrusting their research with us, to the reviewers for their thorough and constructive evaluations, and to our readers for their continued engagement with the academic discourse.

We hope that the research presented herein inspires further inquiry and contributes meaningfully to the advancement of knowledge in the human and social sciences.

The Chief Editor
Global Journal of Human-Social Science
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Neighborhood-Scale Urban Forest Structure and Health Inventory as Indicators of Green Infrastructure and Climate Resilience: The Case of Chatham, Chicago

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PEER REVIEW

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Abstract

Urban forest inventories are vital for understanding the ecological and social functions of neighborhood-scale arboreal systems, especially in communities experiencing climate-related stress. This study integrates field sampling, and high-resolution (1m x 1m) LiDAR data to establish a comprehensive urban tree inventory for the Chatham neighborhood in Chicago, a community historically burdened by flooding, noise pollution, heat vulnerability, and limited green space. Findings demonstrate that trees in Chatham are predominantly tall, with an average height of 19 meters, and that canopy coverage constitutes approximately 17% of the neighborhood, higher than previous city estimates but still considerably below the recommended 40% urban canopy benchmark. Field assessments further indicate that crown vigor, as well as the health of leaves, trunks, twigs, and other woody components (including bark and branches), are adversely affected, suggesting substantial biotic and abiotic stress factors, which underscores the need for proactive urban forest management like regular tree inspections, inventories, removal or pruning of dead branches, and effective storm preparedness and emergency response. Additionally, it emphasizes the importance of targeted planting initiatives in areas with sparse tree cover and of implementing neighborhood-specific greening strategies to enhance climate resilience.

Urban forest inventory

LiDAR canopy analysis

Tree-desert mapping

Environmental justice

Ecological services of Urban trees

AI USE STATEMENT

No generative AI was used for analysis or results.

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The authors declare that they have
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Keywords: *Urban forest inventory, LiDAR canopy analysis, Tree-desert mapping, Environmental justice, Ecological services of Urban trees*

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1. Introduction

An urban forest inventory is a meticulous compilation of data on trees in urban environments, including street trees, trees in parks and gardens, small or fragmented woodlands, and solitary trees (Konijnendijk et al., 2006; Gala & Boakye, 2020). It involves a systematic collection, documentation, and analysis of information about urban tree species, location, diameter at breast height, height, canopy size, crown condition, health status, structural defects, pest or disease symptoms, and maintenance needs (Morgenroth & Östberg, 2017). Globally, urban tree inventories have been employed to study, quantify, and model the complex ecosystem services of urban forests, thereby driving scientific research in climate change mitigation, urban biodiversity, and public health (Miller et al., 2015; McPherson et al., 2016). It also quantifies the ecological, social, and economic advantages conferred by trees, including biodiversity support, carbon sequestration, pollution reduction, urban heat mitigation, recreational opportunities, and long-term climate resilience (Pataki et al., 2021; Morton Arboretum, 2022). The presence of healthy, well-distributed trees in the neighborhood can mitigate localized flooding by enhancing soil

infiltration and reducing stormwater runoff, thereby constituting a vital element in climate resilience strategies (Nowak, 2010; Berland et al., 2017; McKenzie, 2022). The predominant urban tree species in the Midwestern United States include Maple, Honey Locust, and Crabapple, along with smaller numbers of Eastern Cottonwood and Mulberry (Bentrup & Dosskey, 2022).

Chicago boasts one of the largest and most diverse urban forests in the United States, comprising millions of trees distributed across streets, parks, private lands, and remaining natural areas (Nowak, 2010; Morton Arboretum, 2022). The monitoring and management of this forest are crucial for advancing understanding of the city's neighborhood-scale urban forest structure, canopy inequality, tree health vulnerability, and environmental and green infrastructure planning. Numerous studies (e.g., Nowak & McPherson, 1993; Nowak et al., 2013; Nowak & Greenfield, 2018) have produced varied findings from comprehensive citywide urban tree inventories, with implications for quantifying and analyzing ecosystem services alongside maintenance requirements. For instance, Nowak et al. (2013) estimated that there are approximately 157,142,000 trees in the Chicagoland region, whereas the city itself contains

an estimated 17 million trees (Nowak, 2010; Morton Arboretum, 2022). These trees provide an approximate canopy cover of 16% in the Chicago metropolitan area, although this coverage varies substantially across neighborhoods: some highly vegetated areas reach 50%, while others fall below 5%. The Chatham neighborhood was reported to have a coverage rate of 8.5%, placing it at the lower end among Chicago neighborhoods (Morton Arboretum, 2022; Robinson, 2023; Li & Sharma, 2024). The city is documented to comprise approximately 103 tree species, of which 37% are native to Illinois (Morton Arboretum, 2022). In addition, Morton Arboretum (2022) identified a decrease in the city's canopy coverage from 19% in 2010 to 16% in 2020, primarily attributable to the loss of mature ash trees caused by invasive pests and heightened competition from invasive European buckthorns. Municipal data, including 311 service requests, have further underscored issues such as pest infestations, broken branches, and pruning requirements, thereby indicating potential declines in the health of the existing urban canopy (City of Chicago, 2022). Together, these efforts demonstrate that Chicago's tree inventories are essential to foster maintenance and management that helps their upkeep for providing services that improve air quality, cool neighborhoods during extreme heat events, and reduce flood risks, services particularly vital in a city vulnerable to climate-related challenges, such as the 1995 heatwave.

Nevertheless, much of the current knowledge is derived from citywide inventories and analyses that yield important averages, which tend to obscure variability across neighborhoods. Localized dynamics, such as those within the Chatham community, remain insufficiently examined in this scheme, despite their significance for addressing equity issues and enhancing neighborhood resilience. For instance, Nowak et al. (2008) developed a ground-based methodology to assess forest structure and services in Chicago, whereas McPherson et al. (2016) quantified the economic and ecological value of street trees throughout the city. These studies have significantly contributed to understanding urban tree benefits at the city scale; however, they offer limited insight into intra-neighborhood variation and the role of trees in mitigating localized flooding risks. Additionally, recent studies have begun integrating advanced technologies, such as high-resolution remote sensing (LiDAR), to map canopy structures (e.g., Alonzo et al., 2016; Li & Sharma, 2024) and yet few studies have combined LiDAR data with comprehensive field inventories at the neighborhood level to transition from citywide averages to a more detailed understanding of how urban forests contribute to climate adaptation and resilience in vulnerable communities.

Therefore, the goal of this study is to develop a comprehensive neighborhood-scale urban tree inventory for the Chatham neighborhood in Chicago using an integrated approach that combines field sampling, trees crown-health assessments, and high-resolution LiDAR data. Specifically, the objectives were to characterize the distribution, species diversity, composition, and structural attributes; assess tree health and crown characteristics; and measure canopy area, tree height, tree density, and canopy density using high-resolution LiDAR data. By addressing these objectives, the study seeks to compile data that may help understand trees contributing to the neighborhood's climate resilience, environmental quality, flood mitigation, and neighborhood greening strategies, and to support efforts towards urban forest management and planning in a vulnerable South Side Chicago community.

2. Data and methods

2.1. Site Description

The study was conducted in Chatham, one of the 77 community areas of Chicago, on the city's South Side (41°44.36' N, 87°36.94' W). The Chatham Community Area covers 7.56 sq. km and was originally a swampy area known as "Mud Lake." This community extends from 79th Street in the north to 95th Street in the south, and is geographically bounded by S. Wallace Street, S. Stewart Avenue, and S. Holland Road to the west, as well as S. Dauphin Avenue and the Metra railway tracks to the east. The area was initially settled by railroad workers and subsequently developed into a middle-class neighborhood featuring a diverse array of housing styles (see Figure 1).

The Chatham neighborhood possesses a significant historical significance as a stronghold of the African American community, with more than 95% of its population identifying as Black (Hunley, 2019; Hunley & Gala, 2020). According to Elwood (2006), the population of Chatham comprises 30,783 residents and 14,957 households. In recent years, the neighborhood has offered opportunities and options for low-, middle-, and high-wage households, supported by 5,373 businesses that employ 28,501 individuals and attract approximately 2 million visitors annually. The number of households in Greater Chatham increased by 0.8%, rising to 47,950 in 2020 from 46,444 in 2015, reflecting a net gain of 1,506 households. This growth aligns with the City of Chicago's overall population increase, which rose by 1% from 2.724 million in 2015 to 2.746 million in 2020. The educational profile of the Greater Chatham area indicates relatively high educational attainment, with 20 percent of residents holding a bachelor's degree or higher. However, the area has a 30% unemployment rate, compared to Chicago's overall rate of 22% (Vasović, 2020). Correspondingly, the area has experienced rising poverty levels, with the percentage of households living in poverty increasing in recent years to over 30 percent, compared with the overall city rate of approximately 10 percent (Toussaint-Comeau & Newberger, 2017).

Approximately 36.3% of the land area, corresponding to 684 acres, is designated for transportation purposes. Just 2.2% and 3.4% of the land are occupied by open and vacant spaces, respectively (Chicago Metropolitan Agency for Planning, 2023). Land uses include residential neighborhoods, schools, churches, community gardens, public parks, and open spaces, all of which host a variety of tree species and green space. The region is distinctive in its high proportion of transportation infrastructure (36%) and a comparatively low percentage of open or vacant land (less than 6%), which constrains opportunities for new tree planting (Figure 2). Additionally, the area is particularly vulnerable to flooding, owing to its low elevation and a landscape comprising over 50% impervious surfaces (Vela, 2024; Lee et al., 2025). Notwithstanding these challenges, the neighborhood holds potential for greening initiatives, especially within existing open spaces, which could also aid in flood mitigation. Escalating weather phenomena, such as intense rainfall, exacerbate existing flooding, leading to property damage and financial losses for residents (Sinha, 2023; McKenzie & Gala, 2023). In the case of Chatham, the decline of mature ash trees due to disease and pests, amid current tree-planting strategies, may result in the loss of these trees at an irreparable rate (Brandt et al., 2016).

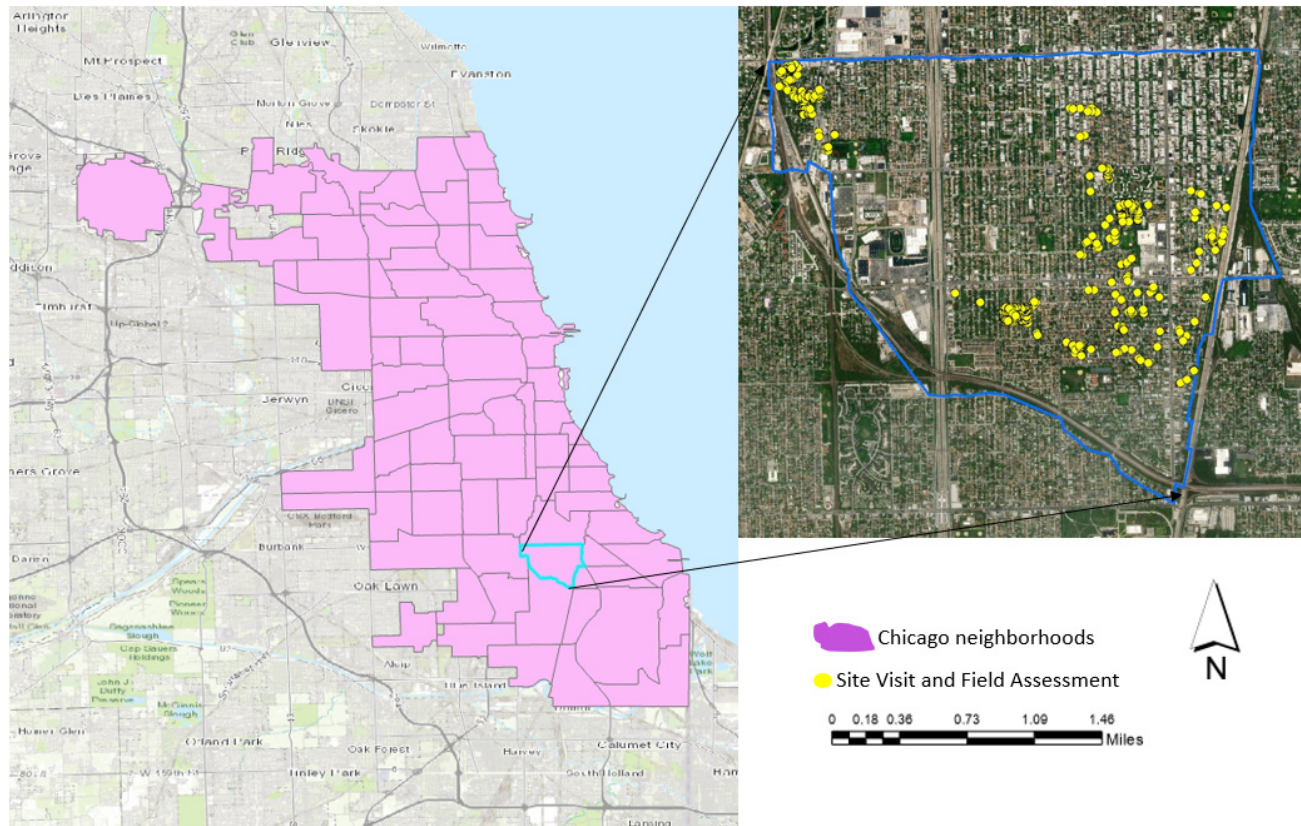


Figure 1. Chatham Neighborhood, Chicago

Table 1. Tree measurement tools, measurable parameters used in the Chatham

Method/Tool	Instruments Used	Measurable Parameters	Application Focus	Notes
Field Measurement &	Morton Arboretum field key, USDA Forest Services species sheets, and the HTHC field guide	Tree species, health indicators (disease, dieback, defoliation, discoloration, galls, pest/insect damage, exudation, bark fissures, cracks, wounds), crown characteristics (vigor, transparency, light exposure)	Standardized digital data collection in the field; Basic tree inventory; tree health assessment	Form allows efficient data storage and consistency
Smartphone (iPhone 12 camera)	Survey123 Mobile Form iPhone 12 photo + notes	Crown condition, canopy transparency, and visual risk indicators	Visual documentation; photographic record for later verification	Useful for crown health verification and transparency analysis
LiDAR (GIS/Remote Sensing)	LiDAR dataset	Tree height, canopy coverage, canopy area, tree count	Mapping urban forest structure: canopy-flood relationship	Provides large-area coverage, useful for flood risk modeling

2.2. Data Description, Acquisition, and quality control

This study integrated multiple datasets to characterize tree distribution, types, composition, and structure; assess tree health indicators and crown conditions; and quantify canopy area, tree height, and tree and canopy density across the Chatham neighborhood. Data sources included field-based measurements, crown-health assessments, community surveys, and high-resolution remote sensing products. Details of the tools used for the field survey, the specific parameters measured, and their application within the study are provided in Table 1.

2.3. LiDAR-based assessment of Tree Structure

The High-Resolution LiDAR was acquired from the Illinois Height Modernization project (ILHMP) (Illinois Height Modernization 2021). The LiDAR scan of the city of Chicago was collected in late spring 2017. At each point, the LiDAR recorded the longitude,

latitude, and elevation at every 0.35 m, which were the heights of grounds (bare surface), vegetation, buildings, water, and other infrastructures, which were classified into ground points, which were used to derive the digital terrain model, and maximum elevation points, which represented the digital surface model (DSM). Vegetation and building heights are differentiated using building vector data from the Chicago Metropolitan Agency for Planning (CMAP) and normalized difference vegetation index (NDVI) from multispectral satellite imagery. Detailed processing workflow for LiDAR point cloud data, classification into digital terrain model (DTM) and digital surface model (DSM), and the validation data found in Li & Sharma (2024). The processed LiDAR data was resampled to 1 m × 1 m resolution to estimate tree height, canopy structure, and building height for the entire city of Chicago. The LiDAR cloud point dataset has been widely used for urban tree inventory and canopy structures to study the ecological services of urban green infrastructure (Guo et al 2020; Li & Sharma, 2024).



Figure 2. Representative pictures of trees within the Chatham neighborhood

The tree and building height data were generated after validation for quality against Chicago's existing building and tree database.

Mapping Tree Density and Canopy Density Utilizing Kernel Density Estimation in ArcGIS Pro. To analyze tree and tree canopy densities, a GIS-based Kernel Density Estimation algorithm (Wang et al., 2020) within ArcGIS Pro was employed. This algorithm generates an aerial surface illustrating the number of trees or canopies within designated areas (e.g., 1 acre, ~ 4046.86 sq. meters with a dimension of ~ 64 m * 64 m), thus distinguishing areas with higher density from those with lower density. Beyond vegetation analysis, such GIS-based Kernel Density estimation has also been applied to examine the spatial distribution of public services, including schools (Lobban et al., 2025), the dispersion of air quality sensors (Pawlowski, 2025), and environmental hazards (e.g., Li et al., 2025). The following section provides the algorithm used to compute the density of trees and tree canopies.

$$\text{Density} = \frac{1}{(\text{radius})^2} \sum_{i=1}^n \left[\frac{3}{\pi} \cdot \text{pop}_i \left(1 - \left(\frac{\text{dist}_i}{\text{radius}} \right)^2 \right)^2 \right]$$

For $\text{dist}_i < \text{radius}$

Where

“
 $i = 1, \dots, n$ are the Trees and Tree Canopies density. Only include points in the sum if they are within the radius distance of the (x,y) location.
 pop_i is the value of the Trees and Tree Canopies density i , which is an optional parameter.
 dist_i is the distance between the Trees and Tree Canopies density i and the (x,y) location where density would be predicted
 $\text{Radius} = 1000$ meters. The distance (area) to which the density is calculated.

The visual evaluation of tree heights, density, and canopy coverage was conducted through map interpretation. First, tree heights, individual trees, and canopy density were interpreted using an image processed with histogram equalization, which adjusts pixel values across the available display range. Subsequently, the canopy area map was produced by classifying the area data into five categories using the Natural Breaks (Jenks) classification algorithm in ArcGIS Pro. This algorithm groups data along the vector to minimize variance within classes and maximize variance between classes.

2.4. Field Survey for Characterizing Urban Trees, Tree Health Conditions, and Indicators

The study integrated field-based urban tree measurements with geospatial data collected through ArcGIS Survey123. Tree species documentation for this inventory was conducted during the summer, from July 1 to 30, using stratified random sampling across residential blocks, school lands, and church properties within the Chatham community. Therefore, the study area was divided into strata, and a total of 495 trees out of an estimated 26,152 neighborhood trees (approximately 2%) were randomly surveyed. During the field survey, each surveyed tree was characterized, in accordance with standard forestry protocols and the Urban Tree Monitoring Protocols field guide (2015). Tree species were identified in the field through visual assessment of morphological features, including leaf shape, leaf arrangement, bark texture, and twig characteristics. For this, the Morton Arboretum field key, USDA (United States Department of Agriculture) Forest Service species sheets, and visual references from the HTHC (Healthy Trees Healthy Cities) field guide were consulted. Crown condition and tree health were visually assessed using standardized protocols adopted from the HTHC Reference Guide, the USDA Forest Service Crown Condition Indicators, and guidance from on-site certified arborists. Crown Light Exposure (CLE) was determined by counting the number of sides (top plus four vertical sides) receiving at least one-third direct sunlight, following the official CLE rating procedure. It was categorized into six classes, with Class 0 representing trees receiving no full light on any side and Class 5 representing trees receiving full light from the top and all four sides. Crown Vigor was rated through a comprehensive assessment of four stress indicators: fine twig dieback, leaf defoliation, leaf discoloration, and the presence of large, broken, or dead branches. Each indicator was visually estimated using the percentage classes provided in the Morton Arboretum guidelines and USDA reference guides, and the overall vigor class (1–5) was assigned based on standardized thresholds.

Leaf health, including the total leaf surface area affected by holes, leaf discoloration (chlorosis), wilting, and browning, was

estimated using HTHC/USDA class thresholds and indicators. HTHC/USDA class thresholds and indicators, ranging from Class 1 (0–1%, trace) to Class 5 (75–100%), were interpreted in such a way that lower classes indicate healthy trees and higher classes indicate stressed trees. Additionally, health conditions, including exit holes, frass, exudation, egg sites, insect presence, damaged buds or fruits, leaf holes, epicormic sprouts, blanding, S-shaped galleries, bark fissures, cankers, galls, wilted or browning leaves, premature leaf loss, deadwood, and wounds, were documented following the pest and stress indicator categories used in the USDA Forest Health Monitoring manuals. All assessments were made visually and confirmed with guidance from the certified arborist to ensure accuracy and consistency. Tree locations were recorded using an iPhone 12 running ArcGIS Survey123, which integrates GPS to georeferenced each urban tree point directly within the digital form. The Survey123 form, developed with guidance from a certified arborist, was used to store species, DBH, crown metrics, and health indicators, ensuring consistency between field observations and later spatial analysis in ArcGIS Pro.

3. Results and Discussions

3.1. High-Resolution LiDAR-Based (1m*1m) assessment of Urban Trees and Tree Canopies

Figure 3 shows the high-resolution Lidar (1m × 1m) characterization of Urban trees in the Chatham neighborhood, including tree heights, density, canopy area, and canopy density. The height of urban trees in the Chatham neighborhood ranges from 2.5 m to 36 m. The average height of the tree is 19m ± SD 6.2. According to The Morton Arboretum's Northern Illinois Tree Species List, urban trees are classified by height as small (7.5 m or less), medium (7.5–12 m), and large (exceeding 12 m). Therefore, on average, trees in Chatham neighborhoods (i.e., 19m) are tall. Only 5% of the trees in the neighborhoods are small (<7.5 m), 85% are tall (>12m), and the remaining 10% are medium-height trees.

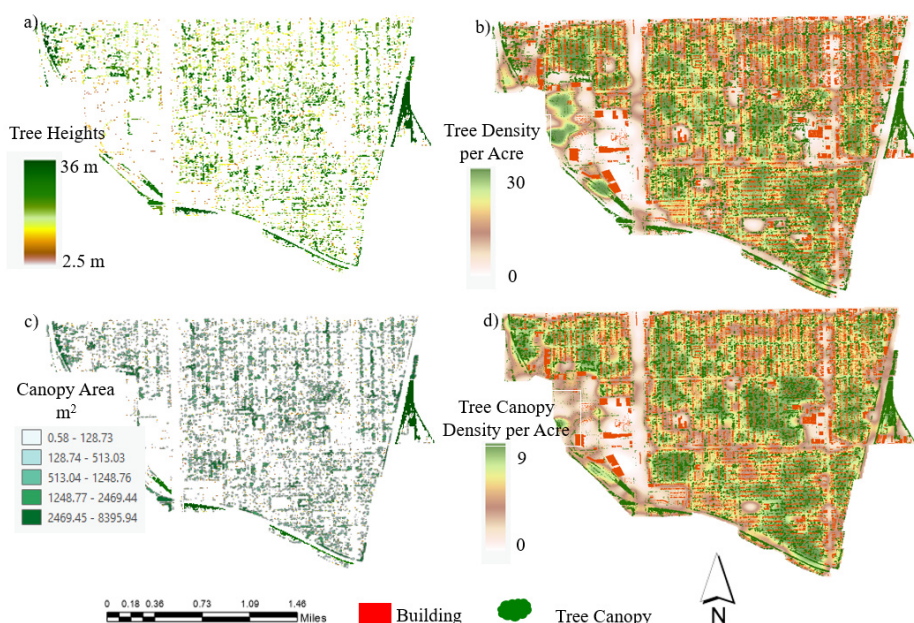


Figure 3. High resolution Lidar (1m *1m) characterization of Urban trees in Chatham neighborhood: a) Tree heights, b) Tree density, c) Canopy Area, and d) Canopy density

The relatively tall trees observed in the neighborhood are concerning for residential areas like Chatham. Typically, medium-sized trees ranging from 9 to 15 meters are recommended for residential neighborhoods to ensure the desired ecological services and environmental benefits (Nowak, 2010). However, trees in Chatham over 15 meters pose risks of interfering with infrastructure, conflicting with utilities, and damaging buildings with their roots. Therefore, it is very important to conduct regular risk assessments through the City's Bureau of Forestry under the Department of Streets and Sanitation (DSS) for Safety, Pruning & Maintenance, and Removal of Hazardous Trees.

The trees in the neighborhood have continuous canopy coverage, ranging from a square meter to 15 acres. On average, the canopy area coverage of the neighborhood trees is $48.43 \text{ m}^2 \pm \text{SD} = 4.49 \text{ m}$, indicating significant spatial variability. Generally, 324 acres (i.e., 1.3 km^2) of the 1889.8 acres (i.e., 7.6 km^2) of the Chatham neighborhood are covered by trees, indicating a 17% tree canopy coverage. This is significantly higher than the Greater Chatham area tree canopy coverage of 8.5 percent reported by Robinson (2023), which is substantially lower than the citywide average of 16.5% (Nowak et al., 2010). However, compared to the earlier American Forests' recommendation of 40% urban tree canopy for Chicago, the Chatham neighborhood's canopy is 59% lower. Additionally, compared to Chicago's greenest neighborhood, Forest Glen, which has 49% canopy coverage (Morton Arboretum, 2022), Chatham has 65% less canopy coverage. Moreover, considering that some green US cities have more than 50% tree canopy coverage (i.e., Charleston, West Virginia (74.7%), Tallahassee, Florida (56.1%), Little Rock, Arkansas (54.9%), Raleigh, North Carolina (54.7%), and Nashville, Tennessee (53.5%)), there is room in Chatham for increased tree canopy goals. Therefore, because of its lower canopy coverage and relatively higher exposure to environmental hazards (floods), noise pollution, and urban heat vulnerability that could have been mitigated by increased urban tree cover, investment in Chatham's green infrastructure is necessary.

The tree and canopy density maps reveal areas of tree desertification, where tree planting can be implemented in the neighborhood to achieve increased canopy coverage. The tree canopy density ranges from 0 (no canopy) to 9 canopies per acre, and tree density ranges from no trees to about 30 trees per acre. On average, there are five canopies per acre, with 14 trees. Low-density areas (i.e., excluding built-up and paved areas) in the neighborhood are treeless and suitable for planting to improve greenery in Chatham. It must be noted that tree deserts emerge in highly paved areas, particularly along major roads where available soil volume is low, and planting strips are narrow. Tree-deficient "desert" areas were also identified along major paved corridors, in open lots, and on vacant land, providing opportunities for strategic tree planting. A strategic urban tree-planting approach involves site selection (placement) and species identification that are believed to enhance the neighborhood's ecosystem services, such as mitigating environmental hazards (e.g., floods), reducing noise pollution, maintaining/increasing carbon storage in vegetation, and improving resilience to urban heat, an approach historically used in Chicago (Berland et al., 2017; Smith et al., 2019; Suh, 2023). It is therefore critical to prioritize these areas for future greening initiatives, thereby simultaneously increasing canopy cover and improving stormwater management capacity.

3.2. Characterizing Tree Distribution, Types, Composition, and Structure

Figure 4 shows the results of tree species compositions, types, forms, distribution, and growing space. Accordingly, the Chatham tree inventory revealed 58 tree types. Most of these trees were deciduous, accounting for approximately 89% of the total tree population, compared to only 11% evergreen. The top five most populous tree types are Honey Locust, White Mulberry, Callery Pear, Common Hackberry, and Colorado Blue Spruce. This composition reflects a typical urban forest profile in the U.S. Midwest, where fast-growing, broadleaf species are favored for shade and cooling (Nowak et al., 2008).

Additionally, Figure 4 showed that most trees were single-stem, with multi-stem individuals making up a smaller fraction of the population. Single-stem forms were most common along residential streets and in institutional landscapes, while multi-stem forms were typically concentrated in parks and open spaces. While the dominance of single-stem deciduous trees enhances shading and cooling, it also increases vulnerability to pests and diseases (Roman et al., 2021). The distribution of trees closely reflects land-use constraints within the Chatham neighborhood. Approximately 36% of the neighborhood is dedicated to transportation infrastructure, while only 2.2% and 3.4% of the land are open space and vacant land, respectively. This imbalance restricts opportunities for tree planting and contributes to uneven canopy distribution across the community. Residential parcels provide the bulk of available growing space, while transportation corridors and commercial zones remain sparsely treed.

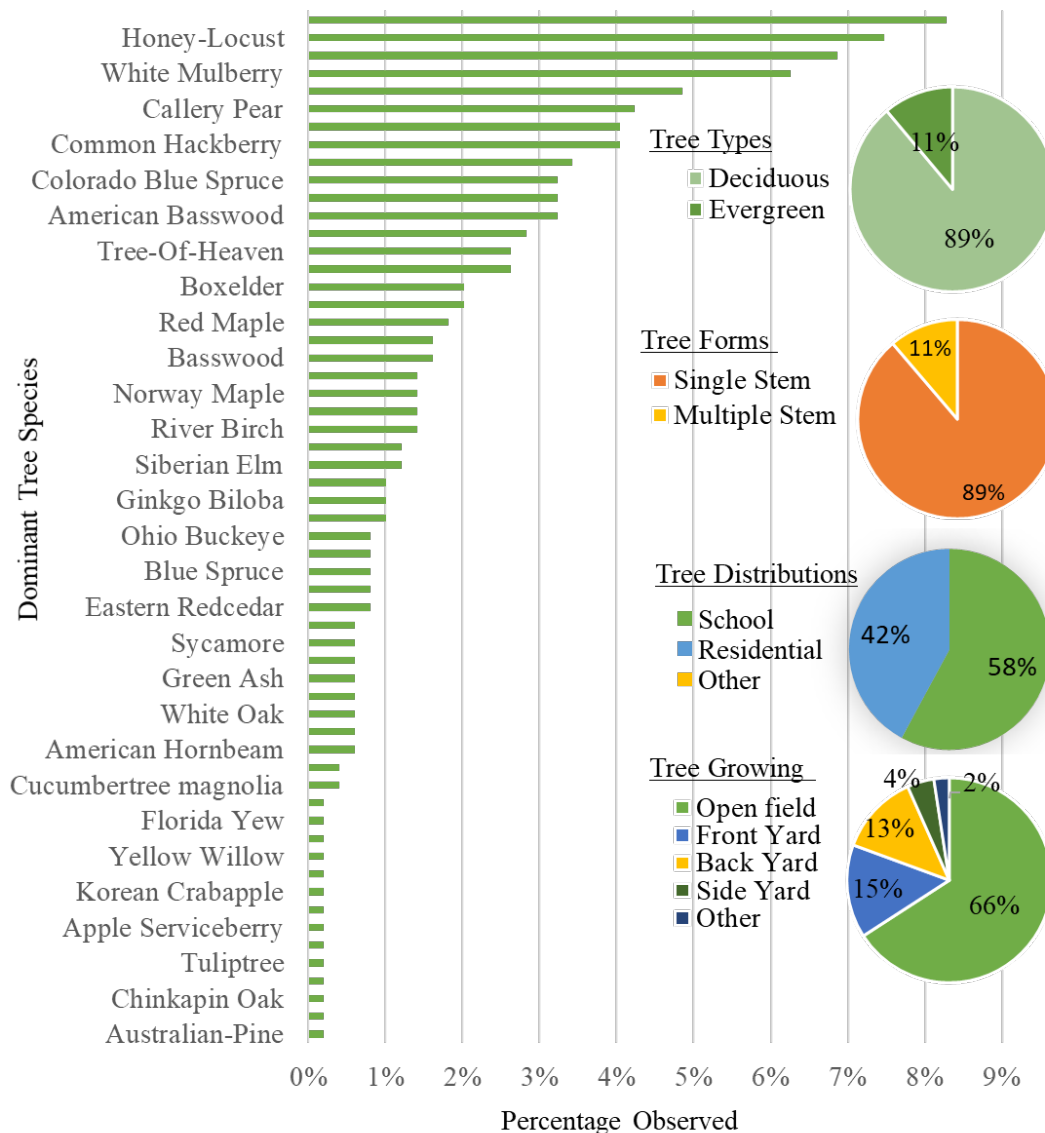


Figure 4. Chatham tree compositions, types, forms, distribution, and growing space

Figure 5 showed the result of field-based assessments of crown characteristics, indicating that most trees had adequate light exposure (i.e., 81%), while the remaining 19% were not adequately exposed, and only 5% of the trees were either one-sided or two sides of the crowns alone were exposed to the sun. Additionally, crown transparency varied, with 62% of the observed trees having a healthy, dense canopy, and several individuals exhibiting thinning foliage (i.e., 19%), particularly among older maples and cottonwoods. Many observed trees maintained moderate to high crown vigor (83%), with some showing noticeable discoloration and dieback, and others dead or nearly dead.

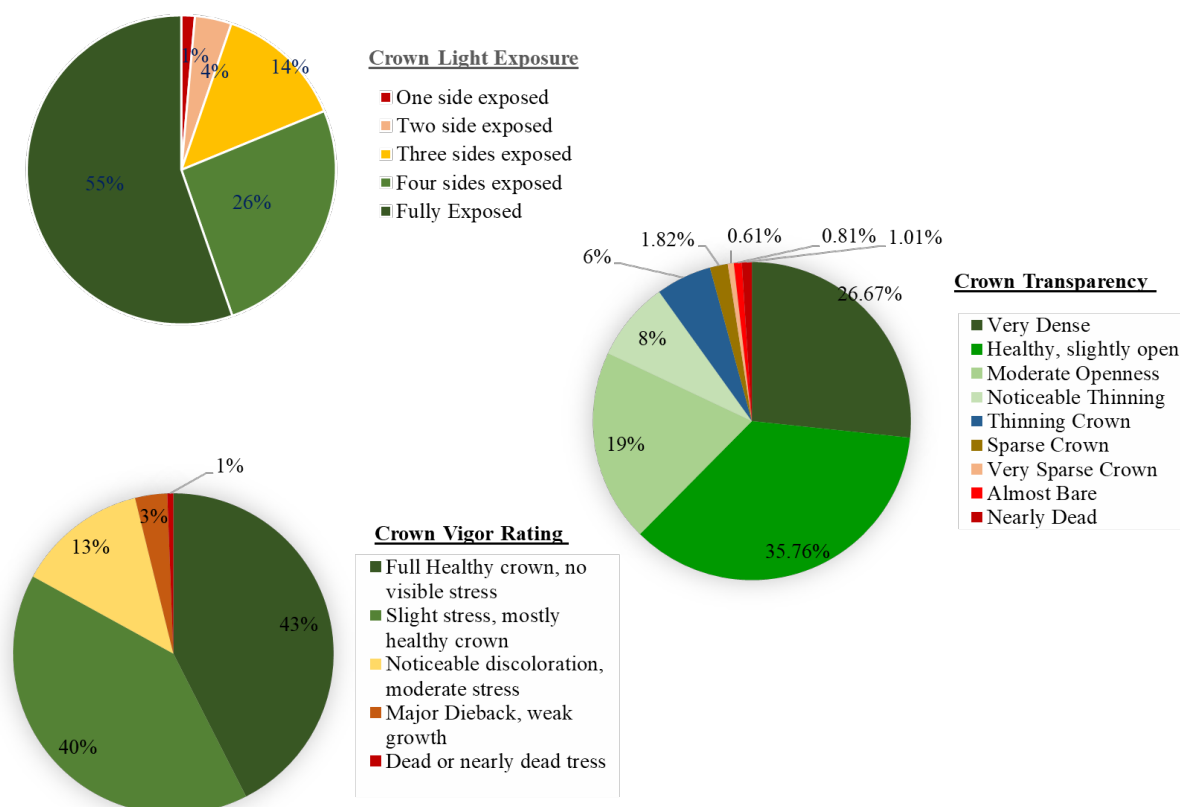


Figure 5. Crown Characteristics

Crown health directly influences a tree's capacity to provide ecosystem services such as shading, cooling, and stormwater interception. It is an important part of the tree that directly influences biomass production, and, in turn, the tree's ecosystem functions (e.g., carbon sequestration) and services (e.g., air pollution control) (Zhu et al., 2021). Full, vigorous crowns maximize shade provision and stormwater interception, while thin crowns reduce these benefits and signal declining long-term survival. Monitoring crown transparency and vigor, therefore, provides an early-warning indicator for management interventions, such as soil aeration, pest control, or selective replacement planting.

3.3. Assessment of Tree Health Conditions and Indicators

Assessment of tree health conditions and indicators was conducted by examining leaf and twig health, leaf holes, and damage to the trees' woody parts (bark and branches).

3.3.1. Assessing Leaves and Twigs Health

Figure 6 shows the results of the field observation that assesses the health conditions of tree leaves in Chatham for leaf discoloration, wilting and browning, defoliation, and premature leaf loss. Accordingly, leaf discoloration, also known as chlorosis (leaf yellowing), is noticed on tree leaves with varying degrees of severity. Leaf discoloration was severe in 7% of the trees and moderate in 21%. In contrast, wilting and leaf browning were observed in 81% of the trees. Tree wilting and browning in urban trees are often attributed to moisture and heat stress, pest infestations, and urban pollution. In contrast, leaf discoloration is attributed to physiological stress from nutrient deficiencies, moisture stress, and pathogen infestations.

Leaf defoliation, defined as premature shedding or loss of tree leaves, was observed on 22% of the trees. However, severe and heavy defoliation, as well as premature leaf loss, were observed in only 1% of the trees. Some abiotic factors, such as air pollution, nutrient deficiencies, herbicide exposure, heat stress, drought, flooding, and excessive soil moisture, are often blamed for defoliation and premature leaf loss (Mazurek & Nowik, 2018). Additionally, biotic factors such as insect pests' defoliators and fungal pathogens can cause defoliation and premature leaf loss. These factors often weaken plant vigor through impaired photosynthesis, stomatal damage, limited root capacity, and crown decline (Mazurek & Nowik, 2018).

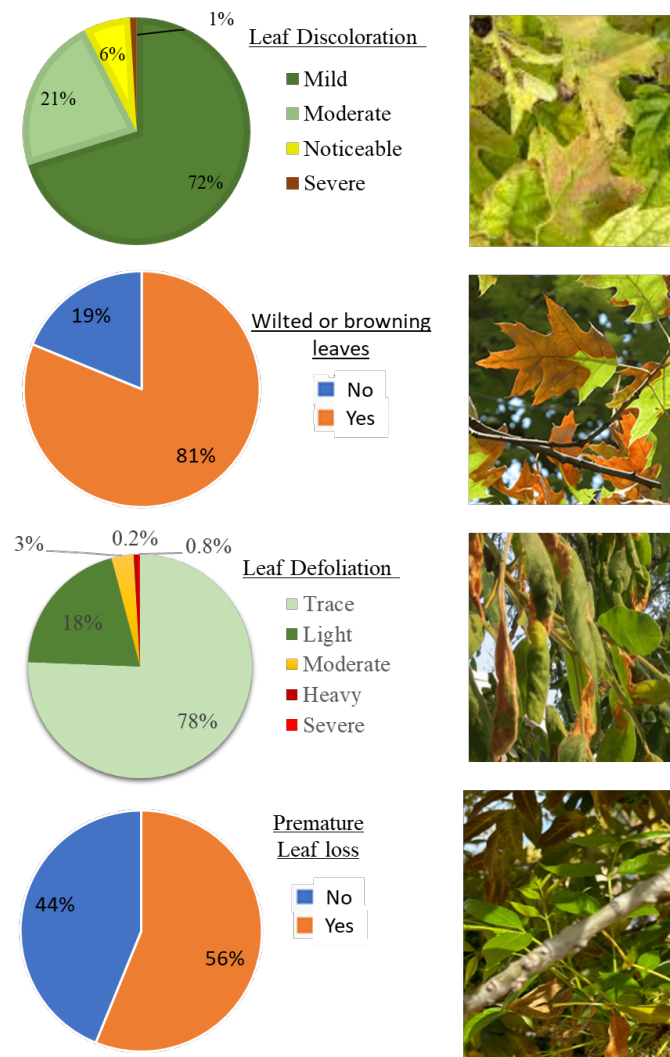


Figure 6. Health conditions of Tree leaves in Chatham.

Figure 7 shows the health conditions of tree twigs in Chatham based on the characteristics of Twigs sprouts, dieback, and injuries or galls. Accordingly, most trees (53%) showed epicormic twig sprouting, whereas the remaining (43%) did not, perhaps indicating stress from physical and physiological factors. Twigs dieback is only observed on 65% of the trees, while the remaining 35% have only a light or marginal mark of twigs dieback, indicating physiological or systemic stresses. Conversely, galls, abnormal growths on twigs caused by pest infestation, are observed on only 9% of the trees assessed, while on the remaining 91%, no signs are observed.

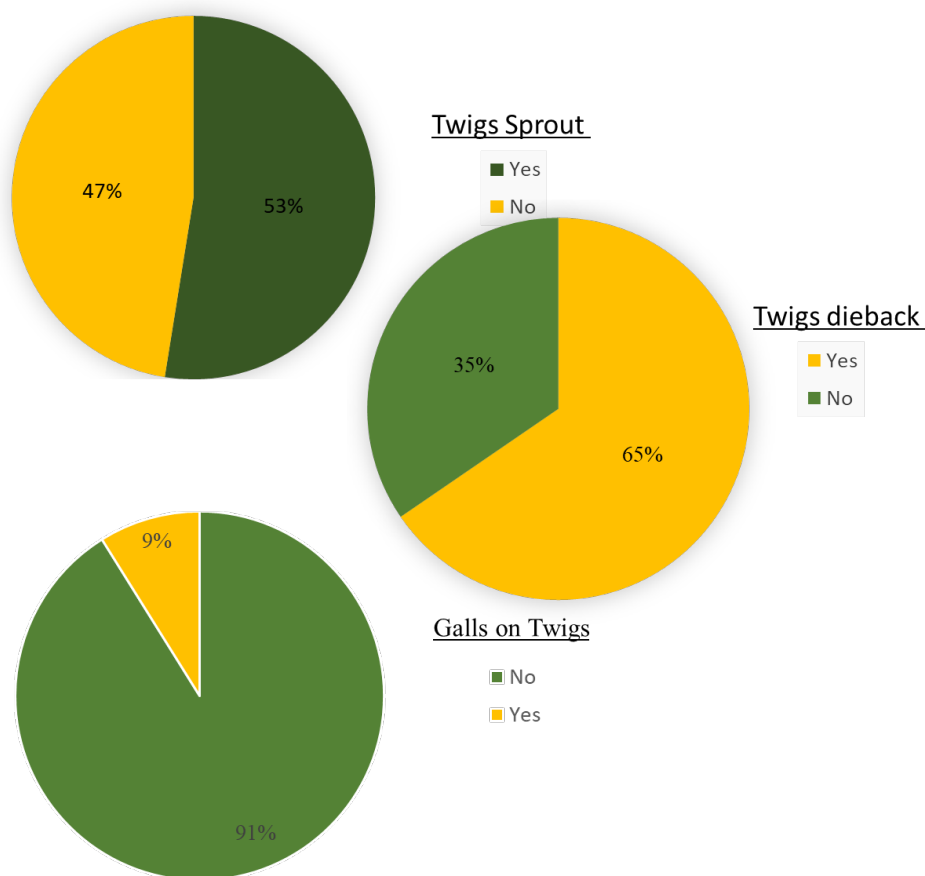


Figure 7. Health Conditions of Tree Twigs in Chatham

Assessing the health conditions of tree twigs, which represent the thinnest and most recent growth supporting branches, leaves, and flowers, is essential for evaluating overall tree health (Camarero et al., 2015). According to Camarero et al. (2015), unhealthy or damaged twigs frequently result from biotic and abiotic stresses or health impacts experienced by trees. Biotic stresses encompass pests such as the Twig girdler beetle (*Oncideres cingulate*), responsible for girdling stems, and pathogens, including canker fungi (e.g., *Cytospora* species). Abiotic factors include frost injury and drought conditions. The deterioration of healthy twigs leads to reductions in root absorption, nutrient transport, leaf and flower development, biomass growth, and overall productivity (Asis & Niscioli, 2024). The Morton Arboretum (2022) reports that phenomena such as leaf chlorosis, browning, wilting, premature leaf drop, and defoliation are prevalent among trees, especially in Northern Illinois, necessitating both short-term and long-term management strategies. In the short term, immediate causes should be addressed through pesticide application, nutrient supplementation, foliar treatments, and adequate watering. Conversely, long-term measures should focus on adopting best management practices that enhance the trees' growing environment.

3.3.2. Assessing the health conditions of the woody parts of the trees (barks and branches)

Figure 8 illustrates holes in the woody parts (barks and branches) and tree leaves in Chatham. Accordingly, holes of varying widths are found on the woody parts (barks and branches) of the trees, although the majority (68%) did not have holes, while the remaining 32% had holes. The trees had round holes (31%) and

D-shaped holes (1%). The round-shaped holes ranged from the tip of a pen or pencil (i.e., 0.5 - 0.7 mm, 2%) to the diameter of a pencil (i.e., 7 - 8 mm, 28%). Similarly, holes are also found on the leaves of trees in Chatham. While 30% of leaves did not have holes, the remaining 70% had holes of varying orientations. Holes are oriented near the outer edge of some leaves (i.e., 5%) and along the central vein of others (i.e., 7%). However, on the majority of the leaves, the holes are found both on the outer edge of the leaves and along the central vein (midrib) of the leaf (i.e., 57%). Caterpillars and fungal or bacterial infections are caused by environmental conditions such as hail and wind abrasion. On the other hand, holes in the woody parts of the plant are attributed to emerald ash borer (EAB), Bark beetles and ambrosia beetles, woodpeckers, Sapsuckers, and insects that drill or bore into the trunk and branches (Kirichenko et al., 2017). These pests can weaken trees by causing them to lose structural strength and rotting the woody parts. It also reduces photosynthetic capacity, thereby limiting carbohydrate production, disrupting water transport systems, and ultimately increasing the risk of tree mortality and urban tree failure.

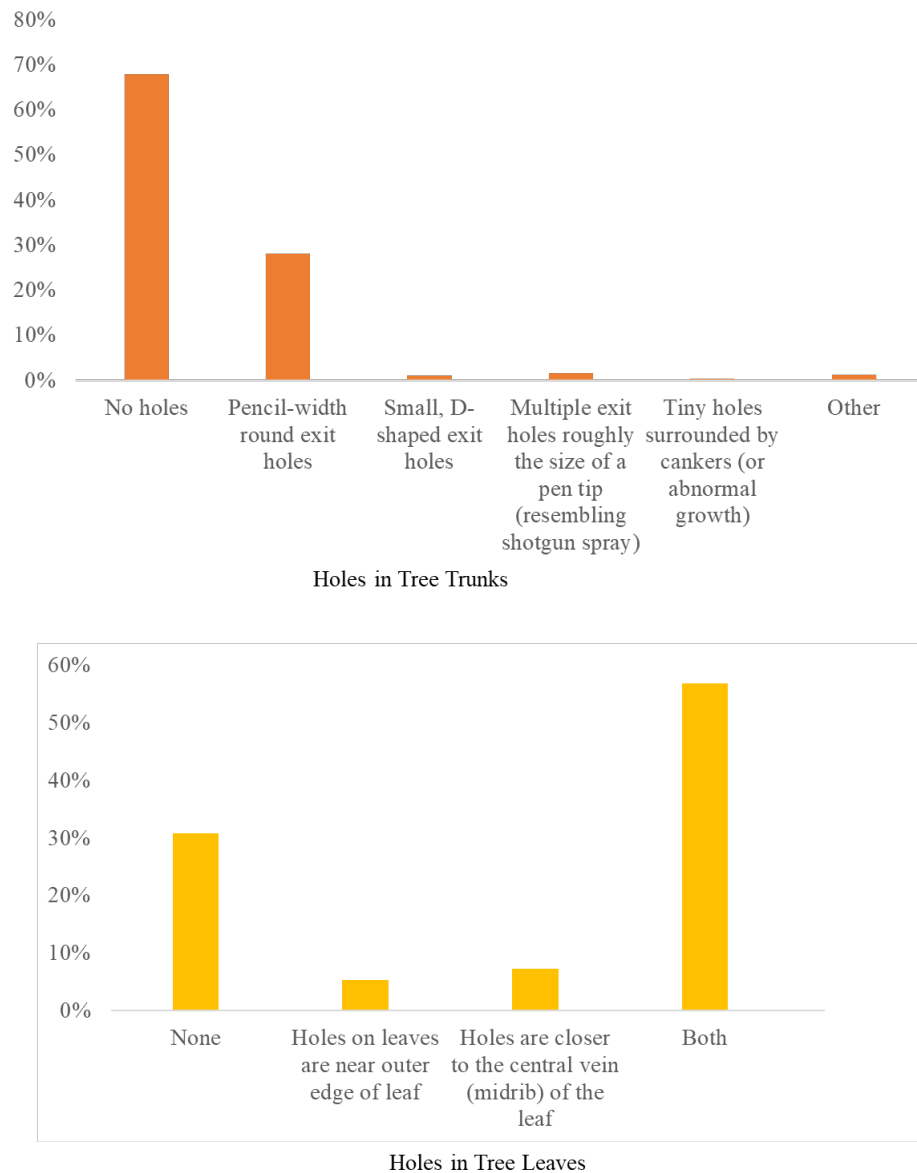


Figure 8. Assessing the holes in the woody parts (barks and branches) of the trees and tree leaves in Chatham

Figure 9 reports field observations for health indicator assessment of bark fissures, S-shaped galleries, dead branches, cankers, and wounds on the woody parts of the trees (barks, branches, and trunks) in Chatham. Accordingly, bark fissures were observed on 54% of the trees, whereas cankers and wounds were observed on 46%. Bark, the protective outer layer of a tree's woody parts, has fissures, wounds, and cracks that expose the vascular tissues and nutrient transport system. As cracks and fissures deepen, pathogens and insect borers may use them as entry points, increasing the risk of structural compromise and failure. The opening can also increase moisture loss, which is critical, especially during drought.

On the other hand, dead branches were observed on 82% of the tree canopies in the order of minor, moderate, and severe damage. Only 18% of the canopies in the Chatham neighborhood showed no dead branches. Dead branches, although most are minor or moderate, can still break under the influence of wind, rain, hail, or snowstorms, posing significant safety hazards to people and

the neighborhood's properties and infrastructure. In the United States, an estimated 34 deaths per year are attributed to urban tree failure (Schmidlin, 2011), and in the Netherlands, there is one incident of urban tree failure per 19,000 inhabitants annually, resulting in average municipal costs of €2,244 per incident paid in compensation (Van Haaften et al., 2016). Since neighborhoods like Chatham have a high concentration of people, vehicles, and infrastructure, urban tree failure can cause severe injury or fatalities to pedestrians, break through roofs, siding, gutters, and fencing, damage parked cars, and fall on power lines, causing outages. Therefore, it is important for Chatham that the city adopt proactive urban forest management strategies, which may include regular tree inspections and inventories, the removal or pruning of dead branches, and proper storm preparedness and emergency response.

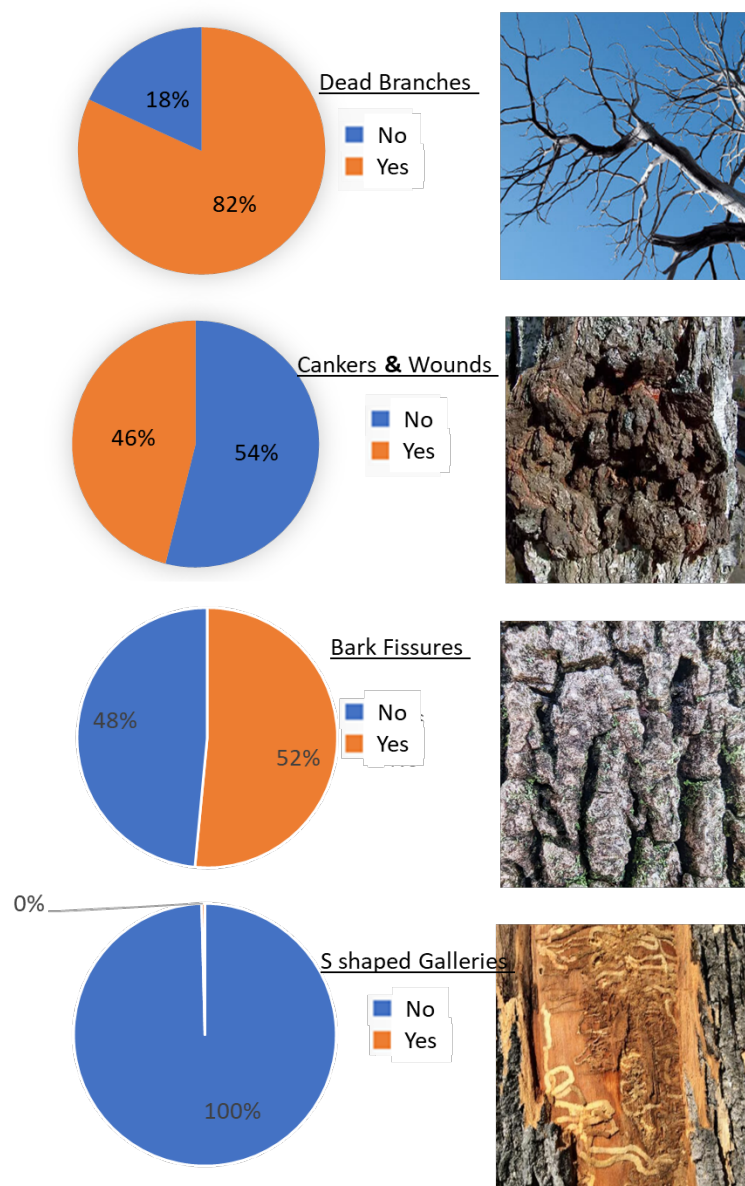


Figure 9. Health conditions of woody parts of the trees (barks and branches) in Chatham

Besides, on the branches that looked relatively healthy, wood-boring insects such as Emerald ash borer, Asian longhorned beetle, and Bark beetle (Ips), or fungi entering through wounds, cracks, or fissures, have been observed in almost 50% of the trees. Such insects and diseases systematically affect the cambium, phloem, and xylem vessels of the trees, impairing water and nutrient transport and weakening structural integrity, thereby lowering crown vigor, accelerating dieback, and increasing tree mortality (Herms & McCullough, 2014; Smiley et al., 2017). Additionally, pests and diseases can significantly reduce the ecological services of urban trees, including their abilities to filter air pollutants, store carbon, regulate stormwater, and reduce urban heat (Nowak, 2010; Vogt et al., 2015), while their sudden outbreaks create substantial economic burdens for municipalities (Herms & McCullough, 2014; Pfisterer & Beane, 2023).

Understanding these hazards is critical for Chatham residents to implement preventive measures, including investing in early monitoring systems, conducting periodic tree health inspections

and regular tree inventories, practicing proactive pruning and removing infested trees and dead branches, and ensuring proper storm preparedness and emergency response. Such prudent activities can extend the lifespan of the existing canopy and reduce replacement costs. The city of Chicago has launched the 2023 Chicago Urban Forest Management Plan, to Chatham's advantage, to support neighbors with street-tree planting, pruning, hazardous tree removal, pest management, storm cleanup, and participation in canopy-equity programs in an effort to maintain the city's environmental quality and strengthen the resilience of Chicago's urban forest (City of Chicago, 2023).

4. Conclusions

Urban forests play a vital role in improving environmental quality, ecological resilience, and public health in densely populated cities. This study presented a neighborhood-scale urban tree inventory for the Chatham community on Chicago's South Side, combining field observations, crown-health assessments, community surveys,

and high-resolution LiDAR data to analyze tree structure, species diversity, canopy features, and health status. The findings offer a thorough understanding of the ecological condition and management needs of Chatham's urban forest and emphasize the importance of detailed-scale analyses in tackling environmental issues and promoting urban equity.

The LiDAR-based analysis showed that urban trees in Chatham range in height from about 2.5 m to 36 m, with an average height of about 19 m. This suggests that many trees in the neighborhood are quite large, surpassing the typical height recommended for residential urban landscapes. While mature trees provide key ecosystem services such as shading, carbon capture, air pollution removal, and stormwater management, very tall trees in densely built residential areas may cause conflicts with infrastructure, buildings, and overhead utilities. Therefore, future urban forestry initiatives in Chatham should focus on choosing species that balance ecological advantages with compatibility with infrastructure. Generally, large trees provide substantial ecosystem services but require regular structural assessment and maintenance in dense residential environments.

Tree canopy analysis indicated that roughly 17% of Chatham is covered by tree canopy, a figure close to Chicago's citywide average but well below the recommended targets for cities aiming to be resilient to climate impacts. Compared to greener neighborhoods in Chicago and other U.S. cities, Chatham's tree cover remains relatively sparse. The spatial distribution of trees also revealed areas of "tree desertification," particularly along heavily paved transportation routes and built-up zones, where limited soil space and impervious surfaces constrain tree-planting opportunities. However, open lots and vacant land within the neighborhood present potential sites for targeted tree-planting efforts.

Species composition analysis identified 58 tree types, mainly deciduous species such as Maple, Honey Locust, Crabapple, Cottonwood, and Mulberry. While this composition reflects typical Midwestern urban forests and provides shade and cooling, the dominance of a few species may increase vulnerability to pest infestations and disease outbreaks. Recent declines in urban canopy due to invasive pests, including the emerald ash borer, highlight the need for diversified planting strategies that improve the ecological resilience of urban forests. Additionally, varying levels of physiological stress and structural defects across the sampled neighborhood trees indicate environmental stress. Notably, a high proportion of trees showed dead branches, which pose significant safety risks in densely populated neighborhoods. Overall, this study shows that neighborhood-level urban forest inventories offer valuable insights often missed in citywide assessments; however, some limitations could be addressed in follow-up studies. Data were collected using field measurements, ArcGIS Survey123 Mobile, citizen reports, and high-resolution LiDAR data. Advanced technologies such as drones equipped with hyperspectral sensors, AI, and machine learning can enhance the accuracy of these findings. Furthermore, this study focused solely on the Chatham neighborhood, one of Chicago's 77 community areas and 33 predominantly African American neighborhoods. Caution is advised when applying these results to the broader city or other demographic areas, and further research across different communities is recommended.

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Turismo como Instrumento Dinamizador do Corredor Rodoviário Bioceânico

Tourism as a Dynamic Instrument of the Bioceanic Road Corridor

Article Record

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Abstract

Tourism has a great potential to accelerate economic growth across the Bioceanic Road Corridor that will link the Atlantic to the Pacific Ocean across Brazil, Paraguay, Argentina and Chile, from Porto Murinho, in the Midwest of Brazil, to Antofagasta, in the north of Chile. If well managed and with the appropriate governance, tourism can generate quality jobs and reduce poverty, as well as create incentives for environmental protection. The promotion of tourism throughout the Road Corridor has the potential to assist policy makers in a smooth transition towards a more inclusive, resilient and sustainable economy. However, these expected changes depend not only in setting up a modern tourism infrastructure. Success will be contingent upon developing public-private and multi-stakeholder partnerships, the integration of tourism and non-tourism enterprises along the value chain, the enhancement of statistical capacity-building and sectorial analysis, as well as the promotion of high-quality education and vocational training, with the technical support of local universities. Policy makers need to understand that positive results are more likely if all countries unite efforts and ensure sustainable use of ecosystems. Despite current fiscal restrictions, there are ways to move ahead by exploiting innovative financing mechanisms and ensuring the effective use of university and private sector capacities.

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Turismo como Instrumento Dinamizador do Corredor Rodoviário Bioceânico

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Abstract

O turismo possui grande potencial para acelerar o crescimento econômico através do Corredor Rodoviário Bioceânico, que conectará o Atlântico ao Pacífico cruzando Brasil, Paraguai, Argentina e Chile, desde Porto Murtinho, no Centro Oeste do Brasil, até Antofagasta, no norte do Chile. Com boa gestão e a governança apropriada, o turismo pode gerar empregos de qualidade e reduzir a pobreza, bem como criar incentivos para a proteção ambiental. A promoção do turismo ao longo do Corredor Rodoviário também pode ser um instrumento para uma transição gradual em direção a uma economia mais inclusiva, resiliente e sustentável. As mudanças esperadas, no entanto, dependem não apenas da instalação de uma infraestrutura moderna. O sucesso estará condicionado ao desenvolvimento de parcerias público-privadas, envolvendo os diversos atores interessados, à integração de empresas do setor de turismo a empresas de outros setores ao longo da cadeia de valor, à melhoria da produção de estatísticas e análises setoriais, bem como à educação e treinamento vocacional, com o apoio das universidades locais. Os tomadores de decisão precisam entender que resultados positivos serão mais facilmente atingidos se todos os países unirem esforços e garantirem o uso sustentável dos ecossistemas. Por fim, apesar das atuais restrições orçamentárias, é possível avançar explorando mecanismos de financiamento inovadores e garantindo o uso efetivo das capacidades das universidades e do setor privado.

Keywords: *corredor bioceânico, turismo*

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1. Introdução

Em reunião realizada à margem do Conselho do Mercado Comum do Mercosul, em 21 de dezembro de 2015, os Presidentes de Brasil, Argentina, Chile e Paraguai firmaram a Declaração de Assunção, por meio da qual se criou um Grupo de Trabalho (GT), coordenado pelas chancelarias e integrado pelos Ministérios de Transportes dos quatro países. O GT está encarregado de realizar estudos técnicos e articular ações transnacionais que viabilizem a implantação do Corredor Rodoviário Bioceânico Porto Murtinho (Brasil) - Portos do Norte do Chile. Na ocasião, o traçado proposto tem sua origem em Porto Murtinho (MS), no Brasil, se estendendo a Carmelo Peralta – Mariscal Estigarribia – Pozo Hondo, no Paraguai, seguindo por Misión La Paz – Tartagal – Jujuy, Salta, na Argentina, e terminando em Sico – Jama - Antofagasta/Mejillones/Iquique, no Chile. Ou seja, conecta o Centro Oeste brasileiro com o chaco paraguaio, as províncias do Norte da Argentina e os portos do Norte do Chile, no Pacífico.

O Corredor Rodoviário Bioceânico Porto Murtinho - Portos do Norte do Chile é, portanto, uma iniciativa que, desde sua origem, goza de elevado apoio político e, como era esperado, alimenta enormes expectativas tanto no setor privado quanto na população local. De fato, a infraestrutura tem condições de transformar a realidade, na medida em que romperá com o isolamento do chaco paraguaio, aliviará as durezas do cotidiano de Porto Murtinho, valorizará

Salta e Jujuy como pontos logísticos e levará carga para os portos chilenos, estimulando o crescimento do setor de serviços. Criará, portanto, novas oportunidades de comércio e investimento nos territórios cobertos pelo Corredor, melhorando as condições de vida da população.

Para a articulação e a implementação das ações acordadas foi instituído um mecanismo de coordenação intergovernamental, ao qual se somaram, por iniciativa dos Coordenadores Nacionais, os interesses privados (Conselho Empresarial) e a experiência e o conhecimento acadêmico (Rede Universitária). A implantação do Corredor Rodoviário Bioceânico é, portanto, um esforço tripartite, que procura, por meio do diálogo e ações coordenadas, garantir o alinhamento dos objetivos estratégicos com as iniciativas empreendidas por todos os envolvidos e interessados, no curto, médio e longo prazo.

Em face da estratégia e da governança criada no âmbito do Corredor Rodoviário Bioceânico, depreende-se que a iniciativa não se resume à implantação de uma infraestrutura viária, mas sim instituir um verdadeiro Corredor de Desenvolvimento.

Com a implantação da infraestrutura física, os recursos humanos e naturais adormecidos das regiões atravessadas pelo Corredor serão mobilizados e, consequentemente, mais emprego e renda serão gerados. Por meio de parcerias entre os setores privados e a articulação de ações promovidas pela esfera pública, pretende-

se somar as vantagens comparativas dinâmicas dos territórios, identificar novas complementariedades comerciais, promover a agregação local de valor, estimular o desenvolvimento dos serviços de logística, transporte e seguros, bem como explorar oportunidades comerciais oferecidas pelo esforço de transição de uma economia primária-exportadora para uma economia de baixo carbono mais diversificada.

A instituição do Corredor Rodoviário Bioceânico cria, portanto, uma situação ímpar: as autoridades dos territórios dos quatro países e os demais “stakeholders” são induzidos a valorizar os territórios de fronteira, a “pensar” seu entorno geográfico e a conhecer em profundidade a realidade dos países vizinhos, ou seja, incorpora-se à perspectiva nacional uma visão transfronteiriça. A fronteira deixa de ser vista como um “muro” e passa a ser considerada uma “ponte”. Além disso, os novos fluxos de comércio e investimento trarão consigo o aumento da presença do Estado e, como resultado, maior segurança nas fronteiras.

O Corredor Rodoviário Bioceânico não oferece apenas uma oportunidade de transformar a realidade local. Além de romper com as fronteiras físicas, passa a valorizar o interesse coletivo das populações beneficiadas pelo Corredor. A riqueza e as vantagens do nosso vizinho nos revigora para além de uma perspectiva meramente mercantilista. Nessa visão, o interesse comum deve ser fortalecido e a todo custo protegido, na medida em que iniciativas unilaterais ou ações motivadas unicamente por interesses pontuais podem comprometer o resultado das ações coletivas. Num Corredor Rodoviário não se pode pensar de modo segmentado ou isolado, nem beneficiar apenas os que estão na origem ou no fim do eixo rodoviário. Os desafios são comuns e as soluções devem ser construídas por todos, de modo a gerar benefícios para todos.

Com objetivos estratégicos acordados previamente e uma abordagem holística e inovadora - amparada em estruturas institucionais tripartites, transnacionais, colaborativas e flexíveis, orientadas pela defesa e preservação do interesse coletivo - ficam criadas as condições que permitem não só transformar a realidade local, mas também alimentar na população um sentido de pertencimento ao espaço sul-americano, aceitando e valorizando seu entorno geográfico. Com efeito, se o japonês se sente um asiático, e o alemão um europeu, o chileno de Antofagasta, o argentino de Salta ou Jujuy, o paraguaio do Chaco e o brasileiro do Centro Oeste ainda não se veem como sul-americanos.

Entende-se que o turismo pode ser um fator dinamizador do Corredor Rodoviário Bioceânico, sendo necessário ressaltar que o desenvolvimento de práticas sustentáveis de consumo e a produção de serviços turísticos exigirão uma mudança de mentalidade dos atores envolvidos. Deverão entender que, no médio e longo prazo, a sustentabilidade e a inclusão social beneficiam os agentes turísticos, os usuários e a economia local, gerando “forward e backward linkages”, em termos de renda e empregos de qualidade.

Este trabalho tem por propósitos oferecer uma visão estratégica e sugerir uma governança alinhada com o tripé criado no âmbito do Corredor, de modo a estimular a articulação em vez de propor ações isoladas ou pontuais. Visa, também, a formular propostas capazes de tornar o desenvolvimento da atividade turística em fator de dinamização do Corredor Rodoviário Bioceânico. Todas as ações ou sugestões partem do princípio de que os benefícios devem ser estendidos a todos os países, em particular às comunidades locais e às pequenas e médias empresas. As soluções ou iniciativas que venham a ser acordadas deverão estar orientadas pelos objetivos e metas do Acordo do Clima e a Agenda para o Desenvolvimento Sustentável 2030 (metas 8,12,14 e 17); devem valorizar a capacidade criativa do indivíduo, incentivar a agregação local de valor, estimular o uso

de energias renováveis e novas tecnologias, bem como promover a utilização sustentável dos recursos humanos e naturais.

2. Turismo, motor do crescimento econômico, sustentável e inclusivo do Corredor Rodoviário Bioceânico

À semelhança do comércio, do investimento ou da integração produtiva, o turismo tem uma natureza transnacional. No entanto, devido à natureza fragmentada da atividade turística, que envolve empresas de todos os tamanhos e o oferecimento de serviços para públicos diversos, com distintos graus de sofisticação e propósito, é necessária uma abordagem holística e multidisciplinar. O planejador não deve ver apenas seu entorno mais imediato, mas também entender as transformações que estão em curso nos quatro países, nos territórios e no mundo. A atividade turística não é exceção. Ela é muito sensível aos efeitos resultantes das grandes mudanças globais atualmente em curso.

O turismo como atividade econômica desempenha um papel fundamental para as economias. Em 2016, nos países que integram a OCDE (OECD, 2018, p.26-27), o turismo foi capaz de gerar 4,1% do PIB, 5,9% do emprego e 21,3% das exportações totais de serviços. Em 2017, o turismo mundial movimentou 1,2 bilhão de pessoas (aumento de 7% em relação ao ano anterior). Foi o maior crescimento registrado nos últimos sete anos. Gerou uma renda global de US\$ 1,3 trilhão. Em 2030, segundo avaliação da OCDE, o número de turistas internacionais deverá elevar-se a 1,8 bilhão de pessoas. Os gastos globais com turismo mais do que dobraram nos últimos anos, em decorrência da melhoria das condições econômicas dos mercados emissores (Europa, Japão e EUA), o advento de novos “players” (China, Índia e Rússia) e o avanço da tecnologia digital e da internet. Na atualidade, o turismo global representa 7% das exportações mundiais de bens e serviços, 10% do PIB mundial e 10% de todos os empregos gerados no mundo. O turismo gera, hoje, mais empregos do que o conjunto da indústria automobilística e química.

Em 2017, a América do Sul (UNWTO, 2017) captou 36,7 milhões de turistas estrangeiros (aumento de 8%), gerando uma receita de US\$ 29,3 bilhões (incremento de 2%). Na região do Corredor, o Chile recebeu 6,4 milhões de turistas, o Brasil, 6,5 milhões, a Argentina, 6,7 milhões e o Paraguai, 1,5 milhão. No conjunto, os quatro países receberam 21,1 milhões de turistas. Naquele ano, o Chile e o Paraguai registraram as maiores taxas de crescimento, respectivamente, 14% e 17%.

Para efeito de identificação do potencial turístico que ainda pode ser explorado, em 2016, a França recebeu 82,5 milhões; os EUA 75,8 milhões; a Espanha 75,3 milhões; a Alemanha 35,5 milhões; o México 35 milhões; a Itália 32,5 milhões; a Grécia 28 milhões; o Japão 24 milhões; o Marrocos 10,3 milhões; a Irlanda 8,4 milhões e o Peru 5,9 milhões. Como se pode verificar, Brasil, Chile, Paraguai e Argentina, em bloco, atraem menos turistas do que o Japão e a Grécia. A Irlanda, país de menor população e território, atrai mais turistas do que Brasil, Argentina e Chile.

Embora esses números mostrem, de um lado, um diferencial expressivo de escala, de outro, escondem o potencial turístico da região. Muito ainda pode ser feito para dinamizar esse potencial adormecido. Para que isso ocorra, porém, algumas dificuldades terão que ser superadas. No plano global, a atividade turística enfrenta enormes desafios. Como era de se esperar, esses também se fazem sentir na América do Sul: 1) a complexidade e a fragmentação da atividade turística demandam abordagens transversais, multidimensionais e multisetoriais; 2) o turismo é impactado por alguns fatores exógenos: a mudança das condições macroeconômicas (taxa

de câmbio, inflação e depressão), os desastres naturais (furacões, enchentes, queimadas, longos períodos de seca) e os solavancos dos ciclos políticos e das tensões geopolíticas; 3) a atividade turística sofre também o impacto das mudanças tecnológicas, do advento das redes sociais, da economia do compartilhamento e do avanço das plataformas digitais; e 4) o turismo sente, como qualquer outro setor, os efeitos das megatendências globais (OECD, 2018, p.63-64) (envelhecimento da população, aumento da classe média global, sustentabilidade ambiental e inclusão social).

Em face dos desafios que a atividade turística enfrenta e das grandes transformações globais, os responsáveis pelo turismo de Mato Grosso do Sul, da região do Chaco paraguaio, das Províncias do norte da Argentina e no Chile poderiam implementar as seguintes linhas de ação:

- Criar uma instância de coordenação permanente no âmbito do Corredor, que esteja orientada por objetivos estratégicos, que conte com a participação dos governos locais, do setor privado e das academias, de modo a definir uma agenda de ações prioritárias e um planejamento de médio e longo prazo. Para tanto, poderiam alinhar as políticas existentes com iniciativas concretas que já estejam em curso; encomendar à academia estudos específicos para a tomada de decisão futura e identificar ações coordenadas que possam atender às necessidades imediatas do setor privado e das comunidades locais;
- Compartilhar e promover políticas de turismo inovadoras, que considerem o avanço da economia digital e os efeitos da economia compartilhada, atendam às demandas específicas de uma população que envelhece e que deve dobrar de tamanho nos próximos 30 anos (1,4 bilhão de pessoas terão mais de 60 anos) (OECD, 2018, p.65); elaborar produtos turísticos que satisfaçam desejos específicos como turismo de aventura, de pesca e gastronômico; ou daqueles que busquem emoções fortes (rafting ou o Rally dos Sertões, de Aquidauana, além de promover ações que respondam às necessidades de turistas com deficiências físicas (cadeirantes, síndrome de Down).
- Essa instância seria também responsável pelo desenvolvimento de iniciativas que tenham foco em segmentos populacionais (Geração Z, nascidos entre 1990 e 2010, e a geração Y ou “milênio”, nascidos entre 1980 e metade dos anos 90), cujos interesses e motivações devem ser melhor identificados e explorados. Esses segmentos populacionais cresceram com a tecnologia digital e a internet e tendem a organizar suas viagens de forma independente, sem utilizar as tradicionais agências de turismo. Recorrem, em grande medida, às plataformas digitais (TripAdvisor, Expedia, Booking.com) e aos “sites” de reserva e avaliação das experiências individuais para definir sua hospedagem (Trivago). Não compram pacotes nem vão a feiras ou recorrem à assessoria especializada. Em 2020, a geração Z deverá atingir 2,6 bilhões de pessoas. O grupo do milênio, por sua vez, é responsável por 20% do fluxo internacional de turistas. Os indivíduos desse segmento gastam com suas viagens em torno de US\$ 203 bilhões por ano (OECD, 2018, p.67). Com o avanço da idade, esses grupos irão envelhecer, mas a vontade de viajar permanecerá viva. Por tenderem a ser mais conservadores no futuro, é necessário que recebam tratamento prioritário, desde agora;
- Apoiar a criação de um ambiente que incentive o turismo e a instituição de empresas de pequeno e médio porte; estimular,

por meio da troca de experiências e conhecimento entre os países, o desenvolvimento de produtos turísticos inovadores, alinhados com a necessidade de preservar o meio ambiente e promover a economia verde;

- Desenvolver um mapa da infraestrutura turística existente, bem como realizar o levantamento dos pontos de interesse para o usuário (restaurantes, hotéis, etc). Para empreender esses e outros trabalhos, será necessário definir uma moeda padrão e harmonizar conceitos e definições, que permitam a comparação de resultados e a elaboração de estudos de interesse comum.
- Criar um Observatório do Turismo. Sua função principal seria a elaboração de estatísticas e indicadores de desempenho. Os indicadores vão permitir que os planejadores possam adequar os serviços ao crescimento e à variação da demanda dos atores da cadeia de valor do turismo, o que permitirá monitoramento e ajustes. A partir dessas informações, os responsáveis pelo setor de turismo do Corredor poderão ofertar cursos de capacitação nas áreas de hotelaria, gastronomia, assim como estágios para treinamento de alunos universitários em empresas argentinas, chilenas, brasileiras ou paraguaias;
- Utilizar os recursos acadêmicos (alunos de graduação, mestres e doutores em turismo) para apoiar os governos provinciais na formulação de programas ou na elaboração de ações transversais e transnacionais, para o setor; e
- Recorrer à cooperação internacional (por exemplo, da Segittur, companhia estatal espanhola) para realizar pesquisa, compartilhar experiências e desenvolver novos serviços ou produtos inovadores. A Colômbia desenvolve uma iniciativa muito similar (Estratégia dos Corredores Turísticos), lançada em 2016, que compreende a promoção de 12 corredores ou regiões, com características ou ofertas muito semelhantes. Outra possibilidade que poderia ser explorada seria a experiência peruana com o Programa “Al Turista, lo Nuestro”, pelo qual procura difundir a comercialização dos produtos e serviços locais (frutas, artesanato, danças folclóricas, etc.).

3. O Corredor Rodoviário Bioceânico, as grandes tendências do turismo e algumas ações específicas

Nos últimos anos, o turismo tem crescido a uma taxa média anual de 3,3%, índice superior à variação do comércio internacional e do produto mundial. Em grande medida, esse expressivo crescimento se deveu ao advento dos mercados emissores emergentes. À semelhança do que se verifica em outros campos, a participação das economias emergentes no mercado mundial de turismo deverá crescer ainda muito mais, de 45%, em 2016, para 57%, em 2030 (OECD, 2018, p.26). Embora os EUA e a Alemanha devam continuar no topo dos “outbound markets”, é inegável o forte aumento do turismo emissor de China, Índia, Coreia do Sul, Turquia, entre outros. Diante dessa tendência, as autoridades responsáveis pelo setor de turismo no âmbito do Corredor Rodoviário Bioceânico deveriam empreender ações específicas para captar esses fluxos de turistas. Dentre as iniciativas, poderiam estar contempladas missões internacionais conjuntas para alguns desses países-alvo, a participação coordenada em feiras de promoção do turismo na Ásia e outras regiões emergentes ou, simplesmente, o convite para que diplomatas desses países, lotados em Embaixadas no Brasil, Argentina, Paraguai e Chile, façam uma viagem de exploração

para conhecer o potencial turístico do Corredor. Para promover as belezas naturais e as possibilidades turísticas do Corredor, os quatro países, com o apoio da academia e de seus departamentos de publicidade e marketing, poderiam elaborar material de divulgação (filmes, conteúdos para redes sociais etc), em inglês, para veiculação nos meios de comunicação em massa na Ásia e em outras regiões do globo.

O setor de turismo é intensivo em mão de obra especializada. E emprega indivíduos de diferentes idades e experiências. No entanto, como outros setores da economia, a atividade turística requer, cada vez mais, pessoas especializadas e bem treinadas. A digitalização e o progresso tecnológico contínuo (big data, blockchain, internet das coisas, inteligência artificial), característica das sociedades modernas, tornaram a necessidade da especialização ainda mais premente. A difusão e a comercialização dos serviços turísticos do Corredor devem fazer uso crescente das plataformas digitais e da internet. Os meios tradicionais de divulgação e venda de pacotes turísticos devem ser gradualmente substituídos por meios eletrônicos.

É fato que várias das propostas ou ideias formuladas demandam recursos financeiros. Diante de um quadro de austeridade fiscal, o tomador de decisão, seja na Argentina, Brasil, Paraguai ou Chile, vê-se impossibilitado de utilizar os tradicionais incentivos econômicos, como isenções tributárias e linhas de crédito subsidiadas, ainda que reconheça a importância da atividade turística para o desenvolvimento local.

Essa dificuldade não deve, porém, representar uma barreira intransponível ou levar ao imobilismo. O compartilhamento de conhecimento e experiências entre entidades interessadas no turismo, a promoção de parcerias entre os órgãos públicos e a academia, a identificação de fontes inovadoras de recursos são algumas das alternativas que poderiam ser exploradas. Na atualidade, os instrumentos de financiamento não se restringem ao tradicional crédito bancário. O mercado financeiro oferece os títulos verde, a abertura do capital acionário, o “crowd-funding” e as fintechs, que reduzem os custos e oferecem outras facilidades ao tomador. O “green bond”, que ajudou a financiar a construção do novo aeroporto da Cidade do México, procura atender às necessidades financeiras de projetos que têm impacto positivo na redução da poluição, no uso de fontes renováveis de energia e na utilização sustentável de recursos de modo geral. Existem, também, fundos soberanos e investidores estrangeiros privados, sempre interessados em bons projetos. Além disso, empresas do setor turístico poderiam juntar-se e coletivamente negociar linhas de crédito bancário em condições mais vantajosas.

Para explorar essas e outras possibilidades de captação de recursos do exterior e nos países do Corredor, sugere-se a elaboração de um Mapa de Oportunidades de Investimento no Setor do Turismo do Corredor Rodoviário Bioceânico. Os projetos listados devem conter dados básicos e produzir um impacto positivo no local explorado, levando em consideração a necessidade de preservação do meio ambiente, a promoção de inclusão social e a criação de empregos para famílias e jovens em situação de vulnerabilidade. Essas informações devem estar refletidas no Mapa de Oportunidades de Investimento.

Iniciativas exitosas dos países que integram o Corredor poderiam ser compartilhadas: o Chile, por exemplo, poderia replicar na região o programa “Foco Destino”, pelo qual procura eliminar brechas de competitividade de alguns destinos turísticos, tornando-os mais atraentes aos olhos de um investidor estrangeiro. É possível, também, fazer uso dos recursos humanos e tecnológicos universitários para desenvolver soluções modernas e eficazes. Os Departamentos de Tecnologia da Informação da Rede Universitária poderiam organizar uma competição entre os alunos para a criação de um aplicativo digital que viesse a promover o turismo no Corredor Rodoviário,

iniciativa de baixo custo e de efeito prático. O grupo ganhador, em reconhecimento do trabalho, poderia receber um prêmio. Diante do valor comercial do aplicativo, não seria difícil identificar um “sponsor”.

De fato, são muitas possibilidades que se descortinam. As universidades poderiam oferecer espaços para cursos de especialização; as agências de turismo poderiam atuar em conjunto ou ainda ofertar estágios para nacionais dos países integrantes do Corredor; uma universidade poderia oferecer cursos à distância, em idioma português e em espanhol, para capacitação de técnicos em turismo; os centros acadêmicos poderiam negociar convênios com restaurantes, hotéis, pousadas, companhias de turismo e outros estabelecimentos e disponibilizar estágios não-remunerados e de curta duração que permitam aos jovens, enquanto cursam a universidade, conhecer o trabalho rotineiro de um serviço turístico. Outra possibilidade seria organizar uma competição entre alunos do segundo grau sobre os melhores destinos do Corredor Rodoviário. Essa iniciativa teria a vantagem de promover entre os jovens a consciência do potencial turístico da região, no entendimento de que eles serão futuros consumidores de serviços turísticos.

Compartilhar recursos, conhecimentos e experiências é, portanto, uma forma simples e barata de superar a carência de recursos. Desenvolver bons projetos e saber vendê-los para investidores em potencial é outra forma de reagir à falta de apoio financeiro. De várias formas, portanto, poderiam ser formados trabalhadores mais produtivos e conhecedores do entorno geográfico e dos costumes nacionais. Sempre é bom recordar que o compartilhamento de experiências e a conscientização de diversos segmentos da população têm como subprodutos a criação de redes formais e informais de contatos que potencializam as oportunidades turísticas presentes e futuras.

Não se pode desconhecer que o nível de atenção e o apoio político e financeiro que um país ou uma região dá ao turismo não é uniforme. Na realidade, depende da percepção que o governo e as altas lideranças nacionais e locais tenham da relevância da atividade turística como geradora de emprego, renda, inclusão social e sustentabilidade. No México (OECD, 2018, p.232), por exemplo, o Plano de Desenvolvimento Nacional 2013-2018 reconhece o papel fundamental do turismo. No Japão (OECD, 2018, p.210), a Estratégia de Revitalização do Japão de 2016 identifica o turismo como um dos dez pilares do crescimento econômico. Na Suíça (OECD, 2018, p.281), o turismo é parte da Nova Política Regional. Diante dessas iniciativas, cabe a indagação: seria possível ter um Plano Regional de Promoção do Turismo para o Corredor Rodoviário Bioceânico?

Os países tampouco veem o turismo doméstico e o turismo internacional sob a mesma perspectiva. Em alguns países, o turismo nacional é visto como uma forma de enfrentar o desafio da sazonalidade, na medida em que permite a oferta de pacotes turísticos em diferentes meses do ano (por exemplo, no Brasil, quando cessa a estação de pesca, surge a oferta de fazendas-hotéis no Pantanal sul-mato-grossense). No entanto, essas iniciativas não devem se limitar à exploração dos produtos existentes. Podem também compreender o desenvolvimento de novos destinos turísticos: Israel oferece todo o ano o produto “deserto” (OECD, 2018, p.45) como atração turística alternativa a seus destinos tradicionais. Nesse contexto, há países que singularizam algumas de suas regiões, valorizando-as como uma experiência única e diferenciada, disponível todo o ano: a Irlanda promove a costa ocidental e suas cidades históricas com o programa “Wild Atlantic Way” (OECD, 2018, p.47), ou convida o turista para um novo “olhar” para a cidade de Dublin, com o programa “A Breath of Fresh Air”. A Itália (OECD, 2018, p.205), por sua vez, promove o “tracking” ao longo do ano com o programa “I Cammini d’Italia”. É,

possível, portanto, dispor de atividades turísticas que minimizem o impacto da sazonalidade.

O Corredor Rodoviário Bioceânico possibilita o desenvolvimento de programas similares, que valorizem a experiência de uma viagem pelo deserto de Atacama, a visita guiada por um biólogo a sítios naturais para conhecer a fauna e a flora, a hospedagem numa fazenda na região do chaco paraguaio para conhecer os costumes e a gastronomia do homem do campo, a visita para saborear os vinhos de montanha do norte da Argentina ou os pratos da gastronomia chilena. São inúmeras as atrações que podem ser exploradas comercialmente ao longo do ano, sem, necessariamente, enfrentar a restrição da sazonalidade.

Outro aspecto que também deve ser abordado é o interesse natural do indivíduo pelos destinos tradicionais, como Miami ou as capitais europeias. Nesse contexto, cabe aos agentes do Corredor divulgarem, por meio de técnicas agressivas de marketing turístico, as vantagens do Corredor e a qualidade dos serviços turísticos. Por meio de campanhas publicitárias adequadas e promoções comerciais focadas, é possível oferecer produtos customizados, que atendam a demandas específicas, geradas pela idade (no Chile, existe o Programa de Férias da Terceira Idade), pelo segmento geracional, seu nível de renda e gosto (pacotes para conhecer as vinícolas da região ou os melhores restaurantes) ou ainda pelo tamanho familiar e idade dos filhos (parques aquáticos e ecoturismo). É possível oferecer descontos para reservas antecipadas ou para grupos. Por meio do apoio de Associações (Associação de Hotéis e Restaurantes), clubes desportivos (golfe, futebol, canoagem, rugby e outros) oferecer uma experiência local a custo promocional ou ainda clínicas desportivas para praticantes de esportes.

Há segmentos da população que, mesmo com recursos para custear outras viagens, estariam propensos a conhecer as vinícolas argentinas e chilenas, a neve da Cordilheira dos Andes e as águas do Pacífico. Com a infraestrutura física que será implantada, o custo e o tempo de uma viagem internacional deverão se reduzir de forma expressiva. Hoje, um deslocamento aéreo a partir de Brasília requer longas conexões e penosos deslocamentos aéreos. Ademais, a variação cambial, a isenção de vistos e a possibilidade de viajar por terra e em veículo próprio são vantagens expressivas, em relação às viagens aéreas para destinos tradicionais, normalmente mais caros e distantes.

As entidades governamentais, promotoras do turismo pelo Corredor, poderiam aplicar recursos com vistas ao desenvolvimento de uma plataforma digital (*"Visit the Beauties of the Bioceanic Road Corridor"*), bem como negociar convênios com operadores turísticos internacionais (Expedia, por exemplo) ou com plataformas digitais de hospedagem mundialmente conhecidas, como a Trivago, para promover o Corredor como destino turístico. A digitalização está transformando o setor de turismo a um ritmo muito acelerado e os operadores regionais devem estar capacitados para responder aos desafios criados por um destino ainda pouco conhecido regional e globalmente.

Serviços logísticos são essenciais para o crescimento do setor do turismo. Na atualidade, não há voos internacionais que conectem Campo Grande a Assunção ou a Salta e Jujuy. Iquique é uma zona de livre comércio que atrai investidores dos quatro quadrantes do globo, mas são poucos os brasileiros que conhecem a cidade e as vantagens fiscais do comércio local. É difícil investir e controlar um negócio distante e de difícil acesso. A razão principal é a falta de voos diretos ou conexões amigáveis. Essa preocupação é ainda mais justificada na hipótese de se desejar atrair grupos específicos, como o turista idoso. Já o turismo corporativo ou de eventos é um

dos nichos turísticos mais lucrativos, mas ainda pouco explorado no Corredor.

Há necessidade de mais vôos diretos e regionais, conectando cidades do Corredor, inclusive vôos de companhias de baixo-custo. Não há necessidade de passar por Buenos Aires para se chegar a Salta ou por Santiago para visitar Antofagasta ou ainda por São Paulo para chegar a Campo Grande. Para promover o turismo, todo e qualquer tipo de barreira deve ser removida, seja ela de natureza física, econômica, legal, administrativa ou de transporte. Ademais, como assinalado, esforços devem ser empreendidos para, quando possível, customizar o pacote turístico, levando em conta a idade, a composição familiar, o nível de renda e o tipo de vida do turista. Deve-se dar atenção às novas formas de avaliação de serviços turísticos, como as *"reviews"* e as notas de usuários em sites especializados.

Fatores que estimulam os movimentos turísticos incluem, entre outros, uma boa acessibilidade, isenção de vistos, trânsito aduaneiro eficiente, sistemas informativos em vários idiomas (português e espanhol), facilidades para os deficientes físicos (a França (OECD, 2018, p.171) oferece o programa *"Tourisme et Handicap"*) ou a possibilidade de conexões multimodais nos grandes centros logísticos (avião, ônibus e veículo). Aviões poderiam ser fretados (vôos *charters*) para escolas, universidades ou empresas interessadas em passar uns dias em San Pedro de Atacama; as empresas de ônibus poderiam fazer o trajeto rodoviário de Salta/Jujuy para o destino final no Chile e se pagaria apenas um só valor (*"ticket integrado"*). Esse pacote poderia incluir hospedagem e alimentação, se necessário.

Em grandes centros urbanos, a exemplo de Campo Grande ou Salta, há também a possibilidade de compartilhamento de residências mediante o aluguel de quartos, o que reduz o custo da estada para um turista de menor poder aquisitivo. No entanto, para turistas exigentes, acostumados a frequentar bons hotéis, é necessário que as principais cidades do Corredor também estejam em condições de oferecer hotéis cinco estrelas. Uma grande cadeia hoteleira (Four Seasons, por exemplo) atrai um turista de maior poder aquisitivo e conhecimento, que busca qualidade, conforto e experiências diferenciadas. A relevância desse turista não é apenas o quanto ele gasta por dia, mas sua rede de contatos e amigos, capaz de multiplicar a divulgação do destino e atrair futuros turistas. O turista de alto poder aquisitivo deve ser visto, ainda, como um investidor em potencial. São conhecidos os casos de turistas estrangeiros que visitaram o Brasil se encantaram com a beleza das praias e a hospitalidade do brasileiro e investiram em pousadas ecológicas. Com políticas e mecanismos em favor de uma economia verde, é possível atrair investimento para projetos inovadores e sustentáveis, capazes de preservar o meio ambiente, promover a inclusão social e estimular a integração das pequenas e médias empresas.

4. Considerações Finais

Não há a menor sombra de dúvida que o turismo será importante fator de dinamização do Corredor Rodoviário Bioceânico. Com a possibilidade de realizar viagens frequentes aos países vizinhos e a um custo mais baixo, o indivíduo passará a ver a fronteira segundo uma outra perspectiva. Os indivíduos acumularão muito mais conhecimento e informação sobre a cultura do país vizinho, suas características, vantagens e fraquezas. Passará, portanto, a ver seu entorno geográfico, indo além da fronteira. Desse modo, eliminam-se algumas barreiras e se reduz progressivamente a desinformação, por vezes responsável por estereótipos equivocados.

O turismo atrairá mais investimento, emprego e renda, valorizando o intercâmbio cultural e a prestação de serviços de toda

natureza. Na esteira do aumento dos fluxos de comércio e investimento, as autoridades locais passarão também a interagir com maior frequência e intensidade. Como resultado, os “policy makers” passarão a ter maior sentido regional e maior sensibilidade para a integração na elaboração das políticas públicas.

No entanto, para que se produzam os efeitos desejados, faz-se necessário que se implante uma governança transnacional e tripartite, amparada em três pilares, o governo, o setor privado e a academia. O turismo tem, por sua natureza, uma tendência natural à fragmentação, devendo ser objeto de uma abordagem holística e multidisciplinar.

O planejador turístico deverá, também, estar atento às grandes transformações nacionais e às megatendências globais, de modo a desenvolver produtos customizados. Para tanto, deverá conhecer as potencialidades de todos os países do Corredor e não apenas as suas. A criação de instâncias permanentes de coordenação, o compartilhamento de informações e experiências, a promoção articulada de políticas inovadoras e a identificação de ações customizadas serão algumas das respostas necessárias para a dinamização do turismo no âmbito do Corredor Rodoviário Bioceânico.

É indiscutível que várias das propostas ou sugestões que venham a ser definidas exigirão recursos financeiros e humanos compatíveis. Aparentemente, essa necessidade poderia constituir uma barreira intransponível e, de antemão, levar ao imobilismo. Esse risco existe. No entanto, conforme indicado, o desenvolvimento de parcerias entre os órgãos públicos, o setor privado e a academia e o compartilhamento de informações e boas práticas, assim como o uso criterioso dos recursos humanos acadêmicos, permitem empreender ações efetivas com um baixo custo financeiro. Ademais, as fintechs, a utilização de instrumentos financeiros inovadores (“crowd-funding”, “green bonds”, entre outros) e a captação de investimentos nacionais e estrangeiros constituem possibilidades que poderiam ser exploradas, de modo a contornar as dificuldades financeiras conjunturais.

Na realidade, em se tratando da implantação do turismo no Corredor Rodoviário Bioceânico, cabe ressaltar que os países têm objetivos convergentes e, como resultado, devem estar dispostos a se ajudarem mutuamente, no entendimento de que os desafios são comuns e as soluções devem ser construídas por todos, de modo a gerar benefícios para todos.

Com objetivos estratégicos bem definidos, apoio político de alto nível, uma governança que favoreça a articulação entre todos os atores envolvidos, criam-se as condições para que se explorem as vantagens comparativas dinâmicas, se agregue valor aos serviços, se valorizem os territórios e o potencial turístico existente, se gere mais renda e emprego, beneficiando, em particular, as pequenas e médias empresas. A transformação da realidade deve ocorrer com o reconhecimento da necessidade de preservar os recursos naturais para as gerações futuras. O turismo não só transforma a realidade local, mas também sensibiliza o indivíduo para a proteção do meio ambiente, a necessidade de promover maior inclusão social e dar todo o apoio possível para a integração ordenada das famílias e comunidades em situação de vulnerabilidade.

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Rethinking Forest Conservation: The Genesis and Evolution of Community Forest Concessions as a Socio-Ecological Governance Model in Guatemala's Maya Biosphere Reserve

Article Record

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Abstract

This study analyzes the historical and institutional genesis of the community forest concessions model in the Maya Biosphere Reserve (MBR), Guatemala, as a case of socioecological transformation in tropical forest landscapes. Using a qualitative historical institutional approach. The research integrates literature review, document analysis and comparative perspectives to examine how the model emerged in response to structural conditions of rural poverty, insecure land tenure, agricultural frontier expansion and weak state presence. The findings show that the concession system evolved as an adaptive governance arrangement that aligned conservation objectives with local livelihoods through the combination of conditional use rights, community organization and economic incentives derived from sustainable forest management. The results indicate that areas under community concessions have maintained near-zero deforestation rates while generating local income, strengthening territorial governance and promoting institutional learning across multiple scales. The study demonstrates that the effectiveness of the model is not attributable to a single factor, but to the interaction of socio-ecological components, including land tenure as a concession's model, incentives, rules, capacities, and actors within a polycentric governance system. The case contributes to the literature by providing empirical evidence on how community-based forest management can reconcile conservation and development objectives. It also highlights key enabling conditions and limitations for policy design and replication in other tropical contexts.

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Rethinking Forest Conservation: The Genesis and Evolution of Community Forest Concessions as a Socio-Ecological Governance Model in Guatemala's Maya Biosphere Reserve

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Abstract

This study analyzes the historical and institutional genesis of the community forest concessions model in the Maya Biosphere Reserve (MBR), Guatemala, as a case of socioecological transformation in tropical forest landscapes. Using a qualitative historical-institutional approach. The research integrates literature review, document analysis and comparative perspectives to examine how the model emerged in response to structural conditions of rural poverty, insecure land tenure, agricultural frontier expansion and weak state presence. The findings show that the concession system evolved as an adaptive governance arrangement that aligned conservation objectives with local livelihoods through the combination of conditional use rights, community organization and economic incentives derived from sustainable forest management. The results indicate that areas under community concessions have maintained near-zero deforestation rates while generating local income, strengthening territorial governance and promoting institutional learning across multiple scales. The study demonstrates that the effectiveness of the model is not attributable to a single factor, but to the interaction of socio-ecological components, including land tenure as a concession's model, incentives, rules, capacities, and actors within a polycentric governance system. The case contributes to the literature by providing empirical evidence on how community-based forest management can reconcile conservation and development objectives. It also highlights key enabling conditions and limitations for policy design and replication in other tropical contexts.

Keywords: *Community sustainable forest management, Institutional innovation, Land tenure security, Polycentric governance, Rural livelihoods, Socio-ecological systems, Tropical deforestation*

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1. Introduction

Tropical deforestation remains one of the most critical global environmental challenges, with persistent losses of forest cover in biodiversity-rich regions (FAO, 2024). This phenomenon is closely associated with structural drivers such as rural poverty, agricultural frontier expansion and weak territorial governance, which together constrain the adoption of sustainable land-use practices (FAO, 2025a; FAO, 2025b; FAO, ILC & CIRAD, 2026; OECD et al., 2025). In Latin America, these dynamics are particularly pronounced in frontier regions characterized by insecure land tenure and limited state presence.

In response, a growing body of literature highlights community forest management as a viable pathway to reconcile conservation and rural development objectives (FAO, 2025; CIFOR, 2025). Evidence shows that some forests managed by local communities exhibit significantly lower deforestation rates compared to strictly protected areas lacking local engagement (Blackman et al., 2017; FAO, 2022), largely due to stronger territorial control and locally aligned incentives (World Bank, 2026). In the Maya Biosphere Reserve (MBR) of Guatemala, recent studies confirm that community forest concessions have maintained near-zero deforestation rates

25 - 30 years after the concessions model started while generating local income, employment and institutional strengthening (Stoian et al., 2018; Ureta et al., 2025; FAO, 2025).

These outcomes are consistent with contemporary theoretical frameworks, particularly socio-ecological systems (SES) and polycentric governance, which emphasize that sustainability emerges from the interaction of actors, rules, incentives and adaptive capacities across multiple levels (Ostrom, 2009; IPBES, 2025; CIFOR, 2025; Allen et al., 2025; Behboudian et al., 2025). In parallel, the literature underscores the importance of economic incentives (such as access to forest markets, value chains and ecosystem service mechanisms) in reducing pressure on forest resources, especially in contexts of rural poverty (Angelsen & Wunder, 2003; World Bank, 2025; FAO, 2025; Pascucci, 2025).

Despite this growing consensus, the emergence of successful community-based forest governance systems remains insufficiently understood from a historical and institutional perspective. In the case of the Maya Biosphere Reserve, the forest concession model did not result from a linear policy design, but rather from a complex process shaped by tensions between strict conservation approaches and sustainable use strategies, within a context of rural

poverty, land tenure insecurity and agricultural expansion during the early 1990s (FAO, 2025; World Bank, 2025).

Unlike exclusionary conservation models, the MBR incorporated a multiple-use zoning scheme that enabled the development of forest concessions as an innovative governance mechanism within protected areas (CONAP, 2001). However, the operationalization of this model was initially driven by external actors, including the OLAFO Project (CATIE) and the Rodale/Center Maya initiative - in coordination with national institutions, contributing to the gradual consolidation of a community-based forest management system (CIFOR, 2025).

Against this background, this study aims to analyze the historical and institutional process that led to the emergence and consolidation of the community forest concession model in the Maya Biosphere Reserve (MBR), Guatemala, and to assess its coherence with contemporary frameworks of socio-ecological systems and polycentric governance, contributing to ongoing debates on how community-based forest management can effectively address deforestation in tropical socio-ecological systems. By doing so, the study provides insights relevant for policy design and for the adaptation of similar models in other tropical contexts under comparable structural conditions.

2. Methodology

2.1. Research Approach

This study adopts a qualitative research design based on a historical-institutional approach, suitable for analyzing long-term transformations in complex socio-ecological systems (Mahoney & Thelen, 2010). The case of the MBR is examined as a critical case of institutional innovation in tropical forest governance.

The analysis is grounded in the recognition that the forest concession model emerged under specific structural conditions, including rural poverty, insecure land tenure, agricultural frontier expansion and weak state presence, factors commonly associated with deforestation dynamics in tropical regions (Curtis et al., 2018; FAO, 2025; Shumi et al., 2024).

2.2. Analytical Framework

The analytical framework integrates three interdependent dimensions that structure the interpretation of the forest concession process in the Maya Biosphere Reserve (MBR) (Figure 1).

These dimensions provide a systemic lens to analyze the interactions between ecological resources, institutional arrangements and socio-economic dynamics, enabling a comprehensive understanding of the model.

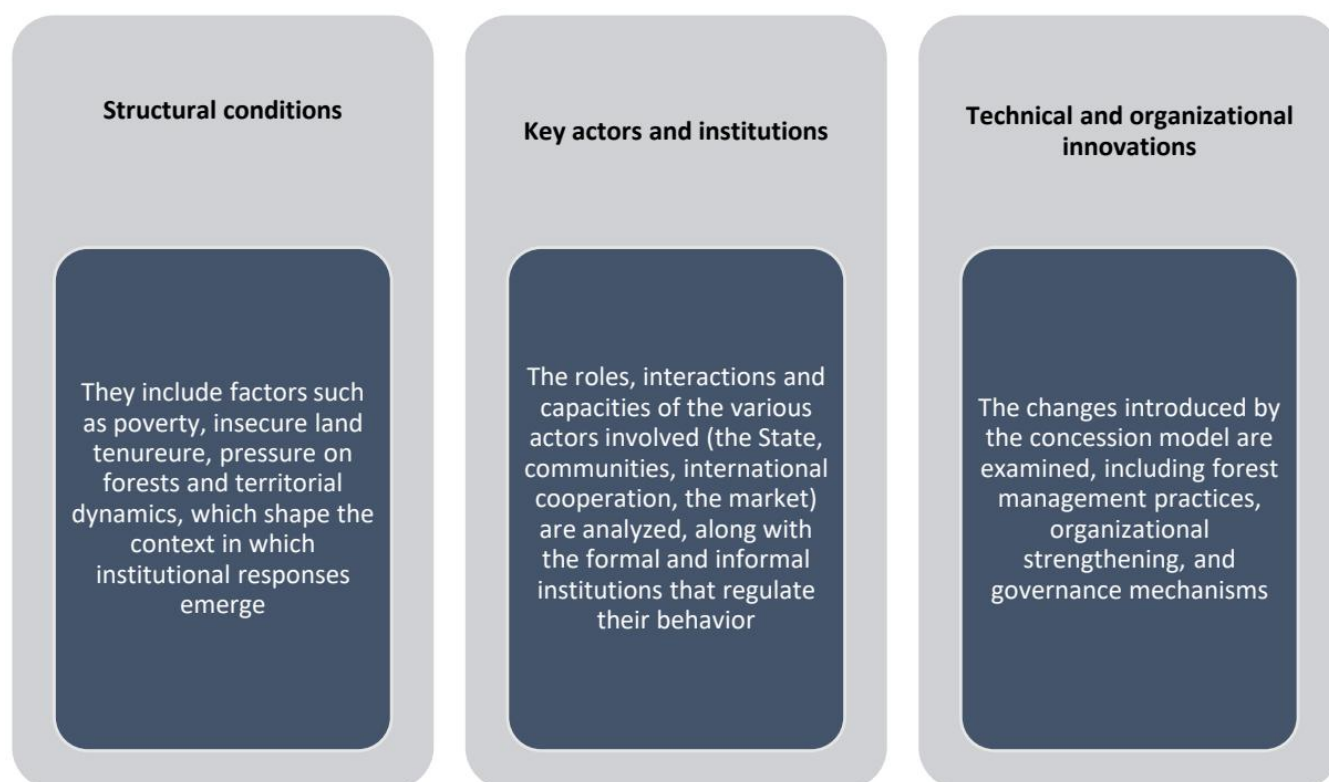


Figure 1. Interdependent dimensions of the analytical framework for the forest concession process in the Maya Biosphere Reserve, Petén, Guatemala.

The study is further guided by an integrated conceptual approach combining elements from socio-ecological systems (SEs), polycentric governance and community forest management (Figure 2). Rather than treating these as separate theoretical domains, they are operationalized as complementary analytical lenses to examine the interaction between actors, institutions and forest resources.

1 SOCIO-ECOLOGICAL SYSTEMS (SES)

It allow us to analyze the interactions between resources, actors, rules, and incentives (Folke et al., 2021).

2 POLYCENTRIC GOVERNANCE

It explains the coexistence of multiple decision-making centers and their contribution to the resilience of the system (Morrison et al., 2019).

3 COMMUNITY FOREST MANAGEMENT

Which provides evidence on the effectiveness of models based on local rights and economic benefits (Blackman et al., 2017).



Figure 2. Conceptual approaches applied to the forest concession process in Petén, Guatemala.

This integrated framework enables the interpretation of the forest concession model as an adaptive institutional arrangement emerging from the interaction of rules, incentives, capacities, and actors.

2.3. Research Design and Methods

The study is structured as an analytical case study, combining multiple methodological strategies:

- Systematic review of scientific literature on forest governance, socio-ecological systems and community forestry;
- Historical-documentary analysis to reconstruct the origin, design, and evolution of the concession model in the MBR;
- Comparative insights from international experiences to strengthen analytical generalization.

2.4. Data Sources

The analysis is based on triangulation of multiple sources, including:

- Peer-reviewed scientific literature;
- Primary institutional documents related to the concession process;
- Technical reports from international organizations (e.g., FAO, CIFOR) and recent empirical and policy-oriented studies (Allen et al., 2025; Cooper et al., 2025);
- Empirical evidence on the performance of community forest concessions in the MBR.

This triangulation enhances the robustness and validity of the findings.

2.5. Analytical Strategy

The case is analyzed as a long-term socio-ecological transition, in which outcomes related to forest conservation, governance and local livelihoods are understood as the result of dynamic interactions among structural conditions, institutional arrangements, and economic incentives.

From this perspective, the forest concession model is interpreted as an adaptive governance system, where conservation outcomes emerge from the alignment of incentives, rules, and local capacities within a multi-level institutional context.

Recent literature emphasizes that such systems must be analyzed through integrated approaches, where outcomes cannot be attributed to a single causal factor, but rather to the specific configuration of institutional arrangements and local capacities (Folke et al., 2021; FAO, 2025).

3. Results

The analysis of the design and implementation of the forest concession model in the MBR reveals a profound socio-ecological transformation. The system transitioned from a context characterized by high deforestation, weak governance and insecure land tenure toward a structured model of sustainable forest management based on rights, multi-level governance, and economic incentives.

3.1. Conceptual explanation of the model

3.1.1. Origin of the concessions

As part of global efforts to recognize the importance of forest biodiversity, the government of Guatemala created the MBR to preserve these fragile and threatened ecosystems. In a relatively short period of time, a marked polarization emerged between the human populations that entered the protected area through the slash-and-burn process and the entities associated with the MBR, while the central government prioritized a restrictive conservation model that initially left aside the realities and needs of local human populations.

The environmental crisis in the MBR reached a critical threshold during the late 20th century, exacerbated by government-mandated activities that led to widespread forest loss through fire. Consequently, international agencies and non-governmental organizations provided technical and strategic support to state institutions, aiming to stabilize the land-use boundary and prevent further forest loss to agricultural expansion.

The forestry concession model originated as an experimental initiative in sustainable forest management with the San Miguel La Palotada community. Comprising 30 families, the community managed a 7,039-hectare domain characterized by the extraction of non-timber forest products (NTFPs), including chicle (*Manilkara zapota*), xate palm (*Chamaedorea* spp. - whose leaves are used internationally in decorative form) and allspice (*Pimenta dioica*). These activities were supplemented by subsistence-level grain cultivation and traditional hunting.

The experimental framework was further tested through the community of La Pasadita. Managing roughly 18,000 ha, this 70-family collective engaged in the same extraction of chicle, xate and allspice as San Miguel; however, it also featured an existing livestock component. The inclusion of cattle fattening within the concession's boundaries marked a critical step in addressing the competition between forest conservation and traditional pastoral land uses.

This model of community concession implied the transfer of rights of use and decision-making from individuals to legally recognized collective entities and required compliance with a series of regulations, assigning the rights through renewable contracts of 25 years. To this end, the Conservation Project for Sustainable Development in Central America, popularly known as the OLAFO/CATIE Project, with donor funds from the Governments of Denmark, Norway and Sweden, and the executing entity CATIE (Tropical Agricultural Research and Higher Education Center), supported the efforts of the Government of Guatemala to create forest concessions in the Multi-Use Zone (MUZ) of the MBR.

Upon demonstrating that the community-based forest management model adhered to established sustainability standards, the National Council of Protected Areas (CONAP) formally granted the San Miguel La Palotada and La Pasadita concessions in 1994 and 1997, respectively. Following these successful pilots, CONAP authorized the scaling of the model to encompass approximately 500,000 hectares within the MUZ. Concurrently, USAID-Guatemala sanctioned a supporting forest concession program to facilitate management within the Maya Biosphere Reserve (MBR).

This has been one of the most serious attempts to formalize sustainable forest management in the region under community land tenure systems, albeit with limited rights.

3.1.2. The Allocation Process for Forest Concessions

It included the recognition of the physical presence of the community and the use of the timber and non-timber resources of the forest. The families that were part of the concessionaire communities also had rights to practice small-scale agriculture and livestock through silvo-agricultural and silvopastoral systems, as well as hunting and fishing.

The criteria considered for granting concessions to the community members were to have a physical presence in the areas requested under concession and to guarantee the sustainable management of natural resources through a contract with CONAP. The minimum organizational model that was found to support the organizations of groups of people who were not communities was that of "associations", which were not only easy to constitute administratively before the departmental government.

This figure of civil association served as the basic legal vehicle to provide legal personality to organized community groups, allowing them to comply with the administrative requirements necessary to formally sign concession contracts with the State.

The key steps to establish an association in Guatemala are those presented in Figure 3.

Constitutive Act	Convening a minimum of six individuals with full legal capacity to conduct the assembly, elect a provisional board of directors, and draft the founding minutes.
Drafting of bylaw	Establishing the bylaws to govern the association, including name, headquarters, duration, purpose, objectives, and the rights and duties of its members.
Notarization and Legal Formalization	Formalizing the minutes and bylaws through a public deed authorized by a notary public.
Legal Incorporation and Enrollment	Submit the documentation to the Civil Registry of the municipal seat or to the Registry of Legal Entities of the Ministry of the Interior, as applicable.
Registration with the Tax Administration Superintendency (SAT)	Once established, the association must be registered with the SAT to obtain a Taxpayer Identification Number, appoint an accountant, and, if applicable, apply for tax-exempt status.
Additional Requirements	Appointing a legal representative and ensuring the association's name does not conflict with an existing entity.

Figure 3. Steps to form an association in Guatemala.

While the “association” was formally registered, an informal community organization was used as a committee for the improvement of the place where they had invaded within the MBR; this as a basis for establishing the legal entity.

Once the concession contracts were acquired, they were formed as a broad scheme of conservation and sustainable development, with an essential role in the buffer zone of the protected areas.

The emerging regulatory framework for forest management introduced formal guidelines developed by the OLAFO Project and

CONAP. These rules were fundamentally shaped by the principles of sustainable natural resource management.

Timber management rights within the concessions were formalized by the State and monitored by CONAP. To mitigate risks associated with the communities’ lack of technical forestry experience, the State reserved the right to rescind contracts if management standards were not met.

The above is represented in Figure 4.



Figure 4. Initial and final conditions of the forest concession process for the Multiple Use Zone of the Maya Biosphere Reserve of Petén, Guatemala.

An aspect that is worth highlighting is that community forest management under **the concession scheme was inspired by a modality of generating sustainable management of**

resources through community social participation, which followed social democratic principles of work. Revenue from sustainable timber management was initially reinvested

into essential local infrastructure, including access roads, health centers, communal stores, schools and potable water systems, fostering social development. As technical capacity and harvest volumes grew, communities transitioned toward industrial value-addition, expanding into the production and export of processed timber. Currently, other products with greater added value are already sold and the wood is sold dry and complying with the requirements of the international FSC (Forest Stewardship Council) certifier, with whom the community concessions of Petén work.

In this sense, the certification of sustainable forest management was based on international standards and was adopted as the

official management standard. Therefore, the management plans of the concessions have support that guarantees their sustainable management at the international level, and imply general plans for 25 or more years, with five-year medium-term plans and annual operating plans. Likewise, as part of the awarding of the concessions, environmental impact studies were prepared, among others. Other requirements were subsequently added, such as the expansion of forest production to include a number of secondary timber species. In this way, the final design of the forestry concession model is shown in Figure 5.



Figure 5. Final conceptual model of the forest concession system in the Maya Biosphere Reserve, Guatemala.

3.2. Transformation of initial structural conditions

The forest concession model emerged as a response to three critical structural problems:

3.2.1. Land tenure insecurity

Prior to the implementation of the model, the absence of clear rights of use generated incentives for short-term exploitation, promoting processes of informal occupation, deforestation and speculative sale of land.

The introduction of forest concession contracts made it possible to:

- Establish conditional rights of use;
- Generate territorial security;
- Discourage the conversion of the forest to other uses.

This change was fundamental to reconfigure the incentives of local actors.

3.2.2. Rural poverty and dependence on unsustainable practices

The communities depended mainly on subsistence systems based on slash-and-burn, which implied constant expansion of the agricultural frontier.

The concession model enabled the following outcomes:

- Diversify sources of income;
- Generate local employment;
- Replace extractive practices with sustainable forest management.

3.2.3. Conflict of approaches in conservation

There was a strong tension between:

- Strict conservation (exclusion of communities);
- Sustainable use with an economic basis.

The concessions model partially resolved this tension through a hybrid scheme that integrated:

- Conservation;
- Production;
- Local governance.

These dynamics are detailed in Table 1.

Table 1. Initial conditions, concession model interventions and results observed in the Multiple Use Zone of the Maya Biosphere Reserve, Guatemala.

Initial structural condition	Previous dynamics	Intervention of the concession model	Observed Result
Insecurity of tenure	Informal occupation, speculative deforestation	Allocation of rights through concession contracts	Territorial security, and reduction of deforestation
Structural rural poverty	Slash-and-burn dependence	Forest income generation (timber and non-timber)	Economic diversification and reduced pressure on forest
Expansion of the agricultural frontier	Conversion from forest to agriculture	Economic incentives to keep the forest standing	Forest cover stabilization
Weak institutional presence	Lack of territorial control	State supervision (CONAP) and community monitoring	Effective territorial control
Conflict of approaches	Conservation vs. productive use	Hybrid model of sustainable use	Conservation-development integration

3.3. Analytical Structure of the Model

The concession model is supported by a diversified set of economic activities that link forest conservation with income generation. These include:

- Sustainable timber production (e.g., *Swietenia macrophylla*, *Cedrela odorata*) for national and international markets;
- Non-timber forest products such as xate (*Chamaedorea* spp.), chicle (*Manilkara zapota*) and allspice (*Pimenta dioica*);
- Agroforestry systems;
- Local value-added processing. These components constitute the economic foundation of the system, enabling the alignment of conservation incentives with local livelihoods (Ureta et al., 2025; Monroy Sagastume, 2025; Rodas et al., 2021; Stoian et al., 2018; Blackman et al., 2017).

3.4. Governance Arrangement: Core of the Model

The forest concession system is structured around three interdependent pillars:

■ RIGHTS

- Allocation of forest concessions;
- Conditional access to land tenure and forest resources for at least 25 years, renewable.

■ CAPACITIES

- Community organization;
- Technical training;
- Implementation of sustainable forest management practices.

■ RULES

- Approved management plans;
- State supervision (CONAP);
- Compliance with environmental and forestry regulations.

This configuration reflects a system of conditional tenure, where access to resources is contingent upon compliance with sustainability standards.

3.5. Transformation of Structural Conditions

The concession model emerged as a response to three critical structural constraints:

3.5.1. Land Tenure Insecurity

Prior to implementation, unclear tenure arrangements incentivized short-term resource extraction, land speculation and deforestation.

The introduction of concession contracts resulted in:

- Defined and conditional use rights;
- Increased tenure security;
- Reduced incentives for forest conversion.

3.5.2. Rural Poverty and Unsustainable Practices

Local livelihoods were largely dependent on shifting cultivation (slash-and-burn), driving continuous agricultural expansion.

The concession model enabled:

- Income diversification;
- Local employment generation;
- Transition toward sustainable forest-based livelihoods.

3.5.3. Conflict between Conservation Approaches

A fundamental tension existed between:

- Strict conservation (exclusionary approach);
- Productive use of forest resources.

The concession model partially resolved this conflict through a hybrid approach integrating conservation, production, and local governance.

3.6. Environmental Outcomes

Environmental results represent one of the most robust findings of the study:

- Significant reduction in deforestation, with near-zero rates in concession areas;
- Maintenance of forest cover relative to non-concession areas;
- Conservation of biodiversity within managed landscapes.

These results demonstrate a transition from active degradation to functional conservation.

3.7. Socioeconomic Outcomes

The model established a forest-based economic system that aligns conservation with livelihoods:

- Increased local income from timber and non-timber products;
- Employment generation within communities;
- Investment in public goods, including education, health, and infrastructure.

Importantly, benefits are both individual and collective, reinforcing social cohesion and institutional legitimacy.

3.8. Governance and Institutional Outcomes

The concession model consolidated a polycentric governance system characterized by:

- Strengthened community organizations;
- Development of technical capacities;
- Implementation of formal rules and management systems;
- Multi-level coordination among communities, government and international actors.

A key outcome is effective territorial control, where communities actively engage in monitoring, enforcement and prevention of illegal activities.

3.9. Productive System and Market Integration

The model established a productive system based on maintaining the forest standing, including:

- Sustainable timber harvesting;
- Non-timber forest product commercialization;
- Value-added processing;
- Forest certification (FSC).

This enabled:

- Integration into international markets;
- Increased economic value of forest resources;
- Stable incentives for conservation.

3.10. Institutional Innovation

The concession model represents a complex institutional innovation emerging from the interaction of:

- State institutions (CONAP);
- Local communities;
- International cooperation (OLAFO/CATIE, Rodale, USAID, among others).

The system is structured around:

- Long-term conditional rights (25-year renewable contracts);
- Strengthened local capacities and community enterprises;
- Formal regulatory frameworks combined with certification mechanisms.

3.11. Integrated Interpretation: Socio-Ecological Transition

Overall, the results indicate that the MBR concession model constitutes a socio-ecological transition characterized by:

From:

- Deforestation
- Tenure insecurity
- Rural poverty
- Weak governance

To:

- Forest conservation
- Defined resource rights
- Forest-based local economies
- Effective territorial governance

The transition reflects a systemic reconfiguration driven by the alignment of incentives, institutional arrangements and local capacities.

4. Discussion

The results obtained in this study confirm that the forest concession model of the Maya Biosphere Reserve (MBR) constitutes a case highly consistent with contemporary approaches of socio-ecological systems, polycentric governance and community forest management. However, beyond its coherence with the existing literature, the case provides additional elements that allow us to deepen the understanding of the processes of institutional transformation in complex tropical contexts.

First, the analysis shows that the performance of the model cannot be explained by a single causal factor, but by the systemic configuration of multiple interdependent components, as summarized in Table 2. This configuration clearly reflects the structure of a socio-ecological system (SES), where the interaction between resources, actors, rules, incentives and capacities generates positive feedback dynamics that favor the sustainability of the system.

Table 2. Configuration of the socio-ecological system (SES) of the Maya Biosphere Reserve (MBR) of Guatemala.

SES Component	Elements in MBR	Function in the system	Result
Resource	Tropical forest (timber and non-timber)	Ecological basis of the system	Forest cover conservation
Actors	Communities, CONAP, international cooperation	Management, regulation and technical support	Multi-level governance
Rules	Concession contracts, management plans, FSC certification	Regulation of the use of the resource	Sustainable management
Incentives	Forest revenues, access to markets	Alignment of economic interests	Reducing deforestation
Capabilities	Community organizing, technical knowledge	Implementation of forest management	Operational efficiency
Interactions	Multi-level coordination and learning	System Adaptation	Socio-ecological resilience

Table 3. Dimensions, indicators and implications of the forest concession model of the Maya Biosphere Reserve of Petén, Guatemala by analytical dimension.

Dimension	Key indicators	Observed results	Implications
Environmental	Deforestation, forest cover, biodiversity	Deforestation rates close to zero	Validation of community forest management as a conservation strategy
Socioeconomic	Income, employment, social investment	Increased income, local employment, investment in community services	Poverty reduction and strengthening social capital
Institutional	Governance, regulatory compliance, territorial control	Organizational strengthening, community monitoring, multilevel articulation	Consolidation of polycentric governance
Productive	Forest production, value added, markets	Community Forest Enterprise Development, FSC Certification	Market insertion and economic sustainability

In particular:

- It coincides with evidence showing that community participation reduces deforestation (Blackman et al., 2017).
- It reinforces the hypothesis that economic incentives are key to conservation (Angelsen & Wunder, 2003).
- It validates the principles of polycentric governance (Ostrom, 2009).

Likewise, the case provides empirical evidence on the importance of institutional innovation processes as shown in Table 3 driven from the territory, rather than from centralized designs.

In this sense, the results observed in the MBR reinforce the hypothesis put forward in the recent literature that sustainability in tropical forest systems depends less on the restriction of access to the resource and more on the quality of the institutional arrangements that regulate its use. This finding is particularly relevant, as it implicitly questions traditional approaches to exclusionary conservation, showing that the inclusion of local actors under regulated conditions can generate better results in terms of conservation.

4.1. Systemic Nature of the Forest Concession Model

The findings confirm that the forest concession model in the MBR cannot be explained through a single causal mechanism, but rather as the outcome of a complex configuration of interdependent socio-ecological components. This aligns with the socio-ecological systems (SES) framework, which conceptualizes sustainability as an emergent property arising from interactions among resources, actors, institutions, and feedback mechanisms (Folke et al., 2021; Ostrom, 2009).

In the MBR, conservation outcomes, particularly near-zero deforestation rates, are associated with the combined effect of clearly defined use rights, locally embedded governance structures, economic incentives, and adaptive institutional arrangements, rather than solely with legal protection or enforcement. This

systemic configuration reinforces recent findings that emphasize the importance of integrated institutional settings in sustaining forest landscapes under pressure (CIFOR, 2025; FAO, 2025; Allen et al., 2025; Behboudian et al., 2025).

4.2. Polycentric Governance, Power and Institutional Coordination

The MBR concession system provides strong empirical support for the theory of polycentric governance, demonstrating how multiple centers of decision-making (communities, state institutions and international actors) can interact to produce effective governance outcomes (Ostrom, 2009; Gatto et al., 2022; Schlager, 2025).

Rather than generating fragmentation, the coexistence of these actors enabled coordination, learning and adaptation across scales. This finding is consistent with recent literature suggesting that polycentric systems are particularly effective in managing complex environmental challenges when supported by coordination mechanisms, clear rules, and differentiated institutional capacities (Kellner, 2024; Enberg, 2025).

However, recent advances in literature highlight that polycentric governance must also be understood through the lens of power relations. Morrison et al. (2019) emphasizes that power asymmetries among actors can shape decision-making processes and influence outcomes within polycentric systems. The MBR case suggests that, while external actors (e.g., international cooperation) played a critical role in initiating the model, the gradual strengthening of community organizations helped rebalance power relations, enabling more equitable governance outcomes.

Similarly, Djenontin and Larson (2025) highlight that effective forest governance depends on the interaction between formal institutions and locally embedded governance systems. The MBR experience confirms this interaction, where state regulation, community organization and external support converged to create a functional governance arrangement.

Furthermore, Faboye (2024) emphasizes the role of hybrid governance systems in which formal and informal authorities

coexist and complement each other. This is particularly evident in the MBR, where community norms and organizational structures operate alongside formal regulatory frameworks, reinforcing system effectiveness.

4.3. Community Forest Management as a Conservation Strategy

The results reinforce the growing body of evidence positioning community forest management (CFM) as a viable alternative to exclusionary conservation models. In line with previous studies, the MBR demonstrates that community-managed forests can achieve equal or superior conservation outcomes compared to strictly protected areas (Blackman et al., 2017; FAO, 2022; Ureta et al., 2025; Shivani et al., 2022).

Importantly, the case highlights that the effectiveness of CFM is not automatic, but contingent upon enabling conditions such as tenure security, organizational capacity, market access and institutional support (Kimengsi et al., 2023; Tiki et al., 2025). The MBR experience illustrates how these factors can be combined to create a functional governance system capable of controlling deforestation and generating local benefits.

Moreover, the findings support recent international evidence showing that participatory forest management contributes not only to conservation outcomes, but also to livelihood improvements and territorial governance (Ota et al., 2023; Sarun et al., 2025; Loomis et al., 2024).

4.4. The Central Role of Economic Incentives

One of the most significant contributions of this study is the empirical confirmation that economic incentives constitute a structural pillar of conservation in tropical forest systems. The MBR model demonstrates that conservation becomes viable when local actors derive tangible benefits from maintaining the forest standing.

This finding is consistent with the foundational work of Angelsen and Wunder (2003) and with more recent analyses emphasizing the role of forest-based value chains, ecosystem services, and market integration in reducing deforestation pressures (World Bank, 2025a; FAO, 2025; World Bank, 2025b).

However, the results also highlight that incentives must be embedded within robust institutional frameworks. Without clear rules and monitoring mechanisms, economic incentives may lead to resource overexploitation rather than conservation. Thus, the effectiveness of incentives depends on their interaction with governance structures and tenure arrangements.

4.5. Institutional Innovation and Adaptive Governance

The MBR concession model represents a case of incremental institutional innovation, emerging from a process of experimentation, adaptation, and learning rather than from a predefined policy design (Mahoney & Thelen, 2010; Pascucci, 2025).

The model evolved through pilot experiences, scaling processes, and the progressive incorporation of actors and institutional arrangements. This adaptive pathway allowed the system to respond to changing environmental, social and political conditions, reinforcing its resilience.

Additionally, the interaction between formal institutions and informal governance systems proved critical. This finding is consistent with literature emphasizing that institutional complementarity (rather than institutional substitution) is key for effective forest governance (López-Vargas et al., 2023; Djenontin & Larson, 2025).

4.6. Territorial Governance and Control

A particularly relevant finding is the emergence of effective territorial control exercised by community concessionaires. Unlike centralized enforcement models, governance in the MBR is grounded in continuous local presence, social legitimacy, and aligned incentives.

This hybrid governance arrangement (combining state oversight with community-based monitoring) has proven effective in preventing illegal activities and maintaining forest cover. Similar findings have been reported in other tropical contexts, where community involvement enhances compliance and enforcement capacity (Forest Declaration Assessment, 2025; Ureta et al., 2025; Cooper et al., 2025).

4.7. Limitations and Enabling Conditions

Despite its success, the MBR model is not free from limitations. Key constraints include:

- Dependence on international cooperation;
- High transaction and compliance costs;
- Uneven organizational capacities;
- Persistent external pressures such as agricultural expansion and illegal activities.

These findings confirm that the model's success depends on specific enabling conditions, reinforcing the argument that community forest management systems require contextual adaptation rather than direct replication (Kimengsi et al., 2023; Tiki et al., 2025; Shumi et al., 2024).

4.8. Implications for Policy and Replicability

The MBR case provides several relevant lessons for forest policy:

- Conservation and production can be compatible under appropriate institutional arrangements;
- Conditional tenure rights are more effective than exclusionary approaches in frontier contexts;
- Polycentric governance requires coordination and institutional clarity;
- Economic incentives must be aligned with governance systems.

However, replicability should focus on underlying principles (such as institutional alignment, tenure security and incentive structures) rather than attempting to replicate the model as a fixed blueprint.

5. Conclusions

This study analyzed the historical and institutional genesis of the community forest concession model in the Maya Biosphere Reserve (MBR), Guatemala, and assessed its coherence with contemporary frameworks of socio-ecological systems and polycentric governance. The findings strongly support that the effectiveness of the model is associated with the systemic interaction of institutional arrangements, economic incentives, and local capacities.

First, the study demonstrates that the forest concession model constitutes a successful example of socio-ecological transformation. The transition from a context of high deforestation, insecure land tenure and weak governance toward a system characterized

by forest conservation, defined use rights and effective territorial governance reflects a structural reconfiguration of the relationship between society and forest ecosystems. This transformation highlights the importance of aligning incentives, institutions, and local actors in the management of common-pool resources.

Second, the findings confirm that community forest management can effectively reconcile conservation and development objectives when supported by enabling conditions such as tenure security, organizational capacity and access to markets. In the MBR, the combination of conditional use rights, community organization and forest-based economic activities has generated a system in which conservation outcomes and local livelihoods are mutually reinforcing.

Third, the study provides empirical support for polycentric governance theory by demonstrating how multiple centers of decision-making (local communities, state institutions and international actors) can interact to produce effective governance outcomes. However, the results also indicate that the effectiveness of such arrangements depends on coordination mechanisms, institutional clarity and shared objectives, rather than on the mere existence of multiple actors.

Fourth, the analysis highlights the central role of economic incentives in sustaining conservation outcomes. The MBR model shows that forest conservation becomes viable when it is economically competitive with alternative land uses. At the same time, the study underscores that incentives must be embedded within robust institutional frameworks to prevent resource overexploitation and ensure long-term sustainability.

Fifth, the study reveals that the forest concession model emerged through a process of incremental institutional innovation rather than through a predefined policy design. This adaptive trajectory (characterized by experimentation, learning and gradual scaling) was critical for the consolidation of the model and its capacity to respond to changing socio-environmental conditions.

Despite its success, the model also faces important limitations, including dependence on external support, uneven institutional capacities and persistent external pressures on forest resources. These findings suggest that the replication of the model requires careful consideration of local conditions and cannot be achieved through simple policy transfer.

Overall, the MBR concession model represents a relevant empirical case demonstrating that conservation in tropical forest landscapes is more effective when based on adaptive governance systems that integrate local actors, economic incentives, and multi-level institutional arrangements. The main contribution of this study lies in showing how such configurations can emerge and stabilize over time, offering valuable lessons for forest policy and governance in other tropical regions facing similar challenges.

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Ecological Collapse and Hypereutrophication in Lake Patzcuaro

Article Record

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Abstract

This study evaluates the physicochemical degradation of Lake Patzcuaro (Mexico), driven by agro-industrial expansion—with 4,806 hectares of new avocado monocultures—and by untreated urban wastewater discharges. Based on multiparametric primary field data collected between 2019 and 2026, including radial sampling around Tecuenita Island, critical anomalies were identified, such as temperatures reaching 31°C, extreme alkalinity with pH levels of 12, and severe hypoxia with dissolved oxygen below 1 mg/L. The comparative historical analysis shows that water quality parameters far exceed current national standards, with electrical conductivity above 1,000 $\mu\text{S}/\text{cm}$, turbidity of 225.6 NTU, and an organic load of 16.3 mg/L BOD₅. The loss of 684 hectares of biofiltration wetlands in the basin correlates directly with the lake's advanced hypereutrophic state, characterized by high concentrations of fecal coliforms and recurrent algal blooms. The results highlight the urgent need for effective environmental governance and concrete hydrological restoration measures to halt a degradation process that, if allowed to continue, will likely become irreversible.

Hypereutrophication

Water Quality

Land Use Change

Physicochemical Analysis

Avocado Monoculture

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Ecological Collapse and Hypereutrophication in Lake Patzcuaro

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Abstract

This study evaluates the physicochemical degradation of Lake Patzcuaro (Mexico), driven by agro-industrial expansion—with 4,806 hectares of new avocado monocultures—and by untreated urban wastewater discharges. Based on multiparametric primary field data collected between 2019 and 2026, including radial sampling around Tecuenita Island, critical anomalies were identified, such as temperatures reaching 31°C, extreme alkalinity with pH levels of 12, and severe hypoxia with dissolved oxygen below 1 mg/L. The comparative historical analysis shows that water quality parameters far exceed current national standards, with electrical conductivity above 1,000 µS/cm, turbidity of 225.6 NTU, and an organic load of 16.3 mg/L BOD₅. The loss of 684 hectares of biofiltration wetlands in the basin correlates directly with the lake's advanced hypereutrophic state, characterized by high concentrations of fecal coliforms and recurrent algal blooms. The results highlight the urgent need for effective environmental governance and concrete hydrological restoration measures to halt a degradation process that, if allowed to continue, will likely become irreversible.

Keywords: *Hypereutrophication, Water Quality, Land Use Change, Physicochemical Analysis, Avocado Monoculture*

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1. Introduction

Accelerated eutrophication of lacustrine ecosystems due to human pressure is one of the most widespread ecological crises globally. Lake Pátzcuaro, situated at 2,040 meters above sea level in west-central Mexico, forms part of the endorheic basin of the Upper Lerma River. This system is particularly significant because it combines open-water areas with extensive wetlands, making it a vital refuge for several species. Historically, the lake has served as a critical habitat for endemic species such as the whitefish (*Chirostoma estor*), the achoque salamander (*Ambystoma dumerilii*), and the Transvolcanic yellowthroat (*Geothlypis speciosa*). The survival of these species depends largely on water quality and stable aquatic environmental conditions.

In recent decades, however, the lake has undergone rapid and severe degradation. Previous studies had already documented initial signs of alteration, including an early mesotrophic condition and a progressive increase in phosphorus levels. This has been compounded by the uncontrolled growth of human settlements around the lake. Many of these areas lack adequate drainage and wastewater treatment, allowing domestic waste to enter the water body directly. This organic pollution is exacerbated by agricultural runoff containing large quantities of fertilizers and herbicides.

Although various studies have addressed lake contamination, there remains a need for clearer integration of forest cover loss caused by agro-industrial expansion with in-situ physicochemical deterioration. Given the observed shifts in the lake's flora and fauna—including invasion by exotic species such as *Eichhornia crassipes* (water hyacinth), *Eucalyptus* and *Casuarina* in terrestrial zones, and *Cyprinus carpio* (common carp) in the aquatic environment—this study seeks to quantify levels of organic, chemical, and thermal pollution in Lake Pátzcuaro. It examines the relationship between land-use changes in forested areas of the basin (2000-2023) and water

quality, based on field measurements conducted between 2019 and 2026.

The working hypothesis posits that the expansion of export-oriented agriculture and unplanned urbanization have exerted intense pressure on water resources. This pressure is associated with critical forest loss and risks to the ecotone; the immediate outcome is evident deterioration in basin water quality, increased environmental risk for local populations, and heightened vulnerability regarding the availability of water for human consumption.

2. Materials and Methods

2.1. Study Area and Spatial Dynamics

The study encompassed the main water body and the shared basin of the municipalities of Pátzcuaro, Erongarícuaro, Tzintzuntzan, and Quiroga. Water sampling stations included direct discharge zones and peninsular areas: San Pedrito, Chupícuaro, Ucazanaztacua, Tzurumutaro, and Tecuenita Island.

2.2. In-Situ Sampling Protocols

Data were drawn from experimental campaigns conducted in 2019-2020 and an intensive update campaign in May 2026. In 2026, radial sampling was performed at 45-degree intervals to cover the eight cardinal directions around Tecuenita Island, regarded as a key visual indicator of the lake's volume and condition. In-situ measurements were taken by submerging sensors for 5-minute stabilization intervals using a Hanna multiparametric meter and an MBL Sciencecube system equipped with pH, temperature, and turbidity sensors.

In accordance with standard pH measurement protocols, both the HANNA multiparameter meter and the Science Cube system were calibrated using pH 4.0, 7.0, and 10.0 buffer solutions to ensure data reliability. Measurements with the HANNA instrument were

conducted in situ by submerging the probe at the lake’s shoreline for five minutes per sample. Conversely, for the Science Cube unit, a sample was collected in a beaker with sufficient volume to fully submerge the sensors while running the logging software on a laptop for one minute.

2.3. Geographic Database Management

Data on avocado monoculture expansion and wetland (tule) loss were obtained by cross-referencing municipal Urban Development Plans

and satellite records (2000-2023), establishing metrics in hectares (ha) by land-cover type.

2.4. Characterization of Ecological Requirements of Target Species

2.4.1. Achoque (*Ambystoma dumerilii*)



Figure 1. Photograph of the achoque, obtained from: <https://oem.com.mx>

The achoque or Lake Pátzcuaro salamander (*Ambystoma dumerilii* Dugès, 1870) is a paedomorphic salamander of the family Ambystomatidae, endemic to Lake Pátzcuaro, Michoacán. Its distribution is highly restricted, occupying an area of less than 10 km² (Aguilar-Miguel, 2005). It reaches approximately 25 cm in total length, remains fully aquatic throughout its life, and reproduces in spring, laying between 100 and 600 eggs (Aguilar-Miguel and Casas-Andreu, 2005). Since pre-Hispanic times, the Purépecha people have used it as food and in traditional medicine, a practice that continues today in the preparation of “achoque syrup” (Huacuz-Elías, 2002). The IUCN categorizes it as Critically Endangered (CR), and NOM-059-SEMARNAT-2010 lists it under Special Protection (Pr). Its main threats are pollution, lake eutrophication, and the presence of invasive species (IUCN SSC Amphibian Specialist Group, 2020; SEMARNAT, 2010).

2.5. Water Quality Requirements

Table 1. Water requirements for the achoque (own elaboration)

Parameter	Required Condition
Temperature	16-22°C
Dissolved Oxygen	High (> 5mg/L recommended for aquatic amphibians)
pH	Near neutral (6.5-8.0)
Turbidity	Low
Contaminants	Absence of toxins, heavy metals, and wastewater discharges

The Mexican Institute for Sustainable Fisheries and Aquaculture Research (IMIPAS) indicates that variations outside the thermal range of 16-22°C, habitat fragmentation, loss of aquatic vegetation, and the presence of toxins cause stress and disease in the species.

2.6. Soil and Habitat Requirements

- Lake bottoms with soft sediments.
- Abundant submerged and emergent vegetation.
- Shallow areas for refuge and feeding.
- Low anthropogenic disturbance.

2.7. Climatic Requirements

- Temperate sub-humid climate.
- Low annual thermal variation.
- Stable hydrological regime that maintains adequate lake levels.

2.7.1. Pescado blanco de Pátzcuaro (*Chirostoma estor*)



Figure 2. Photograph of the whitefish, obtained from: <https://www.gob.mx>

The whitefish (*Chirostoma estor* Jordan, 1879), whose subspecies *C. e. estor* has its type locality in Lake Pátzcuaro, is a fusiform medium-sized fish with a silvery lateral band, two dorsal fins, and a terminal mouth directed upward. It can reach 40 cm in length and 500g in weight (Chacón-Torres and Rosas-Monge, 1995). It inhabits slow-moving, semi-warm waters with pH values between 7.2 and 8.2, prefers rocky shores with filamentous algae, and spawns oviparously between March and May (Chacón-Torres and Rosas-Monge, 1995). Of great sociocultural importance since pre-Hispanic times, it was for decades the main fishery resource for lakeshore communities. However, overexploitation, pollution, and the introduction of exotic species reduced commercial catches from 122.6 tons in 1982 to only 13.0 tons in 1996 (Hernández-Montaño, 2002).

2.8. Water Quality Requirements

It has been documented that the species inhabits slow, semi-warm waters with pH between 7.2 and 8.2 and oxygen concentrations between 4 and 8mg/L. During reproduction, it requires clear, well-oxygenated waters.

Table 2. Water requirements for the whitefish (own elaboration)

Parameter	Required Condition
Temperature	Semi-warm waters (approx. 18-24°C)
Dissolved Oxygen	4-8mg/L
pH	7.2-8.2
Transparency	Medium to high
Turbidity	Moderate; tolerates certain levels

2.9. Soil and Habitat Requirements

- Rocky shores.
- Presence of filamentous algae for spawning.
- Silty and sandy bottoms.
- Aquatic vegetation serving as refuge.

2.10. Climatic Requirements

- Temperate climate of the Mexican highlands.
- Hydrological stability during spring (reproductive season).
- Sufficient rainfall to maintain lake levels.

2.10.1. Transvolcanic Yellowthroat (*Geothlypis speciosa*)



Figure 3. Photograph of the Transvolcanic yellowthroat, obtained from: <https://ebird.org>

The Transvolcanic yellowthroat (*Geothlypis speciosa* Sclater, 1859), also known as the Lerma yellowthroat or black-capped warbler, is a passerine bird of the family Parulidae endemic to the Neovolcanic Axis of Mexico. Its active distribution is restricted to five localities in Michoacán, Guanajuato, and the State of Mexico, including Lake Pátzcuaro (BirdLife International, 2020). The male displays a black mask that blends into an olive-yellowish green back, with intense golden-yellow underparts and dark legs, while the female is duller and shares the dark legs as a distinguishing feature from related species (eBird/Cornell Lab, 2024). It inhabits exclusively lacustrine tule marshes composed of *Typha* sp. and *Scirpus* sp. Only about 8,300 hectares of this habitat remain nationwide, with nearly 80% concentrated in the Michoacán lakes of Cuitzeo, Pátzcuaro, and Zirahuén (Agua.org.mx, 2010). The IUCN categorizes it as Vulnerable (VU), and NOM-059-SEMARNAT-2010 lists it as endangered. Its population is estimated at between 1,500 and 7,000 mature individuals and has been in steady decline since the 1980s (BirdLife International, 2020; SEMARNAT, 2010).

2.11. Water Quality Requirements

Although it does not depend directly on specific physicochemical parameters like fish or amphibians, it requires stable environmental conditions. The degradation of wetlands through water extraction and pollution constitutes one of its main threats.

2.12. Soil and Habitat Requirements

- Permanent wetlands.
- Tule and reed beds dominated by *Typha* and *Scirpus*.
- Hydromorphic saturated soils.

Table 3. Water requirements for the Transvolcanic yellowthroat (own elaboration)

Parameter	Required Condition
Water Quality	Good
Nutrients	Moderate
Pollution	Low
Water Level	Stable

- Marshy areas and floodplains.
- The species is found primarily in cattail (*Typha* spp.) and tule (*Scirpus* spp.) marshes associated with freshwater wetlands.

2.13. Climatic Requirements

- Temperate sub-humid mountain climate.
- Altitudes between 1,800 and 2,600m a.s.l.
- Permanent presence of wetlands throughout the year.

3. Results

3.1. Landscape Alteration and Loss of Biofilters

Spatial analysis reveals a severe and largely irreversible transformation of the lacustrine landscape. In the municipality of Pátzcuaro, the area dedicated to intensive avocado cultivation expanded dramatically from 87.70 hectares in 2000 to 4,894.16 hectares in 2023-an increase of nearly 5,000 hectares. Concurrently, traditional agriculture lost 4,323.08 hectares, and pine-oak forests receded by 1,260.60 hectares.

This agro-industrial conversion directly affected tule wetlands, which are essential for sediment biofiltration and pollutant retention before inflows reach the lake basin. Tule areas in Pátzcuaro decreased from 961.34 to 547.65 hectares.

Table 4. Land Use in Pátzcuaro (own elaboration)

Land Use (Pátzcuaro)	Area 2000 (ha)	Area 2023 (ha)
Agriculture (avocado)	87.70	4,894.16
Tular (Wetlands)	961.34	547.65
Traditional agriculture	18,061.42	13,738.34
Forest	21,612.52	20,351.92

The dynamics of biofilter loss are even more drastic in the municipality of Tzintzuntzan. Records document an increase in avocado hectares, from 5 to 59, while the forest lost 1,398.71 hectares. The most critical issue is the almost total eradication of the riparian strip in this municipality, where the tulares (reed beds/wetlands) went from 293.66 hectares to only 22.71 hectares in the same period.

Table 5. Land use in Tzintzuntzan (own elaboration)

Land Use (Tzintzuntzan)	Area 2000 (ha)	Area 2023 (ha)
Agriculture (avocado)	5	59
Tular (Wetlands)	293.66	22.71
Traditional agriculture	5,743.98	6,384.98
Forest	5,999.25	4,600.54

3.2. Historical Evolution of Water Quality (1990-2024)

The environmental deterioration caused by urban discharges and agricultural runoff has been progressive. A retrospective historical analysis integrating data from Jiménez Baltazar et al., Huerto Delgadillo et al., Tomasini Ortiz et al., and the authors' own samplings demonstrate that the lake's self-purification capacity has been exceeded.

In the 1990s and early 2000s, BOD₅ (Biochemical Oxygen Demand) levels averaged 5.15mg/L, remaining within healthy limits. However, more recent studies (2019-2024) document that the organic load permanently exceeds permissible limits, reaching averages of 16.3mg/L, with peaks of over 130mg/L in direct discharge zones. Total phosphorus has far exceeded the preventive limit of 0.1mg/L, recording values from 0.92mg/L to 1.10mg/L, confirming that the lake is in a state of chronic hypereutrophication.

Current turbidity has reached extreme values of 225.61UNT (exceeding the clean water limit of 5UNT from the NOM-127-SSA1 standard by up to 50 times). This is accompanied by increasingly hard and mineralized water, with an electrical conductivity of 770.05 μ S/cm and 385.02ppm of Total Dissolved Solids (TDS), a direct product of erosion from deforestation and sediments that wash fertilizers into the basin.

3.3. Thermal and Alkalinity Anomalies (2026 Field Campaign)

During May 2026, an intensive radial sampling was conducted on Tecuenita Island, an area geographically in the heart of the lake and considered a critical visual reference by the local population (under the premise "if Tecuenita grows, the lake dies"). The results show critical overheating: compared to historical averages of 17.15°C, the water temperature ranged between 27.83°C and 31.11°C. This thermal anomaly is a direct biophysical consequence of the aforementioned land-use change; the loss of vegetative canopy has induced a severe increase in surface soil temperatures, a condition corroborated in situ through the deployment of stem thermometers across the island. During precipitation events, surface runoff flows over these thermally elevated bare soils, acting as a convective heat vector that transfers thermal energy directly into the lacustrine system, escalating ambient, substrate, and water temperatures well above the 25°C threshold.

Model of Anomalous Heat Transfer and Land-Use Change, Lake Patzcuaro

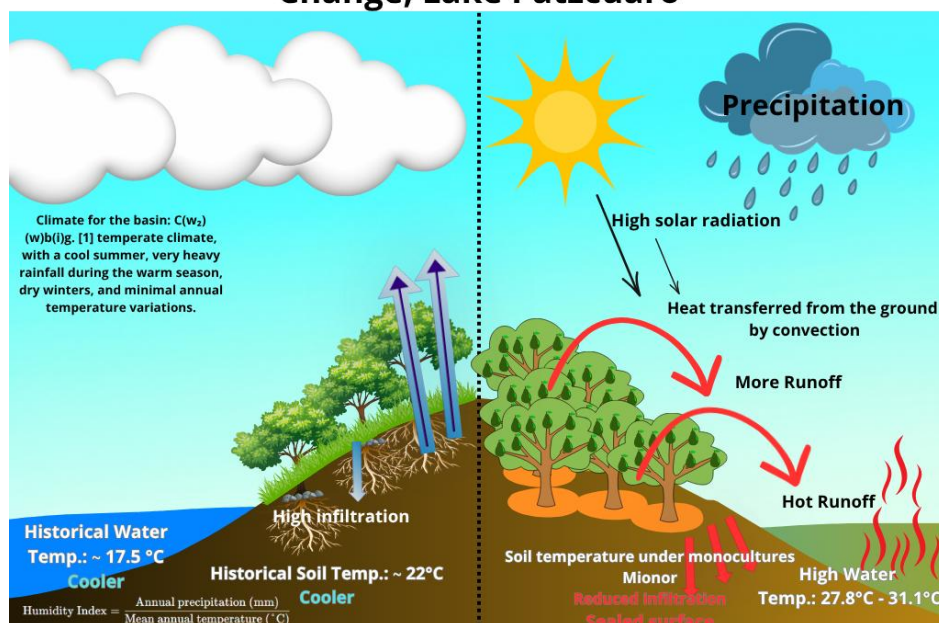


Figure 4. Model of Anomalous Heat Transfer and Land-Use Change, Lake Patzcuaro (own elaboration)

Calidad del agua del Lago de Pátzcuaro, Michoacán, México.

Jersain Jimenez Baltazar, Rubén Hernández Morales, María Ramírez Martínez y Omar Domínguez Domínguez.

PLACE WHERE THEY BELONG: Laboratorio de Biología Acuática “J. Javier Alvarado Díaz” de la Facultad de Biología UMSNH.

Table 6. Water quality of Lake Pátzcuaro, Michoacán, Mexico

Type of Parameter	Parameter	Average Reported Value	Unit	Standard / Source	Evaluation or Potential Use
Field (in situ)	Water Temperature	17.15	°C	CE-CCA-001/89	Suitable for irrigation, livestock, and aquatic life
	Transparency (Secchi disk)	16.59	m	CE-CCA-001/89	Indicator of turbid, mesotrophic waters
	Dissolved Oxygen	4.61	mg/L	CE-CCA-001/89	Suitable for irrigation; slightly low for aquatic life
	Electrical Conductivity	681.18	µS/cm	CE-CCA-001/89	Suitable for agricultural irrigation
	Salinity	0.44	‰	CE-CCA-001/89	Suitable
	pH	7.18	-	NOM-127-SSA1-1994	Suitable (slightly alkaline)
	Total Alkalinity	101.14	mg/L	APHA-AWWA-WPCF (1992)	Suitable
	Total Dissolved Solids	416.24	mg/L	NOM-127-SSA1-1994	Suitable
Laboratory - Chemicals	Ammonium (NH ₄ ⁺)	0.15	mg/L	NOM-127-SSA1-1994	Suitable for irrigation; not suitable for aquatic life
	Nitrites (NO ₂ ⁻)	0.02	mg/L	NOM-127-SSA1-1994	Suitable
	Nitrates (NO ₃ ⁻)	0.03	mg/L	NOM-127-SSA1-1994	Suitable
	Total Phosphorus	1.10	mg/L	CE-CCA-001/89	Not suitable (exceeds 0.1mg/L limit)
	Biochemical Oxygen Demand (BOD ₅)	5.15	mg/L	CNA, 1989	Good quality (low organic matter content)
Laboratory - Biological	Total Coliforms	439.65	NMP/100mL	NMX-AA-042-SCFI-2015	Not suitable for human consumption
	Chlorophyll "a" (general reference)	Indicates mesotrophy with eutrophic zones in the northern basin	µg/L	Lind (1985)	Moderate biological productivity
Organoleptic Properties	Odor and Taste	Unpleasant	Qualitative	NOM-127-SSA1-1994	Not suitable for human consumption

Source: Jersain Jiménez Baltazar, Rubén Hernández Morales, María Ramírez Martínez y Omar Domínguez Domínguez. Laboratorio de Biología Acuática “J. Javier Alvarado Díaz” de la Facultad de Biología UMSNH.

ESTUDIO ECOSISTÉMICO DEL LAGO DE PATZCUARO: Aportes en gestión ambiental para el fomento del desarrollo sustentable

Rubén I. Huerto Delgadillo, Sergio Vargas Velázquez, Carlos F. Ortiz Paniagua.

Place where they belong: IMTA y la Universidad Michoacana de San Nicolás de Hidalgo.

Table 7. Ecosystem Study of Lake Pátzcuaro

Parameter	Average Value	Unit	Sampling Year(s)	Regulatory Reference	Observations
Temperature	21.5	°C	2006-2009	NOM-001-SEMARNAT-1996	Stable temperatures; no marked thermal stratification
pH	7.56 - 9.91	-	2006-2009	NOM-001-SEMARNAT-1996 (6.5-8.5)	High values during algal blooms
Electrical Conductivity	720 - 780	µS/cm	2006-2009	NOM-001-SEMARNAT-1996	High mineralization associated with agricultural runoff
Turbidity	200 - 250	UNT	2006-2009	NOM-127-SSA1-1994 (límite 5 UNT)	Elevated; indicates strong sediment resuspension and load
Dissolved Oxygen (DO)	5.5 - 6.0	mg/L	2006-2009	NOM-001-SEMARNAT-1996	Sufficient for aquatic life, but variable by zone
Total Phosphorus	0.11	mg/L	2006-2009	OECD (1982)	Exceeds eutrophic limits (> 0.1mg/L)
Total Nitrogen	1.25	mg/L	2006-2009	OECD (1982)	Indicates strong input of organic pollutants
Biochemical Oxygen Demand (BOD ₅)	12.5	mg/L	2006-2009	NOM-001-SEMARNAT-1996	High organic load; evidence of wastewater pollution
Fecal Coliforms	> 1,600	NMP/100mL	2006-2009	NOM-001-SEMARNAT-1996	Constant presence; water unsuitable for recreation
Trophic State Index (TSI)	80-95	-	2006-2009	Carlson (1977)	Classified as hypereutrophic
Water Quality Index (WQI)	40-55	-	2006-2009	CONAGUA	Classification: “poor” to “very poor”

Source: Rubén I. Huerto Delgadillo, Sergio Vargas Velázquez, Carlos F. Ortiz Paniagua. IMTA y la Universidad Michoacana de San Nicolás de Hidalgo.

Compendio de estadísticas ambientales 2020

SEMARNAT.

Table 8. Compendium of Environmental Statistics 2020 (SEMARNAT)

Parameter	Value Range (1990-2019)	Unit	Regulatory Reference	Observed Trend
Temperature	18 - 22.5	°C	NOM-001-SEMARNAT-2021	Slight thermal increase; correlated with climate change and reduced water volume
pH	7 - 9.3	-	NOM-127-SSA1-2021 (6.5-8.5)	Elevated alkalinity; possibly due to algal proliferation and agricultural waste
Dissolved Oxygen (DO)	3.5 - 7.1	mg/L	NOM-001-SEMARNAT-2021 (≥ 5mg/L)	Acceptable for aquatic life, with periods of hypoxia (≤ 5mg/L)
BOD ₅	3.5 - 23.5	mg/L	NOM-001-SEMARNAT-2021 (≤ 15mg/L)	Exceeds limit in several years; indicates organic pollution
COD (Chemical Oxygen Demand)	15 - 118	mg/L	NOM-001-SEMARNAT-2021	Very high values (2019); reflects degradation of organic matter
Oxygen Saturation	83 - 107	%	-	Slight decrease after 2014; evidence of reduced natural aeration

The photosynthetic hyperactivity of algal blooms triggered alkalinity levels to reach a pH of 11.83 and 12.00, an extremely caustic condition that creates an adverse environment for endemic species.

The results of the sampling conducted in May 2026 indicate that the deterioration of Lake Pátzcuaro not only continues but has intensified compared to previous studies. The physicochemical variables analyzed reflect an advanced eutrophic state, with signs of hypereutrophication in several areas.

Among the most relevant findings, the elevated water temperatures (between 22°C and 32°C) stand out, which are higher than historical ranges, a product of the lake's reduced volume and its greater exposure to solar radiation. These values accelerate biological processes and favor eutrophication. The pH remained markedly

alkaline, exceeding the recommended limits for the protection of aquatic life, which is evidence of intense proliferations of algae and cyanobacteria.

Likewise, high values of electrical conductivity and total dissolved solids (around 600ppm) were recorded, reflecting strong mineralization caused by agricultural runoff, wastewater discharges, and water loss through evaporation. One of the most alarming indicators was dissolved oxygen, which in several points fell below 1mg/L, generating conditions of severe hypoxia and practically dead zones in the lake.

Turbidity remained high due both to the resuspension of sediments in a shallow lake and the continuous inputs of organic matter and sediments from the basin. Altogether, these data describe an ecosystem under strong anthropogenic pressure, where untreated

Monitoreo de descargas de aguas residuales y su impacto en el Lago de Pátzcuaro, México (2006–2011)

Ana Cecilia Tomasini Ortiz, Luis Alberto Bravo-Inclán, Javier Sánchez Chávez, Gabriela E. Moeller Chávez.

Place where they belong: IMTA.**Table 9.** Monitoring of Wastewater Discharges and Their Impact on Lake Pátzcuaro (Tomasini Ortiz et al.)

Parameter	Average or Median Value	Unit	Maximum Permissible Limit	Compliance	Observations
BOD ₅	40-131	mg/L	30	Non-compliant	All sites exceed limit; worst years 2006-2007
COD	66-88 (median) / up to 728	mg/L	100	Complies	Meets standard on average, but peaks are very high
TSS (Total Suspended Solids)	20-120	mg/L	40	Non-compliant	Exceeds standard at Janitzio, Tzintzuntzan, Guani, and Tzurumútaró Drain
Settleable Solids	≤ 1	mL/L	1	Complies	Meets standard
Fats and Oils	10-20	mg/L	15	Partial	Exceeds limit in some years (2006-2007)
Total Nitrogen (Nt)	11-52	mg/L	15	Non-compliant	Very high; only Tzurumútaró Drain complies
Total Phosphorus (Pt)	7-11	mg/L	5	Non-compliant	Generalized nutrient excess; induces eutrophication
Fecal Coliforms	7.0 × 10 ³ to 1.7 × 10 ⁷	NMP/100mL	1.0 × 10 ³	Non-compliant	Severe bacterial contamination at almost all stations
Helminth Eggs	0-10	HH/L	1	Partial	Non-compliant at Tzintzuntzan and Erongaricuaró (2006-2007)
Cyanobacteria	2.7 × 10 ⁵ - 1.5 × 10 ⁷	cel/mL	- (WHO 2011: > 10 ⁶ = high risk)	Non-compliant	High to very high health risk at Quiroga, Espíritu, and Pacanda
Microcystin-LR (MC-LR)	2 - 3,500	µg/L	1 (WHO, 2011)	Non-compliant	Exceeds safety limit; water unsuitable for consumption/recreation

Source: Ana Cecilia Tomasini Ortiz, Luis Alberto Bravo-Inclán, Javier Sánchez Chávez, Gabriela E. Moeller Chávez. IMTA.

Table 10. Physicochemical Parameters Over Time (own elaboration)

Evaluated Parameter	Historical Range (1990-2010)	Recent Investigations (2019-2024)	Unit
Temperature	17.15 a 18.0	19.2 a 21.72	°C
Turbidity	200 a 250	210 a 225.61	UNT
Electrical Conductivity	681 a 720	690 a 770.05	µS/cm
BOD ₅ (Organic Matter)	3.5 a 12.5	16.3 a > 130	mg/L
Total Phosphorus	0.11 a 1.10	0.92	mg/L

Table 11. In situ sampling on Tecuénita island, own elaboration

Radial Sample (°)	pH	Temperature (°C)
0-360	9.169	30.305
45	8.960	27.834
90	8.843	29.137
135	9.200	30.825
180	9.069	28.771
225	8.988	28.508
270	8.989	30.309
315	9.029	31.113

discharges, intensive agriculture, and land use changes have exceeded the lake's self-regulating capacity.

The current state of Lake Pátzcuaro is critical. Without urgent interventions for pollutant control, restoration of riparian zones, and continuous monitoring, its degradation will continue to advance, severely affecting biodiversity and the traditional activities of local communities.

3.4. Basin-Scale Degradation and Lacustrine Functional Alteration

The observed loss of biophysical resilience in Lake Pátzcuaro corresponds directly to the structural degradation of its upper basin. According to recent regional territorial dynamics in Michoacán, the progressive decline in vegetative vigor, reflected in sustained decreases of the Normalized Difference Vegetation Index and the substitution of forest cover by intensive agricultural systems have altered regional hydrological functionality, reducing aquifer recharge and increasing accelerated surface runoff. When projecting this territorial dynamic onto the lacustrine basin, a negative synergistic effect becomes evident: the loss of riparian wetlands eliminates the primary barrier for sediment and pollutant biofiltration, while soil erosion in the upper reaches drags massive concentrations of agrochemicals and dissolved solids directly into the lakebed. This geomorphological and hydrological alteration suppresses the system's thermal and chemical self-regulating capacity, explaining critical

anomalies such as the abnormal increase in water temperature and the documented chronic hypereutrophication.

4. Discussion

To understand what is happening with Lake Pátzcuaro, one must start with the territory rather than the water. The land use change documented in this work goes beyond a transformation of the agricultural landscape, as established by Reyes Cázares (2026). It is the gradual dismantling of the mechanisms the ecosystem used to absorb human pressure. The expansion of avocado monoculture in the municipality of Pátzcuaro—which went from 87 hectares in the year 2000 to nearly 5,000 in 2023—converted forest soils and traditional milpas into intensive plantations. These rely heavily on agrochemicals like glyphosate and paraquat, whose runoff reaches the lake without any barrier to retain it. In Tzintzuntzan, the process was equally aggressive, with a loss of almost 1,400 hectares of forest during the same period. This local shift reflects a macro-level crisis across Michoacán, where 70% of the state's harvested rainwater is now diverted to agricultural production (Montañez et al., 2021), driven by an export boom that saw statewide avocado plantations surge from 74,969 hectares in 1994 to over 158,800 hectares by 2017 (Montañez et al., 2021). Nationally, this dynamic resulted in the loss of 66,272 km² of forest between 1990 and 2015—an area larger than the state of Michoacán itself (Reyes Cázares, 2018).

What connects this territorial change with the deterioration of the water is the destruction of the tular (reed bed) wetlands. These ecosystems functioned as the last line of filtration between the basin and the lakebed: they retained sediments, absorbed nutrients, and buffered the arrival of pollutants before they entered the lake. The loss of 684 hectares of tulares in the basin—with reductions from 961 to 547 hectares in Pátzcuaro and from 293 to barely 22 in Tzintzuntzan—eliminated this protection in the most critical stretches. Without this natural vegetative canopy to intercept rainfall and stabilize the substrate (Reyes Cázares and Montañez, 2024), excess nutrients, agrochemicals, and the organic load from untreated urban discharges flow directly into the lakebed.

Added to this dynamic is a factor that often remains in the background: the water demand of agro-industrial avocado plantations pressures the basin's groundwater and contributes to the progressive reduction of the lake's total volume. Morphometric tracking illustrates the severity of this deficit: between 1984 and 2025, the lake's total water mirror shrank from 10,732 hectares to an estimated 6,790 hectares, representing a 37% loss of its original aquatic surface (Reyes Cázares and Montañez, 2024). With less water mass, the system loses its capacity for thermal regulation, explaining the most

striking data from the May 2026 intensive radial sampling conducted on Tecuenita Island—a site regarded by the local population as a vital lacustrine biomarker under the premise “if Tecuenita grows, the lake dies” (Reyes Cázares and Montañez, 2024). Compared to historical averages of 17.15°C documented by earlier studies (Jiménez Baltazar et al., n.d.), the water temperatures recorded around the island ranged critically between 27.83°C and 31.11°C. This thermal anomaly is a direct biophysical consequence of the surrounding land-use change; the stripped vegetative canopy has induced a severe rise in bare surface soil temperatures, coinciding with local atmospheric maximums hitting 36.0°C (Reyes Cázares and Montañez, 2024). During precipitation events, surface runoff flowing over these superheated soils acts as a convective heat vector, transferring thermal energy directly into the lake and driving ambient, substrate, and water temperatures well past the 25°C threshold (Reyes Cázares and Montañez, 2024).

Once those thermal thresholds are crossed, hypereutrophication advances under a feedback logic that becomes difficult to stop. Total phosphorus currently reaches 0.92mg/L due to agricultural inputs and untreated urban discharges—almost ten times above the eutrophic limit of 0.1mg/L. That excess of nutrients, combined with anomalous temperatures, triggers cyanobacteria blooms. In their phase of maximum photosynthetic activity, they consume dissolved CO₂ and raise the pH to caustic levels of 12.00 in areas of greatest algal concentration; upon decomposing, they deplete dissolved oxygen to generate severe hypoxia below 1mg/L, while releasing hepatotoxins such as microcystin into the system. Tomasini Ortiz et al. (n.d.) already documented microcystin-LR concentrations of up to 3,500µg/L in direct discharge zones, against the World Health Organization safety limit of 1µg/L. When compared to the 1990s baseline (pH 7.18, temperature 17.15°C, BOD₅ 5.15mg/L), the magnitude of the shift is undeniable: the lake has transitioned from a stable mesotrophic state to chronic toxic hypereutrophication. This empirical reality is corroborated across the basin’s five permanent monitoring stations (Reyes Cázares and Montañez, 2024): current turbidity averages 225.61UNT—exceeding the clean water threshold of NOM-127-SSA1-2021 by more than 50 times (Reyes Cázares et al., 2024)—while electrical conductivity sits at 770.05 µS/cm, placing the lake squarely in the category of “hard water” resulting from chronic agricultural mineralization (Reyes Cázares et al., 2024). Furthermore, total suspended solids reach 385.02ppm, surpassing the 20ppm maximum permissible limit of NOM-001-SEMARNAT-2021 by 1,825% (Reyes Cázares and Montañez, 2024).

The deterioration, however, is not limited to physicochemical parameters. The trophic chains have also been destabilized. The most sensitive endemic species have drastically reduced their populations, leaving space for invasive organisms that aggravate the problem from within. The achoque (Lake Pátzcuaro salamander) needs temperatures between 16 and 22°C and dissolved oxygen above 5mg/L (IUCN SSC Amphibian Specialist Group, 2020), conditions that today are practically nonexistent in the lake. The pescado blanco (white fish) requires clear and well-oxygenated waters during its spring reproduction (Chacón-Torres and Rosas-Monge, 1995), precisely when algal blooms reach their greatest intensity. The void left by these species has been occupied by carp and tilapia, which not only compete directly with native fauna but aggravate conditions by stirring up bottom sediment, increasing turbidity through resuspension, and preying on the early life stages of endemic species. The mascarita transvolcánica (Black-pollled Yellowthroat) faces a different but equally critical dynamic: its exclusive habitat is the lake tulares (BirdLife International, 2020), and the almost total destruction of that cover in the basin explains the sustained

decline of its population since the 1980s. The lake was not damaged on a single front but on all at once; deforestation, agro-industrial expansion, urbanization without sanitation, and invasive species reinforce one another, pushing regional administrative water basins into severe hydrological stress (Montañez et al., 2021) and generating a state of degradation that exceeds the natural recovery capacity of the ecosystem.

5. Conclusions

Field data and comparative historical analysis confirm that Lake Pátzcuaro is going through an advanced phase of physicochemical and biological deterioration, the cause of which is not an isolated factor but the accumulation of decades of anthropogenic pressure on the ecosystem itself. The conversion of thousands of hectares of forests and wetlands into extractive agriculture and monocultures has destroyed the natural mechanisms that allowed the lake to regulate and recover itself. The current documented conditions, with temperatures exceeding historical averages by more than 10degrees, extreme alkalinity, turbidity that multiplies the clean water threshold by 45, and severe bacteriological contamination, mean that the water body can no longer sustain the native species that give it its ecological and cultural character, nor guarantee safe conditions for any direct human use. The proliferation of carp and tilapia has aggravated this scenario, altering the structure of the lacustrine habitat and hindering any spontaneous process of biological recovery.

The results support the working hypothesis: agro-export expansion and peripheral urbanization without sanitation infrastructure are the main drivers of this environmental crisis, added to which is the hydric overexploitation of the basin that reduces the lake’s volume and its thermal regulation capacity. The deterioration was neither sudden nor inevitable; it was the result of territorial policy decisions that prioritized economic growth over the sustainability of the ecosystem and that for decades found no effective institutional counterweight.

Reversing this process requires concrete measures that admit no further delay. The expansion of the agricultural frontier in the basin must be stopped with an effective moratorium that prevents the further conversion of forest soils and wetlands into intensive plantations. In parallel, real control is needed over the clandestine extraction of groundwater that currently feeds monocultures at the expense of the lake’s volume. The wastewater treatment plants of the four riparian municipalities must operate continuously and with sufficient capacity to process current discharges, which today reach the lake practically untreated. To these actions must be added ecological restoration projects that prioritize reforestation with native species on deforested slopes and the active recovery of tular ecosystems in riparian stretches where they practically disappeared. These are the minimum conditions to attempt to return to the lake some of its natural filtration and regulation capacity. Without them, the deterioration will continue to advance to a point where recovery will cease to be a real option.

Future Perspectives: If a participatory governance that involves and professionalizes local inhabitants is not consolidated, the crisis will transcend the mere loss of biodiversity in the different strata of the basin or the depletion of the water mirror. The imminent risk lies in a health emergency of catastrophic proportions, where the physicochemical deterioration and pathogenic load generate epidemiological niches conducive to outbreaks of severe infectious diseases, such as cholera or hemorrhagic fevers similar to Ebola.

If the current trajectory of lacustrine degradation remains undressed, Lake Pátzcuaro faces an imminent transition from severe

physicochemical impairment to total biological collapse. Statistical projections indicate that without urgent systemic intervention, the lake will lose 58.98% of its surface area by the year 2050. This physical contraction, coupled with sustained maximum temperature spikes across the southern basin, directly threatens the survival of its irreplaceable endemic fauna. The achoque (*Ambystoma dumerilii*) and the pescado blanco (*Chirostoma estor estor*) face physiological thresholds that the water column can no longer support; the former is pushed toward extinction by severe hypoxia, while the latter's spring spawning is systematically suffocated by hyper-turbidity and toxic algal blooms. Similarly, the acúmara (*Algansea lacustris*)—already functionally extinct in the wild—faces insurmountable competition and bottom-sediment resuspension from introduced carp and tilapia. On the shoreline, the loss of the tular wetlands seals the fate of specialized avian endemics like the mascarita transvolcánica (*Geothlypis speciosa*), whose nesting canopy has been virtually dismantled. Ultimately, conserving this fauna requires moving beyond isolated species-rescue efforts toward integrated watershed management that addresses the root conflict between human consumption and agricultural water demand.

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Análise das Características Morfométricas na Dinâmica Sedimentar da Bacia Hidrográfica do Rio Incomáti Durante Eventos Extremos de Cheias e Inundações

Morphometric Analysis of Sediment Dynamics in the Incomati River Basin under Extreme Flood and Inundation Events

Article Record

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Abstract

A watershed is considered a natural catchment area for precipitation, whose waters flow through a drainage network to an outlet. In this context, the analysis of morphometric parameters allows the characterization of its geometry, drainage network, and relief, contributing to the understanding of hydrological behavior, erosive processes, and vulnerability to floods. This analysis contributes to hydrological planning and flood management, especially in developing countries, such as Mozambique, where in some cases there is a scarcity of hydrometeorological data. Watersheds are delineated using the Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM), and geometric, hydrographic, and relief parameters are extracted using geographic information systems (GIS) tools, QGIS and ArcGIS. The morphometry of the watershed directly influences the production, retention, and transport of sediments, which in turn reduce the flow capacity and alter the hydrological behavior of the watershed, contributing to the occurrence of regular floods. Studies on soil and water loss due to erosion utilize hydrosedimentological models, such as SWAT (Soil and Water Assessment Tool), a tool that integrates spatial and temporal data, allowing simultaneous simulation of runoff, soil erosion, and sediment transport on a large scale. Sediment production and transport in watersheds and average annual soil erosion are determined using the Universal Soil Loss Equation (USLE) and the Revised Universal Soil Loss Equation (RUSLE), respectively. Given the importance of conducting hydrological and geomorphological studies, and observing the scarcity of research portraying sedimentology and morphometry in Mozambique and the Incomáti River, this article reviews the literature on morphometry and sediment transport in watersheds, analyzing their impacts during floods.

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ARCHIVAL RECORD

Análise das Características Morfométricas na Dinâmica Sedimentar da Bacia Hidrográfica do Rio Incomáti Durante Eventos Extremos de Cheias e Inundações

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Abstract

Considera-se bacia hidrográfica uma área de captação natural de precipitação, cujas águas escoam através de uma rede drenagem até a um exutório. Neste contexto, a análise dos parâmetros morfométricos permite caracterizar a sua geometria, rede de drenagem e relevo, contribuindo para a compreensão do comportamento hidrológico, dos processos erosivos e da vulnerabilidade à ocorrência de cheias e inundações. Esta análise contribui para o planeamento hidrológico e gestão de cheias principalmente em países em vias de desenvolvimento, como é o caso de Moçambique onde em alguns casos há escassez de dados hidrometeorológicos. As bacias hidrográficas são delimitadas utilizando o Modelo Digital De Elevação (MDE), da Missão Topográfica Radar Shuttle (SRTM), e os parâmetros geométricos, hidrográficos e de relevo são extraídos por meio de ferramentas de informação geográfica (SIG), o QGIS e o ArcGIS. A morfometria da bacia hidrográfica influencia directamente na produção, retenção e transporte de sedimentos, os quais por sua vez, reduzem a capacidade de escoamento e alteram o comportamento hidrológico da bacia, contribuindo para a ocorrência de cheias e inundações regulares. Estudos sobre perdas do solo e da água por erosão utilizam modelos hidrossedimentológicos, como o SWAT (Soil and Water Assessment Tool), uma ferramenta que integra dados espaciais e temporais, permitindo simular simultaneamente o escoamento, a erosão do solo e o transporte de sedimentos em grande escala. A produção e o transporte de sedimentos em bacias hidrográficas e a erosão média anual do solo são determinados por meio da Equação Universal de Perda de Solos (EUPS) e da Equação Revista da Perda de Solo (EURPS), respectivamente. Diante da importância de realizar estudos hidrológicos e geomorfológicos, e observando escassas pesquisas que retratam a sedimentologia e morfometria em Moçambique e no rio Incomáti, este artigo revisa a literatura sobre a morfometria e transporte de sedimentos em bacias hidrográficas, analisando os seus impactos durante as cheias e inundações.

Keywords: *Floods, Incomáti, Morphometry, Sediment Transport, Soil Erosion, Watersheds*

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1. Introdução

Conforme definido por (Domingues et al., 2023), a bacia hidrográfica é uma área de captação natural de precipitação que escoar por caminhos de drenagem para um caminho principal de água, até ao ponto de saída da bacia, que geralmente drena no oceano ou lago maior. As características físicas, hidrológicas e de relevo desempenham um papel importante na dinâmica dos rios, pois condicionam o regime de escoamento, produção, retenção e transporte de sedimentos e na resposta da bacia face a eventos de precipitação.

Neste contexto, (Rodrigues et al., 2020) considera que a caracterização morfométrica consiste na estimativa de parâmetros físicos que influenciam no seu regime hidrológico tais como o factor de forma, coeficiente de compactidade, índice de circularidade, densidade de drenagem. Entretanto, para (Raiol et al., 2022) a caracterização morfométrica de bacias hidrográficas consiste na estimativa de parâmetros físicos, hidrológicos e de relevo que influenciam no

seu regime hidrológico. Deste modo, a análise morfométrica de bacias hidrográficas constitui um requisito básico para o desenvolvimento de estudos hidrológicos, tais como a avaliação do sistema de drenagem, risco de inundações, perda do solo e transporte de sedimentos (Melo et al., 2020).

A integração de Sistemas de Informação Geográfica com informações provenientes de dados cartográficos, hidrológicos e imagens de satélite permite a delimitação de bacias hidrográficas. Esta delimitação utiliza informações de uma estrutura numérica de dados chamada Modelo Digital de Elevação (MDE), alguns dos quais são da missão espacial SRTM (Shuttle Radar Topographic Mission) que apresentam modelos altamente precisos com cobertura global e NIMA (National Imaging and Mapping Agency) para obter o modelo digital tridimensional da superfície terrestre, embora (Melo et al., 2020) tenha relatado eficácia na caracterização morfométrica de bacias hidrográficas com o uso do Terrain Analysis Using Digital Elevation Models (TauDEM) e do MDE ALOS.

Quanto ao emprego de geotecnologias para a delimitação de bacias hidrográficas e a extração de parâmetros morfométricos, percebe-se, na literatura, a busca pela utilização de programas livres, como o Quantum GIS (QGIS), o qual permite a automação dos processos de extração das características do meio físico com elevada eficiência, proporcionando economia de tempo (Souza et al., 2021).

O transporte de sedimentos constitui um dos principais processos responsáveis pelas alterações geomorfológicas das bacias hidrográficas e pela redução da capacidade de armazenamento e escoamento dos rios, podendo provocar assoreamento, instabilidade nas margens, aumento do risco de inundações, e carreamento de poluentes e patógenos. Para (Paz et al., 2022), a produção de sedimentos dá-se por diferentes factores como a intensidade da chuva, tipo de solo, uso e cobertura do solo, topografia, entre outros. Esta produção refere-se ao processo de erosão, transporte, deposição e ressuspensão dos sedimentos, oportunamente exportados da bacia durante um certo período temporal. Em contrapartida, (Baldotto et al., 2021), considera que o processo erosivo seja constituído por três fases: desagregação, transporte e deposição, etapas essenciais para entender a dinâmica sedimentológica nas bacias hidrográficas.

Para a estimativa de perda de solos em bacias hidrográficas, utiliza-se variações do modelo empírico da Equação Universal de Perda de Solo (EUPS), como a Equação de Perda de Solo Universal Modificada (EUPSM) e a Equação de Perda de Solo Universal Revista (EURPS). Contudo, para classificar a perda de solos em bacias hidrográficas recorre-se ao modelo SWAT, pois simula em simultâneo a erosão, o transporte de sedimentos e o escoamento ao longo do tempo, considerando vários factores físicos e climáticos da bacia (Kelnier et al., 2026).

No entanto, a obtenção de dados *in situ* para estimar perdas de solo em grandes áreas torna o trabalho demorado e com altos custos. Frente a isso, o uso de geotecnologias e Sistemas de Informação Geográfica (SIG) viabiliza não só a colecta, tratamento, análise e produção de informações inerentes à erosividade, mas também permite o estudo da dinâmica espaço-temporal dos factores que afectam a geração e o transporte de sedimentos (Baldotto et al., 2021).

Neste sentido, o presente artigo tem como objectivo apresentar uma revisão bibliográfica sobre a relação entre as características morfométricas das bacias hidrográficas e os processos de produção, transporte e retenção de sedimentos, destacando a sua influência na ocorrência de cheias e inundações.

2. Metodologia

2.1. Localização da área de estudo

A bacia hidrográfica do rio Incomáti está localizada na região leste da África Austral. É uma bacia transfronteiriça que se estende por territórios da África do Sul, de Moçambique e do Reino Eswatini. A área total da bacia é de aproximadamente 46.748 km², dos quais 2.561 km² (5,5%), 15.506 km² (33,2%) e 28.681 km² (61,3%) estão localizados na Suazilândia, Moçambique e África do Sul, respectivamente. Possui uma área de drenagem de 46.800 km² e as suas nascentes situam-se na área do planalto ocidental do Transvaal, na província de Mpumalanga, a cerca de 2000 m acima do nível médio das águas do mar (Saraiva Okello, 2019).

A bacia do Incomáti inclui os rios Komati, Crocodile, Sabié, Massintoto, Uanetze e Mazimechopes. Os rios Komati, Crocodile e Sabié são as principais sub-bacias, contribuindo com cerca de 94% da descarga natural, com uma área correspondente a 61% da bacia.

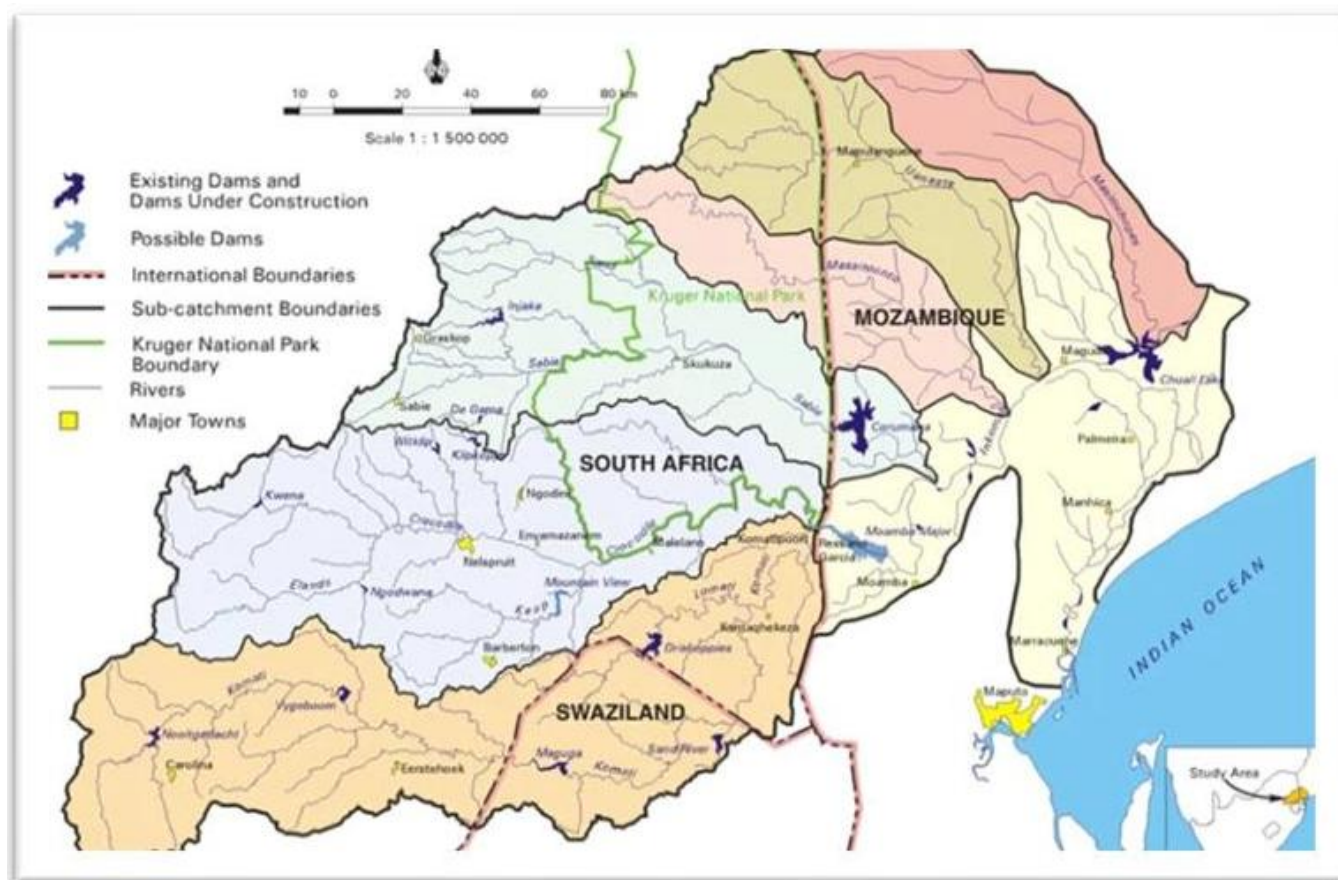


Figure 1. Mapa de localização geográfica da bacia hidrográfica do rio Incomáti.

Fonte: Saraiva Okello (2019)

Table 1. Sub-bacias hidrográficas do rio Incomáti, respectivas áreas e vazão natural.

Sub-bacia hidrográfica	Área de captação (10^6 m^2)	Descarga natural ($10^6 \text{ m}^3 \text{ a}^{-1}$)	mm a^{-1}
Komati	11200	1420	127
Crocodile	10470	1226	117
Sabié	7050	750	106
Massintoto	3430	22	6
Uanetze	3930	14	4
Mazimchope	3970	21	5
Renda	6698	134	20
Bacia total do rio Incomáti	46748	3587	77

Fonte: Adaptado de Saraiva Okello (2019)

3. Caracterização físico-natural da área de estudo

A bacia hidrográfica do Incomáti situa-se na região subtropical, como um todo, apresenta uma precipitação média anual de 740mm que aumenta de leste para oeste e uma evaporação potencial média anual para a bacia como um todo é de cerca de 1900 mm/ano, que geralmente diminui de leste para oeste. Entretanto, na região oeste de alta altitude, a precipitação média anual que varia de 800–1000 mm. A maior precipitação ocorre na bacia superior do rio Sabié, cerca de 1200mm/ano.

As temperaturas variam entre verões quentes e húmidos e os invernos amenos, com uma média anual de 17°C, enquanto o mês mais quente (Janeiro) tem uma média de 21°C e o mais frio (Junho), tem uma média de 11.5 °C. A topografia da bacia compreende as planícies costeiras planas a leste. O rio Incomáti nasce no planalto

do Transvaal, a cerca de 2000m de altitude, na parte oeste da bacia, e desagua nas planícies costeiras perto de Maputo, em Moçambique.

Os solos da bacia são altamente variáveis. Na parte da bacia do Komati (na África do Sul) ocorrem solos franco-argilosos, enquanto que na grande parte sul-africana do rio Incomáti ocorrem solos franco-argilosos pouco profundos, com relevo acentuado. As partes orientais da bacia são constituídas principalmente por solos argilosos de profundidade moderada, com relevo ondulado.

Em relação à cobertura do solo, a bacia é caracterizada por uma grande variedade de vegetação natural que variam entre praias, dunas recentes, arbustos e florestas tropicais, como também a presença de diferentes tipos de savana e pastagens.

4. Delimitação de bacias hidrográficas

No âmbito de um estudo morfométrico desenvolvido por (Raiol et al., 2022), a delimitação de bacias hidrográficas foi feita através da aquisição de dados SRTM (Shuttle Radar Topography Mission) de resolução 30x30m, no qual foram utilizados os Sistemas de Informação Geográfica, o QGIS e o ArcGIS, para a delimitação

de bacias hidrográficas utilizando o UTM (Sistema de Projecção Transversa de Mercator), com o auxílio de imagens do Google Earth para a identificação de rios, de modo a gerar mapas hipsométricos, declividade, orientação do terreno e ordem dos rios.

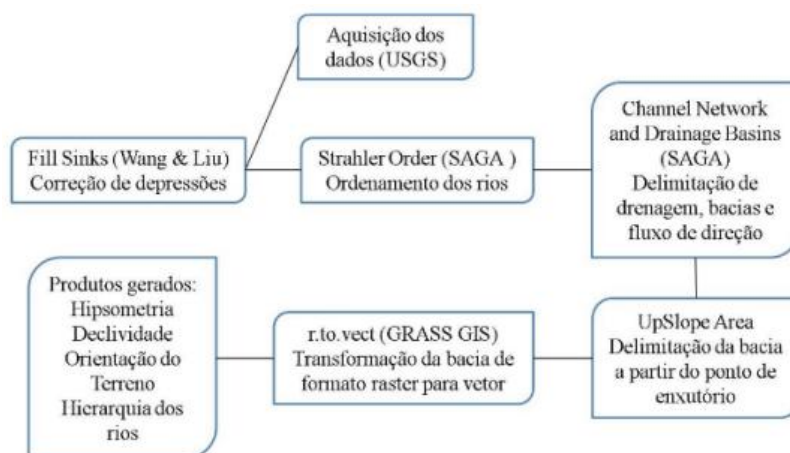


Figure 2. Fluxograma esquemático dos procedimentos adoptados.

Fonte: Raiol et al. (2022)

A classificação da ordem dos rios foi realizada segundo o método de Strahler, enquanto a declividade e o mapa de orientação do terreno foram elaborados conforme os procedimentos propostos por Lombardi Neto e Jonathan Reades, respectivamente.

Após a delimitação de bacia hidrográfica e a elaboração de mapas, foram calculados os parâmetros morfométricos relacionados à geometria, rede de drenagem e relevo da bacia. O perfil longitudinal foi obtido com base em pontos distribuídos ao longo do rio principal, permitindo estimar a declividade média e a declividade relativa. O tempo de concentração também foi determinado, este parâmetro é essencial para compreender o escoamento na bacia e apoiar na previsão de cheias e projectos de drenagem.

De acordo com (Domingues et al., 2023) as características morfométricas de bacias hidrográficas se dividem em três grupos: ge-

ométricos, rede de drenagem e relevo. Estes servem para avaliar a forma e o potencial hidrológico da bacia; compreender a organização da rede hidrográfica e o comportamento do escoamento; e, os que influenciam diretamente os processos de erosão, transporte de sedimentos e resposta hidrológica da bacia, respectivamente.

No entanto, (Melo et al., 2020) analisou as características morfométricas do rio Real, no Brasil, na qual a delimitação foi realizada por meio de processamento de dados SRTM cuja resolução é 90x90 m onde um pixel corresponde a 8100 m² no GrassGIS7.6.1. Foram utilizadas cartas topográficas no formato raster, georreferenciadas pelo sistema Datum WGS 84, que depois foi alterado para o sistema de coordenadas plano, pois o GrassGIS trabalha apenas com coordenadas UTM.

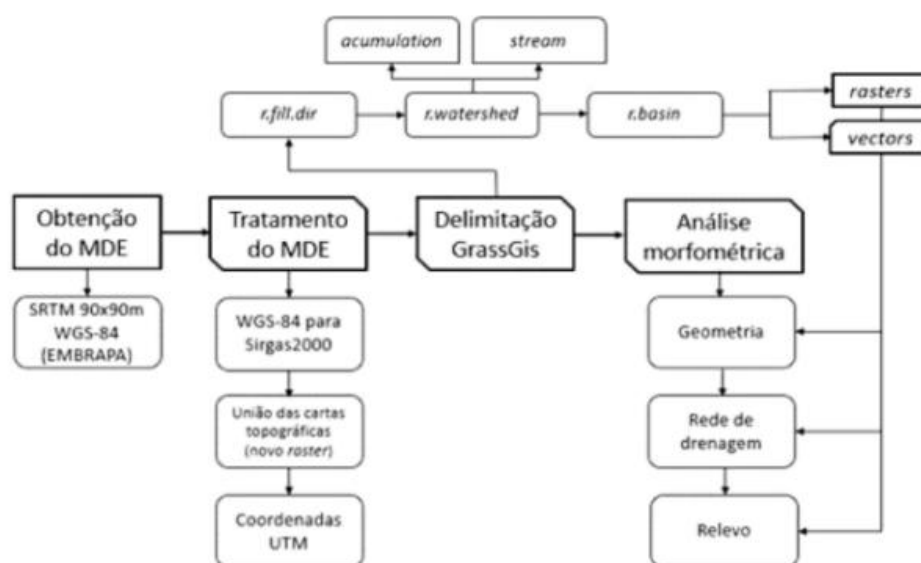


Figure 3. Fluxograma dos procedimentos para a análise morfométrica de bacias hidrográficas.

Fonte: Melo et al. (2020)

Table 2. Parâmetros morfométricos de bacias hidrográficas.

Parâmetro	Equação	Definição
Geométricos		
Área da bacia (A)	A	A = Área da bacia (km^2)
Perímetro da bacia (P)	P	P = Perímetro da bacia (km)
Comprimento axial da bacia (L_a)	L_a	L_a = Comprimento axial da bacia (km)
Coeficiente de compacidade (K_c)	$K_c = 0.28 \times \frac{P}{\sqrt{A}}$	K_c = Coeficiente de compacidade
Factor de forma (K_f)	$K_f = \frac{A}{L_a^2}$	K_f = Factor de forma
Índice de circularidade (I_c)	$I_c = 12.57 \times \frac{A}{P^2}$	I_c = Índice de circularidade
Rede de Drenagem		
Ordem dos cursos d'água	—	—
Comprimento do curso d'água principal (L)	L	L = Comprimento do curso d'água principal (km)
Comprimento total dos cursos d'água (L_t)	L_t	L_t = Comprimento total dos cursos d'água (km)
Sinuosidade do curso d'água principal (SIN)	$SIN = \frac{L}{L_a}$	SIN = Sinuosidade do curso d'água principal
Densidade de drenagem (D_d)	$D_d = \frac{L_t}{A}$	D_d = Densidade de drenagem (km/km^2)
Densidade de rios (D_r)	$D_r = \frac{n}{A}$	D_r = Densidade de rios
Coeficiente de manutenção (C_m)	$C_m = \frac{1}{D_d}$	C_m = Coeficiente de manutenção
Extensão do percurso superficial (E_{ps})	$E_{ps} = \frac{1}{2 \times D_d}$	E_{ps} = Extensão do percurso superficial
Relevo		
Altitude mínima ($H_{\min}$)	$H_{\min}$	$H_{\min}$ = Altitude mínima (m)
Altitude máxima ($H_{\max}$)	$H_{\max}$	$H_{\max}$ = Altitude máxima (m)
Amplitude altimétrica (H_m)	$H_m = H_{\max} - H_{\min}$	H_m = Amplitude altimétrica (m)
Declividade mínima ($D_{\min}$)	$D_{\min}$	$D_{\min}$ = Declividade mínima (%)
Declividade máxima ($D_{\max}$)	$D_{\max}$	$D_{\max}$ = Declividade máxima (%)
Declividade média (D_m)	$D_m = \frac{\sum x}{n}$	D_m = Declividade média (%)
Índice de rugosidade (I_r)	$I_r = H_m \times D_d$	I_r = Índice de rugosidade
Relação de relevo (R_r)	$R_r = \frac{H_m}{L_a}$	R_r = Relação de relevo

Fonte: Adaptado de Raiol et al (2022).

5. Análise morfométrica

Durante este processo, as bacias são subdivididas por subdivisores internos, de modo a tornar mais compreensível o detalhamento da bacia e a identificação de focos de degradação dos recursos naturais. As principais características físicas das subbacias e da bacia principal extraídas pelos atributos associados aos vectores são: área, perímetro, comprimento axial da bacia, comprimento do rio principal, comprimento do talvegue e número total de segmentos de drenagem (Souza et al., 2021).

Para (Rodrigues et al., 2020), o tempo de concentração representa o tempo de resposta a bacia, sendo comumente utilizados em cálculos de precipitações e na elaboração de hidrogramas de projecto, analisa-se para cada sub-bacia por três métodos de cálculo, que são: Dooge, Corpo de Engenheiros dos Estados Unidos da América e Kirpich, cujas equações são descritas a seguir:

$$T_c = 21.88 \times A^{0.41} \times S^{-0.17} \quad (1)$$

$$T_c = 11.46 \times L^{0.76} \times S^{-0.19} \quad (2)$$

$$T_c = 3.99 \times \left(\sqrt{\frac{L}{S}} \right)^{0.77} \quad (3)$$

6. Coleta de dados de campo e análise laboratorial

Durante um estudo desenvolvido por (Kelnar et al., 2026), foram realizadas campanhas de campo, entre as quais quatro para a colecta de sedimentos e dez para medições de vazão, durante um ano e meio de testes, no estação seca e chuvosa. Os sedimentos foram colectados utilizando uma draga Petersen e armazenados em plásticos identificados e posteriormente transportados para o laboratório. A vazão do rio foi medida utilizando um correntómetro fluviométrico da HIDROMEC e um velocímetro acústico Doppler SONTEK FlowTracker. As amostras de água foram colectadas em simultâneo com as medições de vazão, para a análise dos sólidos totais em suspensão, utilizando um amostrador de sedimentos integrador, DH48.

7. Estimativa na produção de sedimentos e a Equação Universal de Perda de Solos (USLE)

A análise de sedimentos em bacias hidrográficas é conduzida por meio de diferentes métodos. A perda directa do solo foi estimada com base na Equação Universal de perda de solos (USLE). A conectividade dos sedimentos foi avaliada a partir do Índice de Conectividade (IC), determina-se a taxa de entrega de sedimentos (SDR), cuja integração desses parâmetros (IC e SDR), estima-se o índice de produção de sedimentos (de Oliveira et al., 2023).

A Equação Universal de Perda de Solos (USLE) é utilizada para estimar a erosão laminar potencial na área de estudo. A USLE permite calcular a perda média anual de solo ($t \text{ ha}^{-1} \text{ ano}^{-1}$) com base em fatores climáticos, topográficos, pedológicos e de manejo:

$$A = R \times K \times L \times S \times C \times P \quad (4)$$

Onde:

- A = Perda anual de solo ($t \text{ ha}^{-1} \text{ ano}^{-1}$);
- R = Fator erosividade da chuva ($MJ \text{ mm ha}^{-1} \text{ h}^{-1} \text{ ano}^{-1}$);
- K = Fator erodibilidade do solo ($t \text{ ha h ha}^{-1} \text{ MJ}^{-1} \text{ mm}^{-1}$);
- L = Fator comprimento de encosta (adimensional);
- S = Fator declividade (adimensional);
- C = Fator cobertura e manejo do solo (adimensional);
- P = Fator práticas conservacionistas (adimensional).

8. Erosividade da chuva (Factor R) e erosivo das chuvas, Índice de Conectividade da chuva (IC)

O factor R representa o potencial erosivo das chuvas, integrando a intensidade e duração. Este factor é calculado com base na equação de Lombardi Neto e Moldenhauer (1992), que utiliza dados mensais e anuais de precipitação:

$$EI = 68.73 \times \left(\frac{p^2}{P} \right)^{0.841} \quad (5)$$

Onde:

- p é a precipitação média mensal (mm);
- P a precipitação média anual (mm).

O índice de conectividade mede a facilidade com que a água e os sedimentos se deslocam de um ponto da bacia hidrográfica até o curso de água principal, ou seja, estima a eficiência de transferência de sedimentos nas encostas para canais de drenagem:

$$IC = \log_{10} \left(\frac{D_{up}}{D_{dn}} \right) \quad (6)$$

Onde:

- D_{up} (potencial de aporte) é relacionado à área de contribuição e declividade média da encosta;
- D_{dn} (resistência distância ao canal) é o caminho mais curto até a drenagem, ponderado pela declividade e uso/cobertura do solo.

Para o cálculo do potencial de aporte (D_{up}) foi utilizada a equação:

$$D_{up} = \sum (A_i \tan \theta_i) \quad (7)$$

Onde:

- A_i = área de contribuição acumulada na célula;
- θ_i = declividade da célula.

9. Taxa de Entrega de Sedimentos (SDR) e Índice Efectivo de Produção de Sedimentos (Eefetivo)

O transporte efectivo de sedimentos na bacia hidrográfica é estimada pela integração da Equação Universal de Perda de Solo (USLE/RUSLE/EUPS) com a taxa de entrega de sedimentos (SDR), que representa uma porção de solo erodido que atinge efectivamente a rede de drenagem. Para estimar o SDR, o Índice de Conectividade atua como uma variável explicativa: $SDR = 1 - e^{-(a+b+IC)}$, onde:

- a corresponde ao intercepto da função logística ($a \approx 0,56$);
- b ao coeficiente angular que controla a inclinação da curva ($b \approx 0,17$).

A exportação efectiva de sedimentos ($E_{efetivo}$) corresponde ao volume de material que é transferido da vertente para o sistema de drenagem. Para sua estimativa, considera-se o produto entre a perda potencial de solo, calculada pela Equação Universal de Perda de Solo (USLE), e o fator de entrega de sedimentos (SDR): $E_{efetivo} = USLE \times SDR$.

9.1. Calibração, testes e análise de sensibilidade do modelo SWAT

De acordo com (Lelis et al., 2012), a calibração do SWAT é essencial devido à incerteza dos dados de entrada, que pode ser feita de forma manual ou automática. Este processo aumenta a fiabilidade das simulações, ainda que dependa da qualidade e quantidade de dados disponíveis, recomenda-se a sua utilização para séries longas. Após a calibração procede-se à sua validação com dados independentes para verificar o seu desempenho, pelo que, a calibração e validação permitem a aplicação confiável do modelo e a extrapolação dos resultados para bacias com características similares.

De acordo com (Pontes et al., 2021), o SWAT divide a bacia hidrográfica em sub-bacias conectadas por uma rede de drenagem, e em cada uma cria Unidades Hidrológicas de Resposta (URHs), correspondentes a combinações únicas no uso e tipo do solo, declividade, permitindo simular de forma detalhada o escoamento, a erosão e o transporte de sedimentos. O SWAT estima o escoamento superficial com a abordagem do número de curva SCS, e o pico de escoamento é obtido:

$$Q_{pico} = \frac{YTC \times Q_{surf} \times A}{3.6 \times T_{conc}} \quad (8)$$

Onde:

- Q_{pico} é a taxa de escoamento máximo;
- Y_{tc} é a fração da precipitação diária que ocorre durante o tempo de concentração.

10. Resultados e discussão

Segundo (Domingues et al., 2023), as geotecnologias desempenham múltiplas funções na colecta, processamento, análise, representação e disponibilização de informações que subsidiam a tomada de decisões para a gestão dos recursos hídricos. Neste contexto, a integração de dados geoespaciais com técnicas de sensoriamento remoto e Sistemas de Informação Geográfica, permite caracterizar a morfometria e a dinâmica de sedimentos, identificando áreas de maior risco de erosão.

- Q_{surf} é o escoamento superficial (mm);
- Área é a área da sub-bacia (km^2);
- t_{conc} é o tempo de concentração para a sub-bacia (hora);

- 3,6 é um fator de conversão de unidades.

O escoamento máximo é calculado a partir do escoamento superficial e do tempo de concentração, enquanto que a erosão e o transporte de sedimentos são simulados utilizando a equação de MUSLE, os coeficientes linear e exponencial, a equação de Bagnold e a concentração máxima de sedimentos, permitindo estimar de forma detalhada o assoreamento, o impacto hidrológico e a gestão integrada da bacia.

O radar SRTM desempenha um papel importante na delimitação de bacias hidrográficas, pois fornece os MDE, a partir do qual são obtidas as informações sobre o relevo, rede de drenagem e a direção do escoamento. Nesse sentido, se percebe a importância das geotecnologias na caracterização morfométrica uma vez que contribuem para a avaliação de impactos decorrentes das ações naturais e antrópicas em bacias hidrográficas.

A diferença entre o valor obtido em alguns estudos e os valores presentes em literatura pode ser justificada pelo desempenho dos softwares para delimitar regiões com altitudes baixas próximas ao nível do mar. Apesar dos obstáculos apresentados, demonstra-se a eficácia do uso do MDE SRTM 90m para delimitação de grandes bacias hidrográficas (Melo et al., 2020).

A análise da geometria da bacia auxilia na identificação de áreas vulneráveis a cheias ou inundações, enquanto que, o coeficiente de compactidade (Kc), fator de forma (Kf) e o índice de circularidade (Ic) demonstram a tendência em ocorrer esses eventos face a ocorrência de precipitações normais. Quando essas variáveis se aproximam de 1, a probabilidade da ocorrência de desastres hidrológicos aumenta significativamente, esse valor indica que a bacia apresenta um formato mais achatado. Em contrapartida, quando essas variáveis tiverem valores menores que 1, indicam menor vulnerabilidade à ocorrência de cheias e inundações, devido à sua forma mais alongada (Domingues et al., 2023).

As características do relevo colaboram diretamente na velocidade do escoamento superficial ou subterrâneo. Essas variações nas altitudes influenciam a distribuição espacial e/ou temporal do transporte e deposição de sedimentos e a capacidade de infiltração do solo (Ogarekpe et al., 2020). Para além disso, o relevo também influencia nas características da rede de drenagem, os vales profundos e os rios íngremes são mais propensos à erosão resultante da topografia acidentada.

Além disso, os estudos de Marinho et al. (2020) demonstram a relação existente entre a densidade de drenagem e a rede de rios, tendo em vista que áreas com elevada densidade de drenagem frequentemente apresentam uma rede de rios densa. Isso tem implicações significativas na resposta da bacia a eventos climatológicos extremos, configurando-se como elemento crítico para a gestão de riscos. Diante do exposto, os estudos morfométricos de bacias hidrográficas são fundamentais para a gestão adequada dos recursos hídricos e a prevenção de desastres naturais.

A ausência de cobertura vegetal, intensidade de chuvas e o alto grau de declividade, contribuem para o aumento da velocidade de escoamento e menor infiltração de água pelo solo, tendo como resultado a degradação do solo por processos de erosão (de Domingues et al., 2023).

Para (Ogarekpe et al., 2020), a densidade de drenagem (Dd) mede a proximidade, em termos de proximidade, dos canais fluviais dentro de uma bacia. Os valores de Dd são normalmente altos nas regiões de material subsuperficial impermeável e relevo montanhoso, implicando altos volumes de inundação e vice-versa. Quanto maiores os seus valores, maior o escoamento. Portanto, os fatores compostos

foram por meio de alta permeabilidade e capacidade de infiltração com menor escoamento superficial.

No estudo desenvolvido por (Pontes et al. 2021), o modelo SWAT demonstrou desempenho satisfatório na estimativa mensal de vazão, embora tenha superestimado os valores devido à seca severa, com precipitação anual 28% inferior à média histórica, evidenciando limitações na representação de padrões climáticos não contemplados na calibração. Apesar da elevada incerteza, as cargas de sedimentos simuladas foram consideradas adequadas, sendo a maior incerteza comum em bacias pequenas e quando o intervalo de simulação excede o tempo de concentração. Apesar de não representar plenamente a interação entre cobertura do solo e erosão de encostas, o SWAT fornece estimativas confiáveis do aporte de sedimentos a jusante e da sedimentação em reservatórios, sendo adequado para pequenas bacias com relevo complexo.

11. Conclusão

A análise morfométrica constitui uma abordagem essencial para compreender a dinâmica hidrológica e sedimentar das bacias hidrográficas. Os parâmetros morfométricos influenciam diretamente a produção, retenção e transporte de sedimentos, especialmente durante eventos hidrológicos extremos, como cheias e inundações.

Os sedimentos gerados pela chuva variam conforme o tipo de solo. Solos mais argilosos e ricos em matéria orgânica produzem partículas maiores, enquanto solos menos argilosos geram partículas mais pequenas. O tamanho dos sedimentos depende da textura e da estabilidade dos agregados do solo. O modelo RUSLE integrado a um SIG se configura como uma ferramenta possível de ser aplicada em local com precariedade de monitoramento sedimentométrico, ressaltando a economia de custos e tempo para execução de análises, embora medidas de conservação sejam essenciais para controlar a erosão e gerir eficazmente os recursos hídricos.

A aplicação de SIG e sensoriamento remoto se mostra eficaz na avaliação dos atributos morfométricos de tais áreas. Os parâmetros podem ser aprimorados em estudos futuros, dados adicionais de alta resolução podem ser utilizados para revelar mais detalhes. Neste contexto, a integração de estudos morfométricos na gestão de bacias hidrográficas revela-se fundamental para promover o uso sustentável dos recursos hídricos, reduzir riscos de inundações, conflito de uso do solo e vulnerabilidade hídrica os quais servirão para tomada de decisão do poder público na implantação de políticas de uso do solo e das bacias hidrográficas.

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Les Femmes Peulhes dans la Sous-Préfecture de Togoniéré au Nord de la Côte d'Ivoire, entre Résilience et Adaptation

Fulani Women in the Sub-Prefecture of Togoniéré in Northern Côte d'Ivoire: Resilience and Adaptation

Article Record

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Abstract

This paper examines the resilience and adaptability of Fulani migrant women in Togoniéré in a context where their entire community is struggling to integrate into border areas under pressure from natural resource exploitation. The methodology for this research is based on documentation relating to women's activities in general and those of Fulani women in particular. It is accompanied by a survey of 366 women in 18 villages within this administrative district to assess their activities. The results indicate a diversity of activities carried out by Fulani women, such as livestock farming, agriculture, and trade. However, they face obstacles such as limited access to land resources and credit. Despite this, these activities have a positive impact on their income and social status. This situation requires the strengthening of their activities, in particular by facilitating their access to credit, strengthening support networks, and promoting gender equality for more sustainable empowerment.

Adaptation

economic conversion

empowerment

Fulani women

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ARCHIVAL RECORD

Les Femmes Peulhes dans la Sous-Préfecture de Togoniéré au Nord de la Côte d'Ivoire, entre Résilience et Adaptation

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Abstract

Cette contribution examine la capacité de résilience et d'adaptation des femmes migrantes peules de Togoniéré dans un contexte où l'ensemble de leur communauté peine à s'intégrer dans les zones frontalières en proie à une pression sur les ressources naturelles. La méthodologie pour cette recherche s'appuie sur la documentation autour des activités des femmes en général et celles des femmes peules en particulier. Elle s'accompagne d'une enquête auprès de 366 femmes réparties dans 18 villages rattachés à cette circonscription administrative, pour apprécier leurs activités. Les résultats indiquent une diversité d'activités menées par les femmes peulhs telles que l'élevage, l'agriculture et le commerce. Toutefois, elles font face à des obstacles tels que l'accès limité aux ressources foncières et au crédit. Malgré cela, ces activités ont un impact positif sur le revenu et leur statut social. Une situation qui requiert le renforcement de leurs activités notamment en leur facilitant l'accès au crédit, en renforçant les réseaux de soutien et en promouvant l'égalité du genre pour une autonomisation plus durable.

Keywords: *Adaptation, autonomisation, femmes peulhes, reconversion économique, résilience*

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1. Introduction

Les années 1970 ont été marquées par une sévère sécheresse qui a touché l'Afrique dans son ensemble, et plus particulièrement l'Afrique de l'Ouest. Ce phénomène a conduit les éleveurs peulhs et leurs troupeaux à modifier leur système d'élevage. Ces changements entraîneront un déplacement massif vers des zones plus favorables à l'élevage. La Côte d'Ivoire s'est retrouvée au centre de ces migrations pastorales, particulièrement dans sa région nord (Véronique ANCEY, 1997, p.670). Mais dans ce milieu caractérisé par l'introduction accélérée de l'élevage et de la culture attelée qui en découle, se heurte rapidement aux logiques de subsistance établies et aux manques de structures foncières appropriées. Des conflits surgissent un peu partout autour de la cohabitation agriculteurs-éleveurs avec pour sujet principal la sécurité des cultures vivrières (Kouamé Hyacinthe KONAN et al, 2016, p.24; Dabié Désiré Axel NASSA, p.77). En dehors de la cohabitation des peulhs avec les communautés autochtones qui a toujours existé sur fond de tension agriculteurs-éleveurs, l'attentat du 11 juin 2020, les attaques meurtrières du 29 mars et 12 juin 2021 attribuées à des groupes se réclamant du prédicateur Peulh salafiste Amadou Koufa vont amplifier le malaise des communautés peulhs (KONAN Kouamé Hyacinthe, 2025, p34).

La pression démographique et les dégâts de cultures que provoque la présence d'un cheptel important sont les facteurs explicatifs de l'embarras actuel des communautés autochtones hostiles à la présence peulhe sur des terroirs aux ressources surexploitées. Cette hostilité des paysans, entame profondément l'intégration des Peulhs et aggrave la crise foncière touchant la région Nord du pays (Youssof DIALLO, 1995, p.7). Dans cet espace fragilisé par ces

nombreuses contraintes où l'économie de la femme peulhe a toujours été greffée sur l'activité pastorale des hommes, la question que soulève cette étude est celle de l'adaptation de ces femmes face aux défis d'ordre socio-économique et environnementales auxquels elles sont désormais confrontées. L'objectif de cette contribution est de montrer les stratégies adoptées par les femmes peulhs pour se maintenir dans cette zone frontalière.

2. Méthodologie

2.1. Présentation de la zone d'étude

Togoniéré est une localité située dans le département de Ferkessédougou dans la région du Tchologo au Nord de la Côte d'Ivoire (cf. Figure 1).

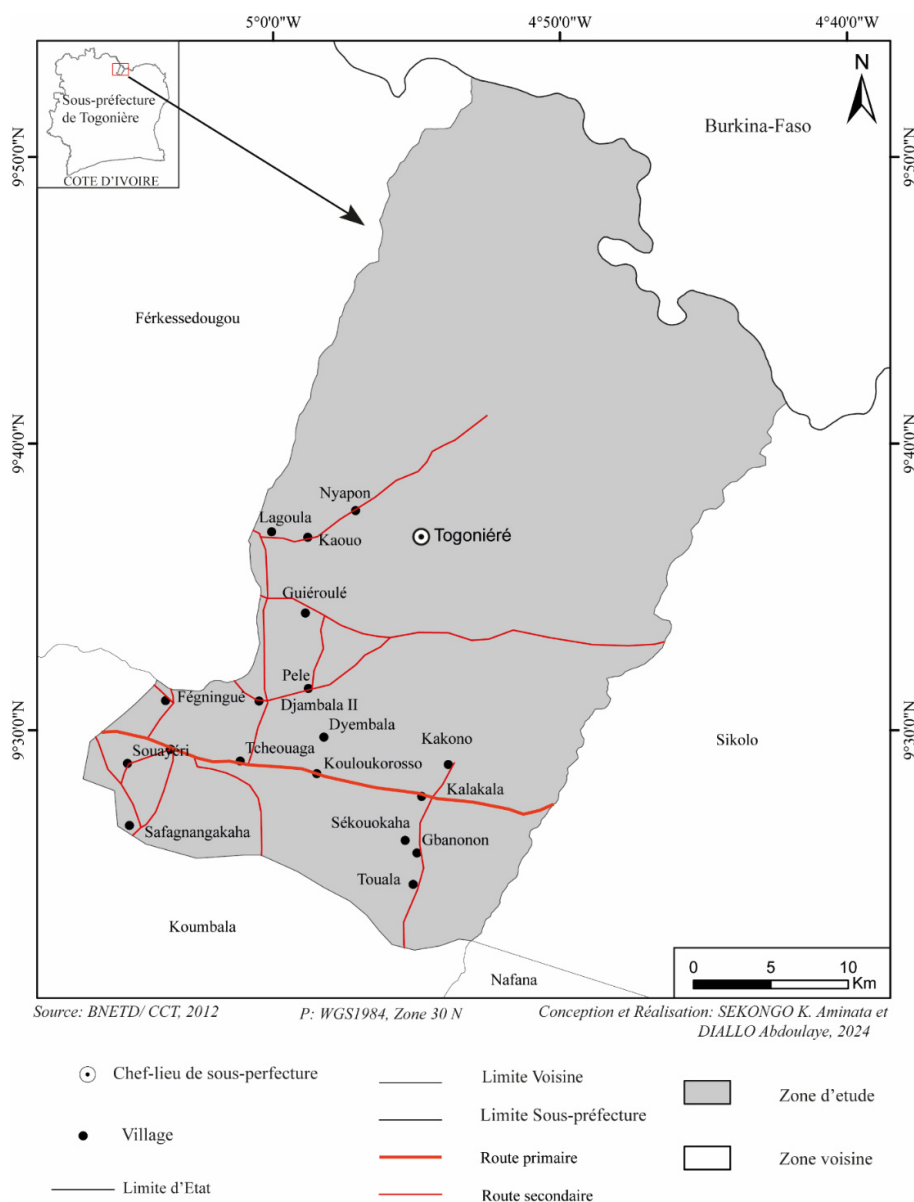


Figure 1. Localisation de la zone d'étude

La population de cette circonscription administrative est estimée à 15025 habitants (RGPH, 2021), dont 7775 Hommes et 7567 femmes. Le relief y est peu accidenté, avec des plateaux, des plaines et des vallées étroites. La végétation est composée d'arbustes nains, dominée par les bois de baobab, de Karité et de néré. Les sols sont sableux et sablo-gravillonnaire. Le climat est de type soudano-Guinéen, avec une grande saison sèche de mi-October à mi-Mai et une saison de pluie de mi-Mai à mi-October. La faune locale comprend des lièvres, des phacochères, des pintades sauvages et des perdrix. Togonière est également propice à l'agriculture vivrière (le riz, mil, maïs) et aux cultures de rente telles que la coton culture, les cultures de la noix de cajou et de la mangue.

2.2. Les données utilisées

Les données utilisées dans cette étude ont été obtenues à partir d'un échantillonnage aléatoire simple, technique qui garantit l'égalité des chances de sélection pour toutes les femmes peulhes de la population cible. Cette approche présente l'avantage de ne pas introduire de

biais de sélection liée à des caractéristiques préconçues et permet d'obtenir un échantillon représentatif de la diversité de la population étudiée. La procédure de sélection s'est déroulée en plusieurs étapes permettant d'assurer le caractère aléatoire du choix. Dans un premier temps, il a été établi avec l'aide des chefs de village et des leaders des communautés peulhes, des listes exhaustives des femmes peulhes résidant dans chaque village retenu. Ces listes ont été constituées sans considération des activités exercées, du statut matrimonial, de l'âge ou de l'origine géographique des femmes. Dans un second temps, un tirage aléatoire a été effectué au sein de chaque liste villageoise. Cette sélection aléatoire a été réalisée en attribuant un numéro à chaque femme recensée, puis en utilisant une table de nombres aléatoires pour déterminer les enquêtées retenues. Cette procédure garantit que chaque femme peulhe de la population cible avait une probabilité égale d'être sélectionnée, indépendamment de ses caractéristiques personnelles ou économiques. Pour la détermination de la taille de l'échantillon la méthode de la boule

de neige a été retenue permettant d'obtenir cet échantillon comme l'indique le tableau suivant:

Table 1. Nombres de femmes peulhs interrogés par villages

Village d'enquête	Nombre de femmes peulhs enquêtées
Togoniéré	55
Diawarakaha	12
Djo	16
Droukrosso	27
Diembala1	13
Diembal2	17
Korkana	22
Djeyenin	16
Djelebele	37
Gbamga	26
Kalakala	52
Kakono	14
Touala1	08
Touala2	09
Gbanono	13
Sefognekaha	08
Miliminin	13
Fognoguet	08
TOTAL	366

Source: nos enquêtes, 2025

2.3. Traitement de l'information

Le traitement statistique a consisté à traiter les données statistiques recueillies sur le terrain. Les données statistiques concernaient les différentes données numériques recueillies lors de l'enquête de terrain. Leur traitement a permis de réaliser des graphiques (courbes et diagrammes) et tableaux (simples, dynamiques croisés) à partir des données statistiques obtenues. Ces graphiques et tableaux ont permis d'avoir une vision globale et synthétique des phénomènes en vue d'une bonne analyse. Le traitement s'est fait à l'aide du logiciel EXCEL.

Quant au traitement cartographique a permis de transformer les données recueillies en cartes. En effet, les données recueillies lors des enquêtes de terrain ont permis de réaliser des cartes. Ces cartes, une fois réalisées, ont permis de voir la répartition spatiale des activités économiques menées par les femmes peulhs dans la sous-préfecture de Togoniéré. Les logiciels de cartographie utilisés ont été les suivants: ArcGIS et QGIS.

3. Résultats

3.1. Les systèmes d'activités traditionnelles des femmes peulhs

En remontant dans l'histoire du nomadisme, on peut retenir deux principales formes de vie des peulhs: les éleveurs et les éleveurs-agriculteurs. Les éleveurs ont une économie à dominante pastorale et dépendent uniquement de leurs animaux. Leur habitation est de type mobile avec un genre de vie nomade. La vente et le troc du lait leur permettent de se procurer des céréales. Pour ce qui est des éleveurs/agriculteurs, ils dépendent également de leur élevage, tout en pratiquant certaines formes d'agriculture constituée uniquement de champs de case sur de petites superficies (Boubié BASSOLET, 1999, p212).

Les peulhs installés dans le Nord de la Côte-d'Ivoire, quant à eux sont des transhumants immigrés des régions sahélo-soudaniennes.

Si ces peulhs sont marqués par une tendance à la sédentarisation, les enquêtes auprès des femmes permet de situer leurs origines (cf. tableau suivant).

Table 2. Répartition des femmes peulhs selon leur pays d'origine

Pays	Effectif	Pourcentage
Burkina Faso	198	54.1%
Côte d'Ivoire	78	21.3%
Mali	67	18.3%
Niger	23	6.3%
Total	366	100.0%

Source: nos enquêtes, 2025

Nos études révèlent que plus de la moitié des femmes enquêtées (54.1%) sont originaires du Burkina Faso, probablement en raison de la proximité géographique de Togoniéré avec ce pays. La forte représentation des peulhs plus anciennement établis qu'on appelle peulhs de Côte d'Ivoire (21.3%) et du Mali (18.3%) témoigne des mouvements migratoires transfrontaliers caractéristiques des populations peulhs nomades et semi-nomades dans la sous-région ouest-africaine.

Pour ce qui concerne leurs activités économiques, elles tournaient jusque-là autour des produits de l'élevage. Certaines développent des parcelles agraires et la majorité pratique l'embouche de moutons pour compléter leurs revenus provenant du lait, dont la quantité est affaiblie par les multiples sécheresses, la dégradation des sols entre autres l'embouche consiste à acheter avec leurs économies de la vente de lait, un jeune mouton et des compléments alimentaires qui vont servir à le nourrir suffisamment (Madina QUERRE, 2003, p.50). La vente du lait reste une activité essentielle des femmes peulhs. Une partie de ce produit intervient prioritairement dans l'alimentation des ménages et l'autre partie du lait entre dans les activités de commercialisation des femmes soit sous forme de lait frais, soit sous formes de ses produits dérivés (lait caillé, beurre, du lait, fromages, etc.). Les revenus des femmes provenant du lait leur servent à acheter les condiments, ustensiles de cuisine, colliers, pagnes, savons, etc. Ainsi, les activités de commercialisation liées au lait donnent aux femmes la possibilité d'une émancipation économique et sociale. Le lait pour les ménages peulhs en général, et les femmes en particulier représente donc toute leur économie, leur vie sociale et leur identité. La transformation agroalimentaire du lait et ses produits dérivés (fromages) occupe ainsi traditionnellement les femmes peulhs et contribue à plus de 50% au revenu annuel de leurs ménages.

3.2. Une tendance à la diversification des revenus dans un contexte de sédentarisation

Au regard des contraintes climatiques, socio-économiques vécues par les communautés peulhs et qui touchent le pastoralisme, les femmes diversifient leurs activités économiques. Dans un contexte marqué par l'effondrement des revenus laitiers (conséquence d'une baisse de la production) les femmes continuent de vendre du petit bétail mais elles ont développé d'autres qui n'existaient pas (ou très peu) dans les habitudes économiques des femmes peulhs. Les femmes peulhs ont particulièrement investi le secteur du petit commerce (24.3% selon notre enquête), développant des réseaux de distribution qui s'étendent des villages aux centres urbains régionaux. Cette évolution témoigne d'une capacité d'adaptation remarquable aux opportunités de marché et aux exigences de l'économie monétaire locale. L'élevage, bien qu'en déclin relatif chez les femmes (36.1% seulement pratiquent encore cette activité), demeure une composante importante de l'économie locale. Les

stratégies d'élevage évoluent vers des systèmes plus intensifs, notamment pour la volaille qui représente 50.8% des activités d'élevage féminines. Dans l'ensemble, les activités dans lesquelles elles sont impliquées se répartissent de la façon suivante:

Table 3. Répartition des femmes peulhs selon leur domaine d'activité

Activités	Effectif	Proportion
Ménagère	156	42.6%
Commerçante	89	24.3%
Agricultrice	45	12.3%
Artisane	18	4.9%
Éleveur	28	7.7%
Autres	30	8.2%
Total	366	100.0%

Source: nos enquêtes, 2025

Le commerce constitue désormais la principale activité économique formelle (24.3%), suivi de l'agriculture (12.3%) et de l'élevage (7.7%). Près de la moitié des femmes (42.6%) se déclarent ménagères, révélant soit une inactivité économique formelle, soit des activités domestiques non comptabilisées. La vente de bijoux traditionnels (perles, bracelets, colliers), d'accessoires féminins ou de commerce de détail révèle une stratégie d'adaptation aux goûts locaux et à la demande urbaine croissante.

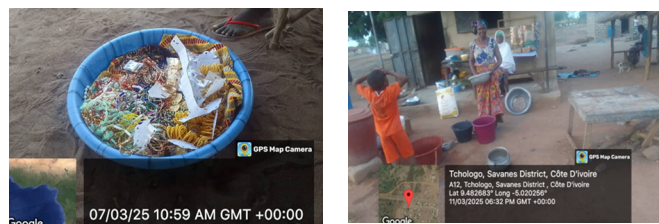


Figure 2. Vues de commerce de détail développé par les femmes peulhs (Source: Sekongo, 2025)

Cette évolution vers des commerces fixes et équipés marque une transition majeure par rapport aux activités commerciales ambulantes traditionnelles. Ces investissements révèlent la capacité d'épargne et d'accumulation de certaines femmes, contribuant au développement économique local. Cette activité nécessite un capital initial modéré et s'appuie sur les réseaux d'approvisionnement transfrontaliers caractéristiques des communautés peulhs. Cette spécialisation témoigne de la capacité des femmes peulhs à identifier et exploiter des niches commerciales rentables, contribuant aux 24.3% d'activités commerciales identifiées dans notre enquête. Elles s'engagent également dans la transformation alimentaire avec la production de pâte de manioc destinée à confection de mets locaux tels que *l'attiéké*, *le placali* et *le gari*.

Ce changement dans les pratiques est liée du point de vue de Claude Arditi (2001, p.1) à la sédentarisation qui entraîne de nombreuses conséquences tant sociales qu'économiques incluant les mutations dans habitudes alimentaires et culturels.

Cette activité de transformation illustre l'intégration réussie des femmes peulhs dans les filières agroalimentaires locales. La fabrication d'attiéké et de placali, produits de base de l'alimentation ivoirienne, témoigne d'une adaptation culturelle remarquable dépassant les frontières ethniques traditionnelles. Cette activité génératrice de revenus combine savoirs techniques locaux et demande alimentaire urbaine croissante. L'utilisation d'équipements traditionnels à

l'instar de cette presse artisanale révèle non seulement une diversification alimentaire mais traduit une stratégie d'insertion économique locale et contribue à la sécurité alimentaire communautaire.

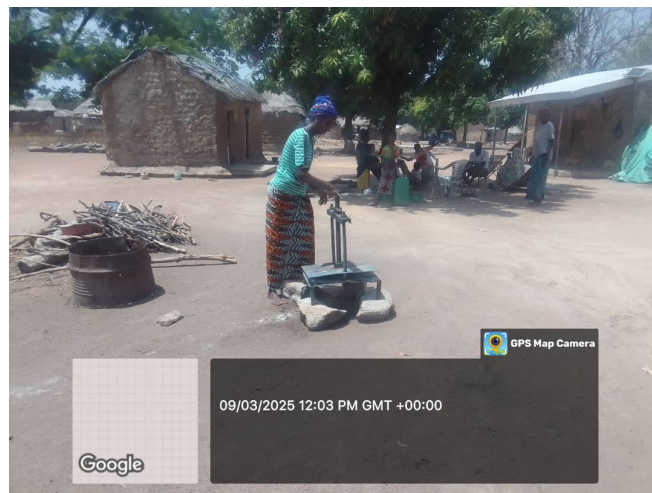


Figure 3. Vue d'une femme peuhle manipulant une presse artisanale de pâte de manioc (Source: Sekongo, 2025)

Les pratiques agricoles autrefois caractérisées par l'agriculture de case a également connu une mutation. A cet effet, la pratique des cultures maraîchères traduit cette évolution de l'agriculture de case en agriculture orientée vers le marché dans un contexte de contraintes foncières vu que 63.9% des enquêtés exploitent moins d'1 hectare de terres agricoles.

Une situation qui traduit le niveau d'adaptation à de nouvelles pratiques agricoles et économiques. Cette dynamique de reconversion économique des femmes peulhs se traduit également par la multiplication des petits métiers tels que la confection artisanale des nattes (cf. Figure 5).

L'artisanat traditionnel avec la fabrication de nattes témoigne de la persistance des savoir-faire ancestraux générateurs de revenus complémentaires.

Bien que l'élevage constitue l'activité habituelle des Peulhs, près 64% des femmes enquêtées ne pratiquent plus cette activité ancestrale. Cette rupture avec la tradition pastorale s'explique par plusieurs facteurs. la sédentarisation progressive des communautés nomades, la perte du cheptel due aux aléas climatiques et économiques, ainsi que le transfert croissant de cette responsabilité vers les hommes dans l'organisation familiale. Néanmoins, plus d'un tiers des femmes (36%) perpétuent encore cette tradition millénaire, témoignant de la résistance culturelle et de l'adaptation des pratiques pastorales aux contraintes contemporaines. Cette évolution marque une transformation socio-économique majeure dans l'identité peulh traditionnelle. Une tendance similaire de diversification des revenus dans un contexte de sédentarisation est décrite par Isabelle DROY et Jean-Étienne BIDOUE (2014, p.79) et fait cas des femmes peulhs de Djougou au Bénin qui avec leurs filles, exercent de façon autonome plusieurs activités simultanément ou échelonnées dans l'année : agriculture, transformation de produits agricoles. Cette situation diffère d'une époque dépeinte par Jean-Marc Bellot (1980, p.21) au cours de laquelle les revenus des femmes peulhs se limitaient aux revenus tirés de la vente des produits laitiers et artisanaux.



Figure 4. Vue d'activités maraîchères menées par les femmes peulhes



Figure 5. Fabrication artisanale de natte
(Source: Sekongo, 2025)

3.3. La création des coopératives, un moyen de résilience des femmes peulhes

Les femmes peulhes de la sous-préfecture de Togonière ont développé des formes d'organisation collective pour optimiser leurs activités économiques et renforcer leur capacité d'action. Bien que plusieurs coopératives existent dans la zone, seule la coopérative Weyanpeni de Lavé a été étudiée à titre d'exemple pour analyser en profondeur les mécanismes organisationnels adoptés par ces femmes. La coopérative Weyanpeni de Lavé constitue un modèle représentatif des structures associatives féminines peulhes dans la région. Créée dans l'objectif de mutualiser les ressources et de développer des activités génératrices de revenus, cette organisation illustre la capacité d'adaptation et d'innovation des femmes peulhes face aux défis économiques actuels. Son fonctionnement révèle les stratégies collectives mises en place pour surmonter les contraintes individuelles et créer des synergies économiques.

Cette coopérative s'organise autour de principes de solidarité communautaire et de gestion participative, caractéristiques des traditions d'entraide peulhes adaptées aux exigences modernes de développement économique.



Figure 6. Vue d'une réunion de la coopérative Weyanpeni
(Source: Sekongo, 2025)

La coopérative Weyanpeni de Lavé a élaboré des stratégies de développement qui s'appuient sur la diversification des activités et l'amélioration progressive des capacités techniques et financières de ses membres. Ces stratégies révèlent une vision à long terme du développement économique féminin, dépassant les approches de subsistance pour viser une véritable accumulation de capital. Les perspectives d'expansion s'orientent vers l'intégration verticale des filières, notamment dans l'agriculture et l'élevage, permettant aux femmes de contrôler l'ensemble de la chaîne de valeur depuis la production jusqu'à la commercialisation. Cette approche témoigne d'une maturité économique croissante et d'une compréhension des mécanismes de création de valeur ajoutée. L'innovation organisationnelle constitue également un axe de développement privilégié. La coopérative explore des partenariats avec d'autres structures similaires dans la région, créant un réseau d'organisations féminines peulhes capable de mutualiser les ressources et de négocier collectivement avec les partenaires techniques et financiers. Cette stratégie de mise en réseau révèle une capacité d'adaptation aux exigences modernes du développement économique tout en préservant l'identité culturelle peuhle. Malgré les efforts consentis en multipliant les initiatives les revenus des femmes peulhes de Togonière restent faibles comme l'indique la figure suivante:

La situation économique est précaire avec plus de la moitié des femmes (51.6%) gagnant moins de 50.000 F CFA par mois et près d'un quart (24.3%) sans revenus monétaires. Seulement 24% génèrent des revenus supérieurs à 50.000 F CFA, dont une infime minorité (5.7%) dépasse 100.000 F CFA. Cette faiblesse des revenus témoigne de la vulnérabilité économique de cette population et des défis auxquels elle reste confrontée.

3.4. Les défis des femmes peulhes

L'une des contraintes majeures pesant sur les femmes peulhes est l'accès difficile à l'eau. La nécessité de se déplacer vers des points d'eau naturels (marigot) révèle l'insuffisance des infrastructures hydrauliques locales. Cette activité chronophage limite le temps disponible pour les activités génératrices de revenus et constitue un frein au développement économique féminin.

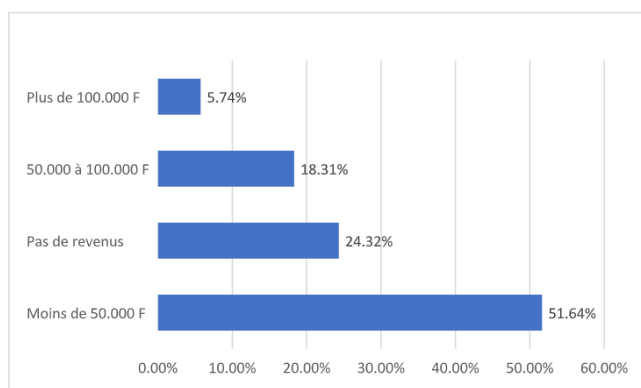


Figure 7. Répartition des femmes selon les tranches de revenus mensuels (Source: nos enquêtes, 2025)



Figure 8. Source d'approvisionnement en eau (Source: Sekongo, 2025)

Ces sources utilisées pour pallier l'insuffisance des infrastructures hydrauliques modernes souligne les risques sanitaires et la vulnérabilité en termes d'approvisionnement en eau. Par ailleurs, le manque de financement constitue la principale contrainte pour 54,1% femmes peulhs, limitant ainsi l'expansion de leurs activités économiques. Aussi, l'accès aux soins de santé reste le défi majeur car l'essentiel (73,0%) qui n'ont pas accès aux centres de santé. Cette situation expose cette population à des risques sanitaires majeurs, particulièrement graves pour les femmes en âge de procréer. L'amélioration de l'accessibilité aux soins constitue une priorité de santé publique. L'insuffisance d'infrastructures sanitaires constitue la principale barrière à l'accès aux soins pour la moitié des femmes (50,2%), révélant un déficit structurel majeur dans l'offre de santé. Les contraintes financières représentent le second obstacle pour un tiers des enquêtées (33,3%), soulignant la précarité économique qui limite l'accès aux services médicaux. La distance géographique complète ce tableau en affectant 16,5% des femmes, particulièrement celles résidant dans les zones rurales éloignées.

4. Conclusion

Cette étude révèle des transformations profondes dans les stratégies d'adaptation de cette communauté traditionnellement pastorale. L'analyse démontre une mutation significative du modèle économique peulh ancestral vers une diversification remarquable des activités génératrices de revenus. Les femmes peulhs de Togonieré développent des stratégies d'adaptation économique pour surmonter les difficultés dans d'autres activités génératrices de revenus se trouve largement confirmée. Ces femmes ont opéré une transition majeure de l'élevage traditionnel vers des activités commerciales, agricoles et artisanales, témoignant d'une capacité d'innovation et de résilience exceptionnelle face aux contraintes du moment.

Si l'agriculture demeure présente, c'est désormais le commerce qui constitue l'activité économique dominante, marquant une rupture

avec l'identité pastorale historique. L'organisation en coopératives, illustrée par l'exemple de Weyanpeni de Lavé, confirme l'évolution vers des formes collectives modernes d'entrepreneuriat féminin. Les contraintes foncières constituent un frein majeur, accompagnées de défis multidimensionnels incluant l'accès au financement, aux services de santé.

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Analise das Areas de Sedimentacao Durante Eventos de Cheias e Inundacoes na Bacia Hidrografica de Inhanombe: Caso de Estudo do Distrito de Maxixe Provincia de Inhambane

Analysis of Sedimentation Areas during Flood and Inundation Events in the Inhanombe River Basin

Article Record

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Abstract

Sedimentation in river basins is a crucial process that impacts water quality, river morphology and natural resource management, especially during flooding events. This review article addresses the analysis of sedimentation areas in the Inhanombe River Basin, located in southern Mozambique, highlighting the application of the SWAT (Soil and Water Assessment Tool) and SDR (Sediment Delivery Ratio) models. The physiographic, hydrological and land use and cover aspects that influence hydrosedimentological processes in the basin are discussed. The SWAT model is presented as an effective tool to simulate sediment production and transport, while the SDR model is used to estimate the fraction of sediment that actually reaches water bodies. The article highlights the challenges related to model exclusion, the spatial variability of data and the complexity of environmental processes, addressing the integration of high-resolution data, remote sensing and continuous monitoring as strategies to improve the accuracy of simulations. The combination of SWAT and SDR models provides an integrated approach to identify critical sedimentation areas, contributing to the planning and sustainable management of water resources in the region.

Morphology

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Analise das Areas de Sedimentacao Durante Eventos de Cheias e Inundacoes na Bacia Hidrografica de Inhanombe: Caso de Estudo do Distrito de Maxixe Provincia de Inhambane

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Abstract

Sedimentation in river basins is a crucial process that impacts water quality, river morphology, and natural resource management, especially during flood events. This article holistically analyzes the sedimented areas in the Inhanombe River Basin, located in southern Mozambique, highlighting the application of the SWAT (Soil and Water Assessment Tool) and SDR (Sediment Delivery Ratio) models. Physiographic, hydrological, and land use/land cover aspects influencing hydrosedimentological processes in the basin are discussed. The SWAT model is presented as an effective tool for simulating sediment production and transport, while the SDR model is used to estimate the fraction of sediments that effectively reach water bodies. The article highlights the challenges related to model calibration, spatial variability of data, and the complexity of environmental processes, suggesting the integration of high-resolution data, remote sensing, and continuous monitoring as strategies to improve the accuracy of the simulations. The combination of SWAT and SDR models provides an integrated approach to identifying critical sedimentation areas, contributing to the planning and sustainable management of water resources in the region.

Keywords: Sustainable management, Water resources, Morphology, Sediment transport

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1. Introdução

A análise da sedimentação em bacias hidrográficas é um componente fundamental para o entendimento dos processos ambientais que afectam a dinâmica dos corpos de água e o equilíbrio dos ecossistemas associados. O transporte e a deposição de sedimentos influenciam directamente a qualidade da água, a morfologia dos rios e a capacidade de armazenamento de reservatórios, além de impactar nas actividades humanas como a agricultura, a urbanização e o manejo dos recursos hídricos (Brandão, 2024). Entender esses processos é fundamental para ações planejadas que garantam a sustentabilidade ambiental e o uso eficiente dos recursos naturais.

A sedimentação está intimamente ligada às características morfológicas da bacia e ao uso do solo (Silva, 2014). Em áreas montanhosas, o relevo acentua a erosão e aumenta o transporte de sedimentos durante eventos de cheias, enquanto em regiões urbanas, as mudanças no uso do solo modificam a geomorfologia e os padrões de sedimentação, afetando os canais fluviais (Betocco et al., 2023). A composição química dos sedimentos também serve como indicador de qualidade ambiental, auxiliando no monitoramento dos impactos antrópicos.

Deste modo a Bacia Hidrográfica do Rio Inhanombe, em Moçambique, enfrenta uma pressão crescente nos recursos hídricos devido ao aumento populacional e à expansão da agricultura irrigada. Um estudo de Notisso e Formiga (2020) mostrou que, em cenários futuros de médio e alto crescimento até 2040, a bacia terá dificuldades para garantir o abastecimento de água, com falhas frequentes especial-

mente em períodos críticos. Isso destaca a necessidade de análises planejadas dos processos hidrológicos e sedimentológicos para apoiar a gestão sustentável e a mitigação dos impactos ambientais causados por eventos extremos, como cheias e inundações.

2. Caracterização da Bacia Hidrográfica de Inhanombe

Este estudo tem como objectivo a análise das áreas de sedimentação durante eventos de cheias e inundações na Bacia Hidrográfica de Inhanombe, utilizando os modelos SWAT (Soil and Water Assessment Tool) e SDR (Sediment Delivery Ratio).

A bacia do rio Inhanombe situa-se na província de Inhambane no sul de Moçambique. Tem uma área de 1.284 km², com cerca de 66 km de comprimento do rio principal, desaguando na baía de Inhambane (Notisso & Formiga, 2020). A precipitação média anual é de 850 mm, variando de 600 a 1100 mm, do interior para litoral.

O período chuvoso vai de novembro a março, apresentando uma crista¹ em janeiro e fevereiro. A maior demanda de água na bacia é a irrigação agrícola com cerca de 9,4 hm³/ano representando cerca de 80,3% da demanda total, seguida de abastecimento doméstico com 2,0 hm³/ano para a cidade de Maxixe e 194,7 m³/ano para o distrito de Homoine correspondentes a 17,1 e 0,9%, respectivamente, os restantes 1,8% correspondem a indústria e pecuária (Notisso & Formiga, 2020).

¹ Nesses meses ocorre o maior volume ou a maior frequência de precipitações dentro do período chuvoso.

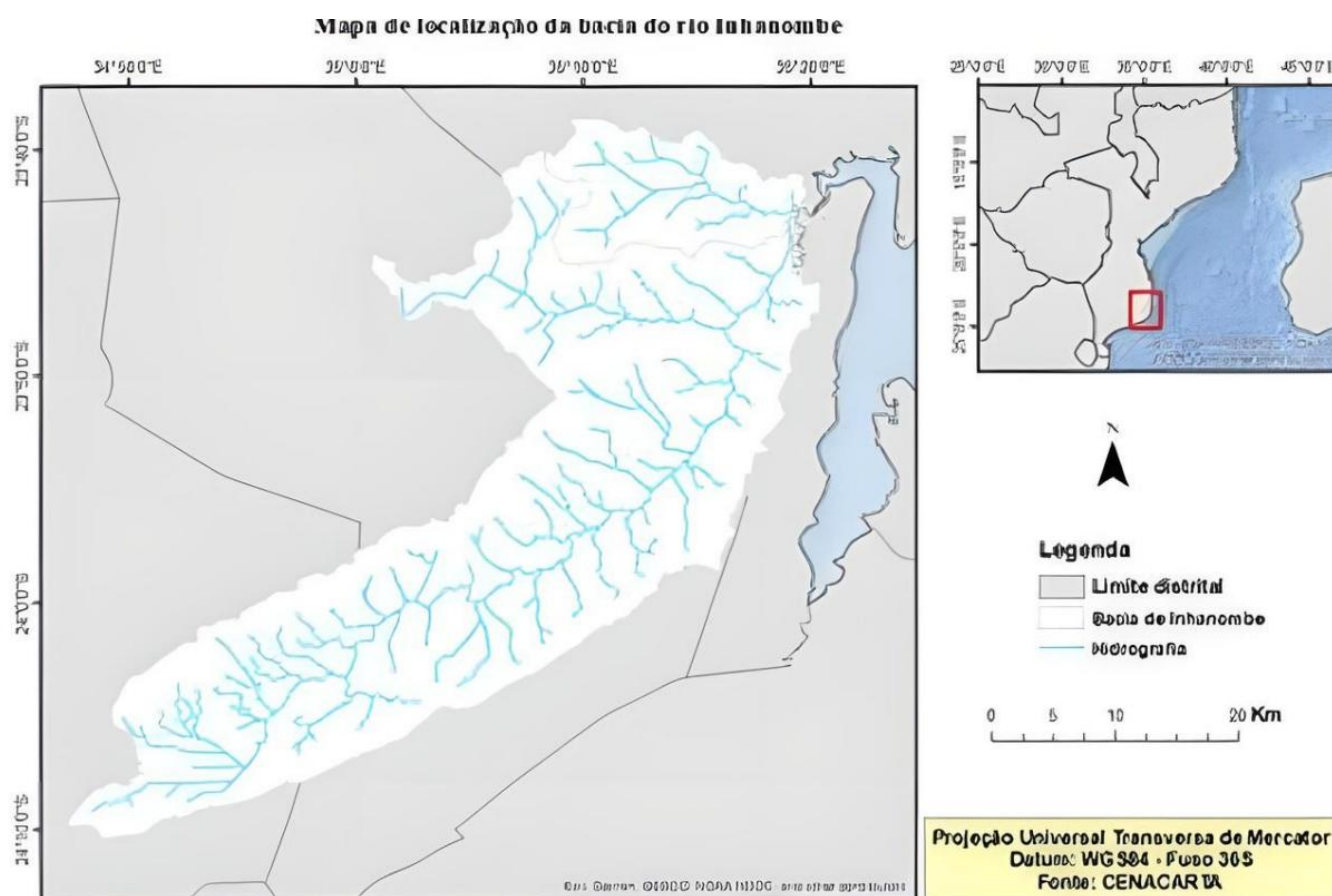


Figure 1. Mapa de Localização da Bacia do Rio Inhanombe

A demanda total estimada de água superficial em 2009 foi de 11,7 hm³/ano, mas prevê-se que aumente para 30,0 hm³/ano em 2035. A população abastecida na bacia cresceu de menos de 37.000 em 1997 para cerca 85.097 em 2017. A demanda de água para irrigação é de 17.181 m³/ha/ano. A bacia tem uma área potencial para agricultura de 1.344 ha, destes apenas 555 ha² são utilizados actualmente (Notisso & Formiga, 2020). O parque industrial é quase inexistente e não se espera um crescimento considerável.

A Bacia Hidrográfica de Inhanombe apesar de pequena, tem uso intenso da sua água sendo de destacar o abastecimento à cidade da Maxixe e à irrigação. O aumento da demanda de água para abastecimento doméstico e irrigação agrícola na bacia é cada vez mais preocupante numa altura de grandes incertezas de variáveis hidrológicas e climáticas na região de África Austral (Minella et al., 2007).

Não há registro de conflitos de uso de água na bacia, mas a necessidade de satisfazer a demanda cada vez maior para o desenvolvimento econômico e social na bacia pode originar conflitos no futuro devido à escassez de água.

Segundo Brandão et al. (2024) os conflitos surgem frequentemente quando diferentes usuários de água (incluindo o meio ambiente) competem por um suprimento limitado de água. A alocação de água deve considerar três princípios fundamentais: equidade, eficiência e sustentabilidade (Ghimire et al., 2024).

3. Revisão dos Modelos SWAT (Soil and Water Assessment Tool) e SDR (Sediment Delivery Ratio)

3.1. Modelo SWAT (Soil and Water Assessment Tool)

O Soil and Water Assessment Tool (SWAT) é um modelo hidrológico amplamente utilizado para simular o impacto das práticas de uso do solo, manejo da terra e mudanças climáticas nos recursos hídricos e de sedimentos em bacias hidrográficas (Silva & Medeiros, 2014). Desenvolvido pela Agência de Pesquisa Ambiental dos Estados Unidos (USDA-ARS), o SWAT permite a modelagem de processos hidrológicos, erosão do solo, transporte de sedimentos e nutrientes ao longo do tempo em extensas áreas de drenagem (Silva & Medeiros, 2014).

O funcionamento do SWAT baseia-se na subdivisão da bacia hidrográfica em subbacias e na separação das unidades de resposta hidrológica, que combinam diferentes tipos de uso do solo e cobertura vegetal. O modelo simula processos como a infiltração, escoamento superficial, evapotranspiração, percolação, transporte de sedimentos e nutrientes, considerando variáveis climáticas, características do solo e práticas de manejo (Santos et al., 2018). O SWAT opera em escala diária, permitindo análises detalhadas de eventos hidrológicos e sedimentológicos.

Entre as principais aplicações do SWAT destacam-se a previsão da qualidade e quantidade de água, análise da erosão do solo e sedimentação, avaliação de impactos ambientais, planejamento do uso sustentável do recurso hídrico e suporte à tomada de decisão em gestão ambiental (Marmontel et al., 2019). Além disso, o modelo

²Habitantes

é capaz de integrar diferentes cenários de uso do solo e mudanças climáticas, auxiliando na avaliação de estratégias de conservação.

As vantagens do SWAT incluem sua capacidade de lidar com grandes bacias hidrográficas, a integração de múltiplos processos ambientais, a flexibilidade para simular diversas condições e a ampla aceitação na comunidade científica, o que facilita o acesso a suporte, documentação e bases de dados. Sua estrutura modular permite adaptações e ajustes para diferentes contextos regionais (Santos et al., 2018).

3.1.1. Estudos que Utilizaram o SWAT para Modelagem Hidrológica e Sedimentação

Diversos estudos têm aplicado o SWAT para análise hidrológica e de sedimentação em bacias hidrográficas de diferentes características. Segundo Arnold et al. (1998) apresentaram o desenvolvimento inicial do SWAT e demonstraram sua capacidade de simular o impacto do uso do solo e práticas agrícolas na erosão e qualidade da água em bacias dos Estados Unidos.

Neitsch et al. (2011) aplicaram o SWAT na avaliação da sedimentação em uma bacia hidrográfica tropical, mostrando resultados detalhados sobre a contribuição de diferentes áreas para o transporte de sedimentos durante eventos de chuva intensa.

Na América do Sul, utilizaram o SWAT para modelar a dinâmica hidrológica e sedimentológica em uma bacia do Brasil, comprovando a eficiência do modelo na previsão da erosão do solo e no planejamento de medidas de conservação (Betrie et al., 2011).

3.2. Modelo SDR (Sediment Delivery Ratio)

O modelo Sediment Delivery Ratio (SDR) é uma ferramenta essencial para estimar a fração dos sedimentos erodidos que efetivamente é transportada até o ponto de saída de uma bacia hidrográfica, como rios ou reservatórios. Essa estimativa é crucial para avaliar a real carga de sedimentos que impacta os corpos de água e para planejar medidas eficazes de conservação e manejo sustentável do solo e da água (Xu et al., 2022).

Nos estudos recentes, o SDR tem sido integrado a modelos empíricos e distribuídos, como o RUSLE (Equação Universal de Perda de Solo Revisada) e o modelo InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs), para melhorar a precisão da previsão da entrega de sedimentos em diferentes contextos ambientais e climáticos (Ghimire et al., 2024).

O cálculo do SDR incorpora diversos fatores físicos e hidrológicos, incluindo topografia, cobertura do solo, padrões de uso da terra, distância de transporte e características da precipitação. Por exemplo, Wu et al. (2018) aprimoraram o modelo RUSLE ao incluir o grau de concentração da precipitação para captar melhor a dinâmica da erosão e da entrega de sedimentos nas bacias hidrográficas.

3.2.1. Aplicações e Avanços Recentes na Modelagem do SDR

Nos últimos anos, o modelo Sediment Delivery Ratio (SDR) tem sido amplamente aprimorado e aplicado para estimar a entrega real de sedimentos em bacias hidrográficas. Avanços importantes incluem a integração do SDR com modelos de erosão, como o RUSLE, e o uso de dados espaciais de alta resolução e variáveis hidrológicas, que aumentam a precisão das estimativas. Estudos recentes, como os de Ghimire et al. (2024) e Pérez-Cutillas et al. (2025) demonstram a eficácia do SDR para identificar áreas críticas de erosão e apoiar práticas de manejo sustentável. Além disso, melhorias metodológicas, como a incorporação da concentração da precipitação (Xu et al., 2022), aprimoram a modelagem do transporte sedimentar. Revisões recentes destacam os desafios relacionados à complexidade dos processos sedimentares e à qualidade dos dados,

indicando a necessidade de integração com tecnologias avançadas para futuras pesquisas.

3.3. Integração dos Modelos SWAT e SDR nas Análises de Sedimentação

A integração dos modelos hidrológicos SWAT (Soil and Water Assessment Tool) e SDR (Sediment Delivery Ratio) tem sido explorada para aprimorar a análise das áreas de sedimentação em bacias hidrográficas. Embora a combinação direta desses modelos ainda seja pouco comum, estudos aplicam o SWAT para simular a produção e o transporte de sedimentos, enquanto o SDR é utilizado para estimar a fração de sedimentos que efetivamente alcança os cursos de água.

Por exemplo, Lima et al. (2021) aplicaram o modelo SWAT na bacia do Rio Mutum Paraná, Rondônia, demonstrando sua eficácia na análise hidrossedimentológica. Araújo et al. (2019) destacaram a relevância da modelagem hidrológica com SWAT em relevo cárstico para compreender processos relacionados à água subterrânea, ainda que sem integrar diretamente o SDR.

Silva e Medeiros (2014) evidenciaram a eficácia do SWAT acoplado a Sistemas de Informações Geográficas na análise da produção de sedimentos e escoamento superficial, reforçando a importância da integração de ferramentas para a gestão dos recursos hídricos.

Dessa forma, a combinação dos modelos SWAT e SDR, mesmo que utilizada de forma complementar, oferece uma compreensão mais detalhada dos processos hidrossedimentológicos, contribuindo para a gestão sustentável e prevenção dos impactos da sedimentação em eventos de cheias e inundações.

Diversos estudos aplicando o modelo SWAT e outros métodos integrados têm demonstrado a capacidade de estimar a produção e o transporte de sedimentos em bacias hidrográficas, identificando áreas críticas para intervenções de manejo ambiental. Os principais desafios enfrentados envolvem a calibração do modelo devido à variabilidade espacial dos dados, a obtenção e atualização de informações precisas sobre uso do solo e solos, e a modelagem em regiões com alta heterogeneidade climática e geomorfológica. Estratégias eficazes incluem o uso de dados de alta resolução, integração com técnicas de sensoriamento remoto, monitoramento contínuo e a combinação de múltiplos modelos e índices de conectividade sedimentar.

4. Conclusão

A análise da sedimentação em bacias hidrográficas, especialmente durante cheias e inundações, é vital para entender a qualidade da água e a sustentabilidade dos ecossistemas. A Bacia Hidrográfica do Rio Inhanombe ilustra essa importância para a gestão de recursos naturais.

Os modelos SWAT e SDR são ferramentas importantes para simular a produção e o transporte de sedimentos. O SWAT modela processos hidrológicos e sedimentológicos em detalhe, enquanto o SDR estima a fração de sedimentos que chega aos corpos de água, ajudando a identificar áreas críticas.

Desafios incluem a calibração dos modelos, a busca por informações precisas sobre uso do solo e a complexidade dos processos ambientais. O uso combinado de ferramentas e um manejo adaptativo são essenciais para a conservação do solo e a sustentabilidade da água. A aplicação integrada dos modelos na Bacia do Inhanombe pode fornecer informações valiosas para uma gestão sustentável, reduzindo impactos da sedimentação e promovendo o equilíbrio ambiental da região.

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