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Fragmentation in the Environmental System of the Ecological Reserves in the Riparian Mangroves of Arroyo Moreno-Tembladeras Wetlands, Veracruz Mexico

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Abstract

Landscape fragmentation is a dynamic process with multiple effects. In addition to reducing the area of priority ecosystems such as mangroves, it also generates alterations in ecological functions and environmental processes, with significant socioeconomic and ecological consequences. The objective of this research was to determine the impact of anthropic development on landscape fragmentation within the Environmental System (ES) that includes the Arroyo Moreno Ecological Reserve (REAM) and the Tembladeras-Laguna Olmeca Ecological Reserve (RETLO), located in central Veracruz Mexico. Fragstats V4.3 Beta software was used to analyze landscape metrics at the patch, class, and landscape levels, using nine indicator metrics for assessing fragmentation. The analysis of the metrics at the three levels showed a reduction in the total area for some classes such as Mangrove (MG), Water Bodies (WB), and Agricultural and Livestock (AL). Class-level metrics such as total area, percentage of landscape, and number of patches showed greater differences for some classes between 2001 and 2023. However, some values increased in 2015. However, this research is considered the first study conducted in the area to comprehensively use a set of landscape metrics at three organizational levels, offering a more accurate description of the status of priority ecosystems (RAMSAR sites) such as the wetlands of the coastal zone of Veracruz. It also demonstrated the importance of the constantly expanding anthropic development in the study area over the last 20 years and the potential pressure it exerts on biodiversity conservation sites such as wetlands.

Keywords: mangroves; ecosystem fragmentation; habitat isolation; land use; anthropic development



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1. Introduction

Landscape fragmentation is the dynamic process by which continuous habitats are divided or reduced into smaller patches or isolated fragments due to natural or anthropic factors. These patches may be more or less connected to each other, forming a mosaic of habitats distinct from the original [1–3]. Fragmentation results in smaller, more isolated patches that are subject to intensified edge effects, often disrupting ecological balance and biodiversity [4–6].

Sustained anthropic disturbances are a primary driver of landscape fragmentation, leading to ecosystem degradation and loss of connectivity between ecological corridors [2,5,7]. Other fragmentation related impacts include reduced tree species diversity and size, as well as diminished structural diversity in forest canopy cover [8]. Once fragmentation begins, it can trigger cascading ecological effects, altering vegetation, soil composition, and hydrological processes [5,6,9].

Protected Natural Areas (PNAs) are designated conservation zones aimed at preserving ecosystems, habitats, and species. Globally, PNAs play a crucial role in conservation and ecological restoration. In Mexico, they fall under federal, state, or municipal jurisdiction and are protected by the General Law of Ecological Balance and Environmental Protection [10–13].

Despite their legal status, PNAs remain vulnerable to landscape changes, requiring continuous evaluation to ensure their effectiveness [14]. Even in RAMSAR designated mangrove areas, land use change is common near protected zones. This can accelerate other forms of environmental degradation such as soil erosion and tidal shifts, which further threaten the resilience of small mangrove patches [1]. The main threats to mangrove sustainability include coastal development, intensive aquaculture, deforestation, climate change, eutrophication, disease, and pollution [9].

In the state of Veracruz, 28 state level PNAs cover 83,439.97 hectares. However, wetlands especially mangroves represent only 2.1% of this area, despite their international importance as RAMSAR sites. In contrast, montane cloud forests and tropical dry forests occupy 31.25% and 25%, respectively [15]. Fragmentation of mangrove is especially critical in tropical and subtropical zones, their loss has become a major environmental issue in recent decades due to functional and ecological degradation, as well as the loss of essential ecosystem services [1,4,8].

Mangroves, located in tropical and subtropical coastal regions, play a critical role in supporting global biodiversity. Despite international conservation initiatives, mangroves are disappearing rapidly due to human-induced pressures [1,16]. These ecosystems support local communities by offering a wide range of ecological, economic, and social benefits [14]. Loss of mangrove cover contributes to increased habitat fragmentation, impairing ecosystem functionality and the services they provide to coastal populations [10,14].

Although mangroves are classified as high-priority conservation sites, formal protection mechanisms have only recently been implemented. For instance, the Arroyo Moreno Ecological Reserve (REAM) was established in November 1999, while the Tembladeras-Laguna Olmeca Ecological Reserve (RETLO) was designated in July 2014 [16,17]. These reserves hold high ecological value as they host both riparian mangroves and coastal dunes a rare habitat combination found only in the states of Tamaulipas and Veracruz. Although both Arroyo Moreno and Tembladeras are designated as PNAs, last one also recognized as a RAMSAR site, these legal designations have not resulted in greater protection for the ecosystems [16].

The main consequences of fragmentation include biodiversity loss, shifts in species composition, and alterations in ecosystem structure and function. In addition, edge effects can lead to changes in both biotic and abiotic conditions within habitat fragments. Biotic changes may affect the abundance and composition of species, directly impacting forest biodiversity. Abiotic changes are mostly associated with microclimatic conditions such as temperature, evapotranspiration, light exposure, wind speed, and humidity, all of which influence species abundance and ecological interactions [1,4,5].

Evaluations of conservation effectiveness in areas protected under the RAMSAR designation have shown promising results. These evaluations often include analysis of mangrove area dynamics, spatial shifts in centroids weighted by area, and changes in

landscape metrics, offering insights into the health and trends of these ecosystems [7]. Tropical forest regions are increasingly degraded and fragmented, posing a major threat to sensitive and endangered species that depend on them for survival [8].

Given their importance, a mangrove monitoring system has been introduced to assess the ecological health and conservation needs of these ecosystems [5]. However, both reserves continue to face environmental pressures that alter their structure and overall ecological integrity [18,19]. Akram et al. [9] identified major obstacles to mangrove restoration and sustainable management, including land use conflicts, weak regulatory frameworks, insufficient policies, and a lack of community awareness.

Landscape ecology provides critical tools for assessing environmental impacts through landscape metrics, allow comparisons of different landscape configurations across time within the same area, examine both composition (types of land cover) and configuration spatial arrangement of those land cover types [20,21]. Key variables in this type of analysis include patch shape and size, ecological corridors, habitat connectivity, and spatial distribution [1,8,20].

The evaluation of these metrics relies on specialized indices that quantify fragmentation complexity and scale [21]. Rivas et al. [22] emphasized the importance of grouping local fragmentation metrics such as area, edge, shape, and isolation to develop integrated indices for assessing fragmentation at the patch level. Consequently, further research is needed to identify how to prevent man-grove loss, restore connectivity among fragmented patches, and highlight the long-term ecological value of mangroves [1].

Analyzing landscape structure and ecological functionality is essential for developing effective conservation and land management strategies [23]. Landscape indices serve as valuable tools for urban planning, land use regulation, and ecosystem restoration efforts [21]. Additionally, the concept of an Environmental System (ES) is widely applied in Environmental Impact Assessments (EIA), providing a spatial framework for environmental monitoring and policy making [12,24].

Loss of mangrove cover contributes to increased habitat fragmentation, impairing ecosystem functionality and the services they provide to coastal populations [25]. This generated the following research question: What are the dynamics of land use change and landscape fragmentation in the Arroyo Moreno-Tembladeras Environmental System in the coastal zone associated with mangroves during the period from 2001 to 2023? Therefore, the hypothesis was raised that “The dynamics of land use change in the Arroyo Moreno-Tembladeras Environmental System in the coastal zone associated with mangroves during the period 2000 to 2023, showed a trend towards an increase in the area of anthropic use and landscape fragmentation.” Therefore, the objective of this research was to determine the impact of anthropic development on the landscape fragmentation within the Environmental System (ES) that includes the Arroyo Moreno Ecological Reserve (REAM) and the Tembladeras Ecological Reserve (RETLO), located in central Veracruz Mexico.

2. Materials and Methods

2.1. Study Area

This study focuses on two ecological reserves: the Arroyo Moreno Ecological Reserve (REAM) and the Tembladeras–Laguna Olmeca Ecological Reserve (RETLO). These areas have been delineated as a single Environmental System (ES) due to the ecological interdependence between their ecosystems. REAM encompasses the Arroyo Moreno mangrove area, while RETLO serves as a hydrological regulation basin within the coastal plain [18,19]. Originally catalogued as a Natural Protected Area with a surface area of 284 hectares, the Arroyo Moreno Ecological Reserve currently covers approximately 249 hectares. In contrast, the Tembladeras wetland spans an area of approximately 1415 hectares. The study

area lies within the Jamapa River sub-basin and is strongly influenced by the hydrological and ecological processes of the Jamapa River (located south of REAM), the associated wetlands of the Arroyo Moreno Reserve, and the San Francisco River, which is situated near Tembladeras [26].

For the purposes of this research, the study area was delineated as an influence zone for the coastal region, encompassing an estimated total area of 4550.71 hectares (Figure 1). The defined polygon intersects the municipalities of Veracruz, Boca del Río, and Medellín, with the following vertex coordinates: 794,801.765711, 2,111,420.720572; 804,017.264684, and 2,119,794.332074. The study area, part of the Veracruz Coastal Plain, is primarily composed of vertisol soils (86.7%) and, to a lesser extent, regosols (13.3%). The wetland system exhibits a marked seasonality that allows for the differentiation of two main climatic periods. The first is known as the “Norts” season, which spans September to April, and is characterized by low precipitation, cooler air temperatures, and frequent incursions of cold air masses from the northern continent. The second is the rainy season, from May to August, marked by high temperatures, intense precipitation between June and August, and light easterly winds [27–29].

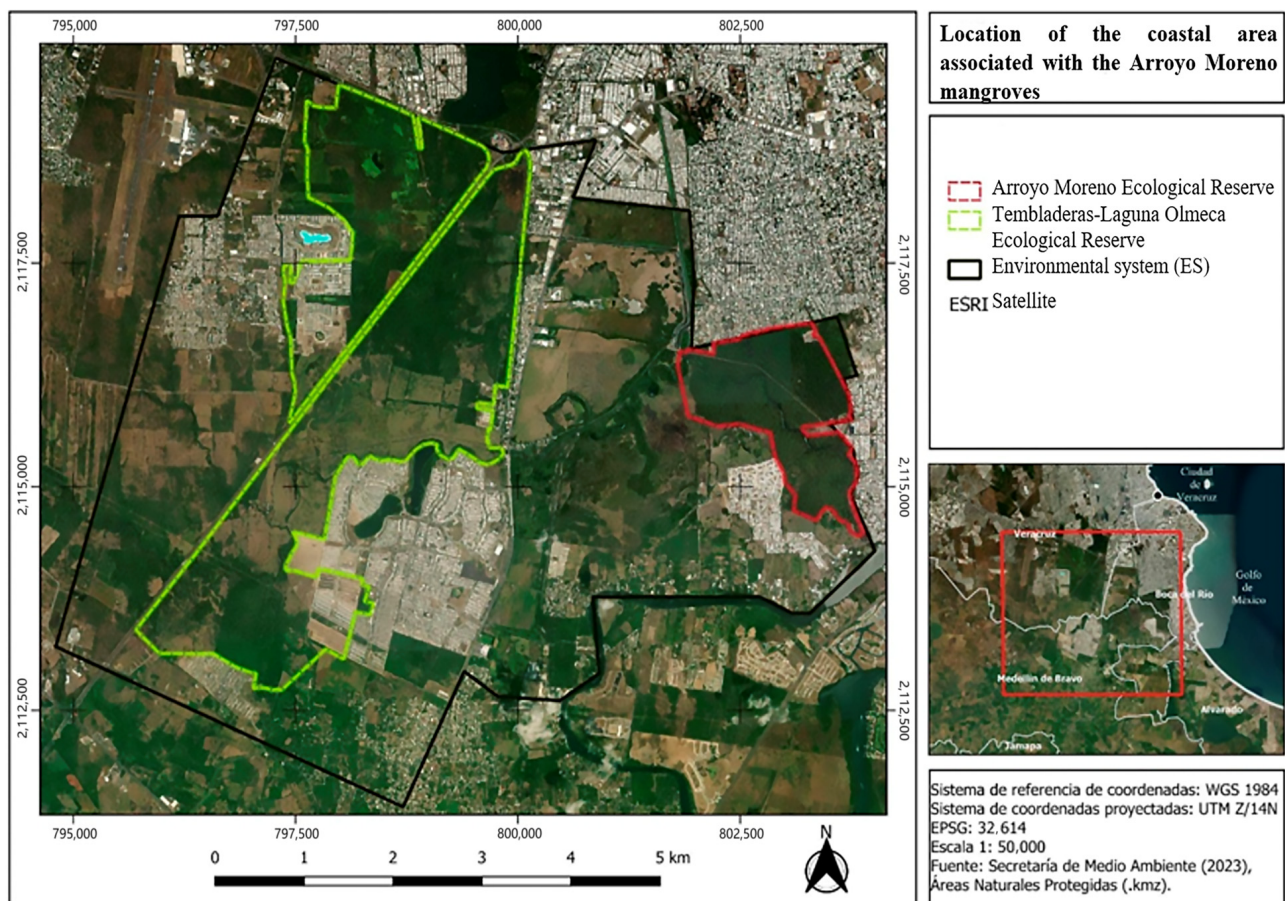


Figure 1. Study area delineated within the Environmental System (ES), encompassing the Arroyo Moreno Ecological Reserve (REAM) and the Tembladeras-Laguna Olmeca Ecological Reserve (RETLO). The polygon represents the influence zone across the municipalities of Veracruz, Boca del Río, and Medellín, based on WGS 1984, UTM Zone 14N (EPSG: 32614) spatial reference.

The study period covers 20 years following the official designation of the Arroyo Moreno Ecological Reserve, enabling a longitudinal analysis of landscape fragmentation. This time frame was selected to allow a comparative assessment of ecosystem changes over

time. Analyses focused on the rainy season months, during which vegetation cover is most representative of natural environmental dynamics.

2.1.1. Delimitation of the ES Arroyo Moreno-Tembladeras

The ES delimited in the study area considered the integration of two protected natural areas (PNAs) under state jurisdiction, Arroyo Moreno and Tembladeras; these areas are part of a system of urban wetlands that includes mangroves and interdune lagoons and forms part of the coastal dune system in the central region of the state of Veracruz, Mexico [18–20,27].

One of the most important characteristics of the Arroyo Moreno and Las Tembladeras ecological reserves is that they are surrounded by the urban areas of three municipalities [29–31], which are constantly developing and growing.

This ecosystem as a whole is recognized as a tree lung in the Veracruz metropolitan area due to its importance to the region [18,27]. This environmental system provides various ecosystem services included in the 2030 Agenda for Sustainable Development Goals and targets. These include: biodiversity protection, groundwater recharge and water supply for several municipalities in the region, climate regulation in the area and flood mitigation, among others.

2.1.2. Flora and Fauna with Special Protection in Ecological Reserves

In the case of the flora of Arroyo Moreno, this coastal mangrove is located on the banks of the river of the same name, therefore, it has a greater influence of fresh water that reduces salinity stress. However, the mangrove species that make it up have the basic structure of the Gulf of Mexico mangroves, consisting of species such as *Laguncularia racemosa*, *Rhizophora mangle*, *Avicennia germinans* and *Conocarpus erectus* [18,20,31].

In terms of fauna, Arroyo Moreno is home to a rich biodiversity of birds and other specially protected organisms, including priority bird species such as *Actitis macularius* and other endangered species such as the Canadian swallow (*Tachycineta bicolor*) and the red-tailed hawk (*Buteo jamaicensis*) [11,13,15,18].

The vegetation of Tembladeras-Laguna Olmeca consists of wetlands, mainly lowland floodplain forest, popal and tular; meanwhile, the fauna prioritised for conservation includes the American stork (*Mycteria americana*), which is subject to special protection, and the boa (*Boa constrictor*), which is classified as a threatened species [19,27].

The Arroyo Moreno-Tembladeras Environmental System (ES) is a vital habitat for migratory bird species, highlighting the need to preserve it and, crucially, to maintain connectivity between mangrove fragments and wetlands. Due to its ecological significance, the region is designated as an Important Bird Conservation Area (IBA), specifically “Central Veracruz” (IBA 150), which is home to approximately 236 migratory bird species [17,19].

2.2. Geographic Information Analysis

A supervised classification using the maximum likelihood algorithm was performed in QGIS 3.28.8 Firenze, employing the Semi-Automatic Classification Plugin (SCP) version 7.10.11 both open-source tools. Geographic data were reviewed and compared through visual interpretation (photointerpretation) supplemented by Google Earth Pro 7.3.6, which also served to generate orthophotos; these tools facilitated preprocessing, classification, and post-processing workflows [31].

Additionally, as part of the training and validation protocol for the study area, visits were conducted in three ways: on foot, by boat, and with unmanned aerial vehicles (UAVs) to take aerial photographs of the watershed and its area of influence in the study area. With this, the main land uses and the main Point Sources of Pollution (PSPs) were identified. These sites were georeferenced and mapped using ArGis 10.3.

The classification incorporated aerial imagery captured by a Mavic Air 2S UAV, and the land cover categories were based on official land use and vegetation maps for mangrove ecosystems, obtained in Shapefile format from the National Biodiversity Information System Geoportal (CONABIO) [32,33]. Landsat 7 and Landsat 8 satellite images for 2001, 2015 and 2023, were obtained from the United States Geological Survey (USGS) database [34].

2.3. Landscape Metrics

For the landscape analysis, two primary subsystems were distinguished: A natural subsystem, consisting of mangroves, wetlands, and water bodies within the Tembladeras and Arroyo Moreno reserves. An anthropic subsystem, including urban development, agricultural-livestock areas, secondary vegetation, and non-vegetated surfaces. The analysis of landscape fragmentation patterns was carried out using the FRAGSTATS v4.3 Beta software [35–41].

The land cover classes identified in the classification maps were grouped based and adapted from CONABIO, with modifications based on the works of Acosta et al. [41] and Ciprés-Chávez [38]. Landscape metrics have been widely used to link spatial patterns with ecological processes and functions [30,39]. The term “fragment”, often used interchangeably with “patch”, refers to relatively homogeneous morphological units within a landscape [40].

2.3.1. Patch-Level Characterization

This analysis considered the patches corresponding to the natural and anthropic subsystems, allowing for the assessment of their size using area and perimeter metrics [42,43]. Patch-level metrics are calculated individually for each fragment within a land cover class, with mean values and their corresponding ranges reported. This makes it possible to determine the largest fragment represented across the study area [30,41].

2.3.2. Class- and Landscape Level Characterization

The quantitative analysis of fragmentation at the class level was carried out using metrics such as: Total patch area; Number of patches (NP); Edge density; Shape Index; and the Euclidean nearest-neighbor distance and patch cohesion index. These metrics reveal changes associated with fragmentation processes and contribute to understanding connectivity between fragments of the same ecosystem (Table 1). The metrics obtained from the class analysis were presented in land use maps during the study period.

Table 1. Characteristics and description of landscape metrics used in the study area.

Category	Landscape Metrics	Acronym	Range (Unit of Measurement)	Description
Aggregation	Number of patches	NP	Without limit	Corresponds to the count of fragments within each land cover class.
	Percentage of Landscape	LAND	$0 < \text{LAND} \leq 100$ (%)	An area and edge metric that reveals the percentage of the landscape belonging to class <i>i</i> .
Area	Total Patch Area		Ha (without limit)	Calculated as the sum of the areas (m ²) of all patches belonging to a given ecosystem unit, then converted to hectares by dividing by 10,000
Subdivision	Patch density	PD	PD > 0, constrained by cell size. (Number per 100 ha)	The number of patches of the corresponding patch type divided by the total landscape area (m ²).

Table 1. *Cont.*

Category	Landscape Metrics	Acronym	Range (Unit of Measurement)	Description
Contrast	Total Edge		(m)	The perimeter of the ecotone (transition zone) at the class or landscape level.
	Edge Density		(m/ha)	Represents the total length (m) of all patch edges relative to the landscape area and helps evaluate spatial configuration.
Shape	Shape index	SI	SI > 1, without limit	A value close to 1 indicates compact (square or circular) patches, whereas higher values reflect more complex or irregular shapes
Aggregation	Euclidean nearest neighbor distance	ENND	ENND > 0, without limit. (m)	ENND increases when the mean distance of patches from each type increases.
	Cohesion		0–100%	It evaluates the degree of aggregation and dominance of the coverages that make up a given landscape. Increases as the aggregation and clustering of the coverage increases.
Diversity	Shannon's diversity index	SHDI	SHDI $\geq$ 0 (No diversity), without limit	SHDI increases as the evenness and richness of patch types increase. SHDI value of zero indicates a landscape composed of a single patch, i.e., no diversity.

Source: McGarigal and Marks [35–37,42,43]; Bihamta-Toosi et al. [39].

Class-level analysis groups fragments of the same land cover class—i.e., those representing the same land use or habitat type [41,43]. Some of the indices directly describe the degree of fragmentation (Table 1). In the case of NP, an increase indicates greater fragmentation, reflecting a finer mosaic grain and higher spatial heterogeneity [42–44]. The shape index indicated that more rounded and larger patches generally offer better ecological conditions for fauna, particularly specialist species adapted to interior environments due to lower exposure to external disturbances [43–45]. The ENND informs the degree of isolation between fragments: lower values indicate increased proximity, potentially due to the emergence of new patches; higher values suggest greater isolation [43,46].

At the landscape level, the analysis considered all patches and land cover classes as part of a complete mosaic [36,43]. The metrics used for the analysis at this level were described in Table 1. Among these, the diversity indices are used to assess landscape composition and structure, due to their sensitivity to ecosystem richness and dominance. Shannon Diversity index evaluates landscape heterogeneity based on the diversity of patches, making it useful for comparing different landscapes or changes over time, being particularly sensitive to the presence of rare classes [43,47].

3. Results

3.1. Patch-Level Characterization

This research is the first study to report land use changes and assess the impact of anthropic development using multiple landscape metrics over the last 22 years. The use of these indices as a tool for comparative temporal analysis can offer a clearer perspective on the evolution of trends in the region in the medium and long term.

At the patch level, the natural component showed the smallest changes in average area across its three classes during the 2001–2023 period. However, variations in maximum

size were evident for the mangrove (MG) and aquatic (WB) classes (Table 2). The former recorded 190.80 ha in 2001 and 103.32 ha in 2023; for WB, the area was 8.82 ha in 2001 and 2.43 ha in 2023.

Table 2. Patch-level metrics in the Environmental System (ES) for the years 2001, 2015 and 2023.

Land Use	Class	2001		2015		2023	
		Average Area (ha)	Area Range (ha)	Average Area (ha)	Area Range (ha)	Average Area (ha)	Area Range (ha)
Natural	Mangrove	4.489	0.09–190.80	5.968	0.090–527.85	4.648	0.090–103.32
	Water bodies	0.310	0.090–8.82	0.385	0.090–4.32	0.372	0.090–2.43
	Other wetlands	1.224	0.090–179.28	0.924	0.090–151.02	1.178	0.090–221.22
Anthropic	Anthropic development	0.654	0.090–119.43	4.364	0.090–209.97	3.483	0.090–372.78
	Agriculture/livestock	3.391	0.090–612.54	2.410	0.090–397.44	1.364	0.090–220.05
	Other vegetation	1.457	0.090–284.22	1.819	0.090–146.43	2.733	0.090–160.56
	No vegetation	0.973	0.090–67.50	0.372	0.090–6.48	0.572	0.090–25.38

The anthropic component in the period from 2001 to 2023 showed an increase in area for the anthropic development (AD) and other vegetation (OV) classes; in contrast, a decrease occurred in the areas of agriculture/livestock (AP) and the no vegetation (NV) class. In 2015, class AD had the largest average area with 4.364 ha, while in 2023, the average area was 3.483 ha. However, the maximum value recorded for this class was obtained in 2023 with 372.78 ha (Table 2).

The greatest reduction was recorded in the AP class, which decreased from 3.391 ha and a maximum area of 612.54 ha in 2001; in 2023, the average area was 1.364 ha, and the maximum area decreased to 220.05 ha. The OV class also showed a tendency to double its area, with 1457 ha in 2001 and reaching an area of 2733 ha in 2023.

3.2. Class and Landscape Level Characterization

The anthropic component had the largest total area in 2001, where the AL class, with 1454.76 ha (Table 3), corresponded to 35.70% of the landscape, followed by the OW class of the natural component with 905.67 ha (22.23% of the landscape) (Figure 2). Another class with greater representation in 2001, corresponded to OV 680.22 ha, this represented 16.69% of the landscape; The remaining classes accounted for less than 10% of the landscape in 2001.

Table 3. Class-level analysis of land use in the Environmental System (ES) in 2001.

Land Use	Class	Total Area (ha)	% LS	NP	PD N/ha	Total Edge (m)	Edge Density (m/ha)	Shape Index	EDNN (m)	Cohesion %
Natural	Mangrove	215.46	5.28	48	1.17	41,640	10.22	1.41	128.80	97.47
	Water Bodies	157.86	3.87	508	12.46	113,640	27.89	1.16	97.13	68.33
	Other Wetlands	905.67	22.23	740	18.16	354,810	87.09	1.28	80.72	94.81

Table 3. Cont.

Land Use	Class	Total Area (ha)	% LS	NP	PD N/ha	Total Edge (m)	Edge Density (m/ha)	Shape Index	EDNN (m)	Cohesion %
Anthropic	Anthropic Development	308.79	7.57	472	11.58	120,600	29.60	1.16	107.89	91.03
	Agricultura/livestock	1454.76	35.70	429	10.53	341,250	83.76	1.32	76.78	98.16
	Other Vegetation	680.22	16.69	467	11.46	212,190	52.08	1.28	82.52	95.60
	No Vegetation	351.27	8.62	361	8.86	129,150	31.70	1.24	95.49	90.81

Abbreviations: %LS: % of Landscape; NP = Number of patches; PD = Patch Density; N = Number; m = Meters; EDNN = Euclidian Distance to the Nearest Neighbor.

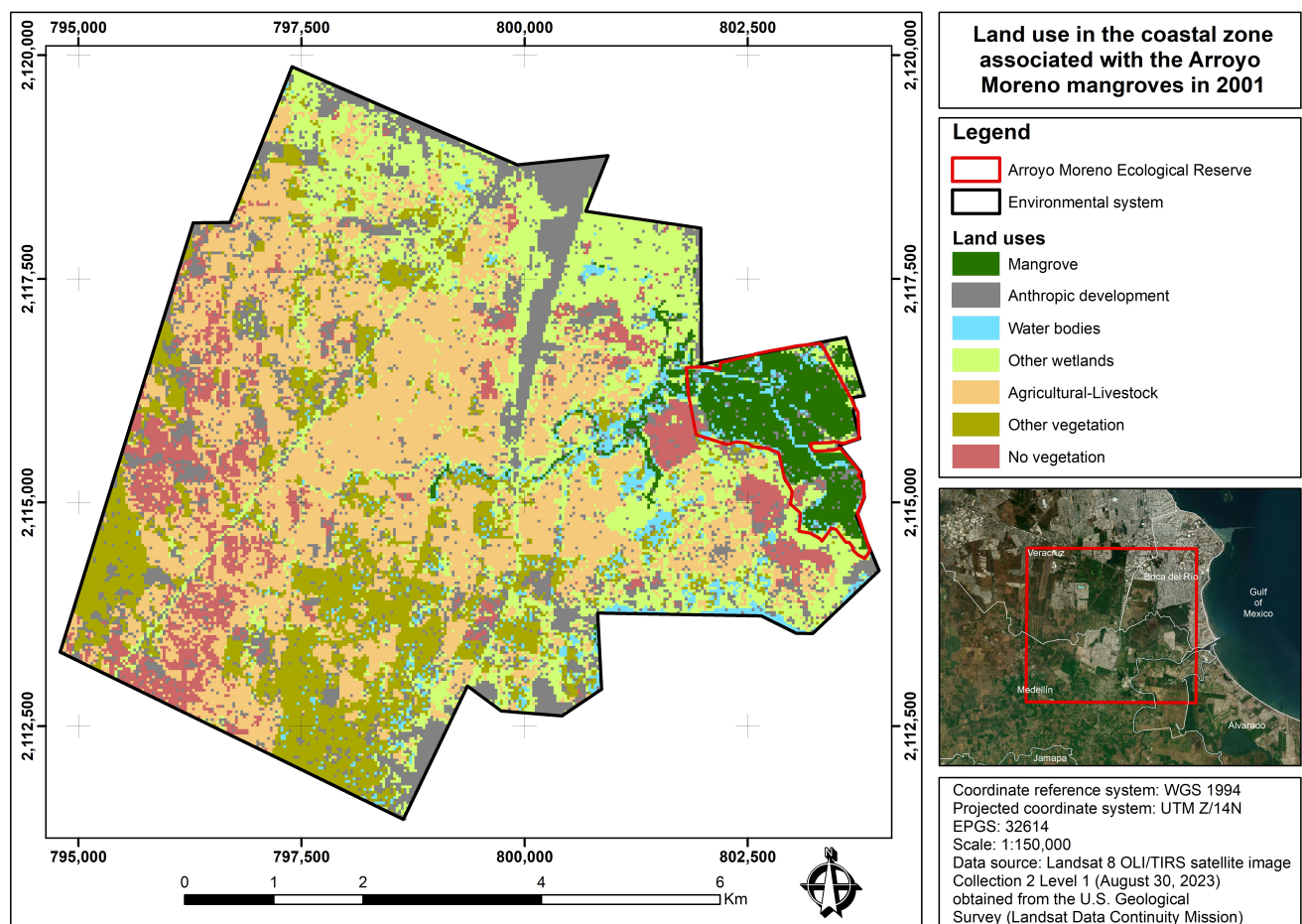


Figure 2. Land use changes in the Environmental System (ES) of the Arroyo Moreno riparian mangrove and Tembladeras ecological reserves Veracruz Mexico in 2001.

Landscape metrics varied across most of the values for the natural and anthropic component classes. However, the OW class had the highest values for NP, PD, total edge, and edge density. In the case of the anthropic component, the classes with the highest values for these metrics were AD and AL.

The shape index values for all classes and both land-use categories were greater than 1. The highest value was observed in the MG class, which had the highest value for the EDNN metric, and for the anthropic component, the highest value was observed in the AD class. The cohesion index for all classes had a value greater than 90, with the exception of the WB class.

The area analyses for the years 2015 and 2023 showed greater variation for the natural and anthropic components (Table 4), with the MG, WB, AL, and AL classes showing the greatest change trends. In 2015, the MG class had the largest total area for the natural component, at 1402.56 ha and representing 30.95% of the landscape; while in 2023, this class, at 181.26 ha, represented 4.83% of the landscape (Table 5). The OW class showed less variation in its total area in 2015 and 2023. However, the WB class had a higher value in 2015 and reduced its area by half by 2023.

Table 4. Class-level analysis of land use in the Environmental System (ES) in 2015.

Land Use	Class	Total Area (ha)	% LS	NP	PD N/ha	Total Edge (m)	Edge Density (m/ha)	Shape Index	EDNN (m)	Cohesion
Natural	Mangrove	1402.56	30.95	235	5.18	210,540	46.47	1.25	97.89	97.69
	Water bodies	23.49	0.518	61	1.34	14,490	3.19	1.13	229.60	70.88
	Other Wetlands	687.15	15.16	744	16.42	343,350	75.78	1.24	88.45	91.75
	Anthropic Development	257.49	5.68	59	1.30	45,270	9.99	1.24	213.13	96.79
Anthropic	Agricultural Livestock	1190.52	26.27	494	10.90	407,850	90.02	1.32	80.40	96.59
	Other Vegetation	891.54	19.67	490	10.81	317,730	70.13	1.28	85.52	93.15
	No Vegetation	77.76	1.71	209	4.61	54,810	12.09	1.12	139.00	65.76

Abbreviations: %LS: % of Landscape; NP = Number of patches; PD = Patch Density; N = Number; m = Meters; EDNN = Euclidian Distance to the Nearest Neighbor.

Table 5. Class-level analysis of land use in the Environmental System (ES) in 2023.

Land Use	Class	Total Area (ha)	% LS	NP	PD N/ha	Total Edge (m)	Edge Density (m/ha)	Shape Index	EDNN	Cohesion
Natural	Mangrove	181.26	4.83	39	1.03	9990	2.66	1.33	145.90	96.13
	Water Bodies	8.55	0.22	23	0.61	1530	0.40	1.16	294.82	64.68
	Other Wetlands	858.51	22.88	729	19.43	236,610	63.08	1.31	78.84	93.33
	Anthropic Development	1051.83	28.04	302	8.05	116,100	30.95	1.29	101.10	96.97
Anthropic	Agricultural Livestock	699.84	18.65	513	13.67	157,560	42.00	1.23	84.30	94.63
	Other Vegetation	841.68	22.43	308	8.21	148,890	39.69	1.30	90.66	95.85
	No Vegetation	109.26	2.91	191	5.0921	37,620	10.02	1.13	166.81	81.61

Abbreviations: %LS: % of Landscape; NP = Number of Patches; PD = Patch density; N = Number; m = Meters; EDNN = Euclidian distance to the nearest neighbor.

The AL class showed a notable decrease compared to 2001 with 35.70%, 26.27% in 2015, reaching only 18.67% in 2023. Furthermore, the AL class showed a drastic reduction in its total area and percentage of landscape compared to the AD class. For the same period, the highest percentages corresponded to the AD (Anthropic Development) class with 28.04% and the OV (Other Vegetation) class with 22.43%.

The NP, DP, total edge, and edge density metrics showed the highest values for the OW and AL classes during 2015 and 2023. The NP showed a significant reduction in the WB class, with only 23 patches, followed by MG (Mangrove), also with 39 patches in 2023 (Table 5). The remaining anthropic component classes in 2023 showed higher total edge and edge density values compared to the natural component classes. The Shape Index was greater than 1 for all classes in 2001, 2015 and 2023. In 2023, the MG class had the highest

value among natural classes with 1.33; for anthropic classes, OV reached the highest value with 1.30 in the same year.

Regarding the EDNN, WB presented the highest value among the classes and for the natural and anthropic components with 294.82 in 2023. For the anthropic component in the same, the highest EDNN values were found in NV in 2015 and 2023, the latter with a value of 166.81. Meanwhile, AD had a maximum EDNN value in 2015 with 213.13 m. The cohesion index values mostly exceeded 90% for both the natural and anthropic component classes, with the exception of the WB class with the lowest value of 68.3% in 2001 and 64.68 in 2021. In 2015, the lowest value was recorded throughout the study period with 65.76%, followed by the WB class with 70.88%.

The dynamics of land-use change in relation to the total area and landscape percentage of the classes showed greater increases for AD and OW in 2023 (Figure 3). Drone flights and tours in the study area demonstrated similarities with the landscape metrics generated for the years analyzed. Similarities in the distribution of uses for the year 2023 were highlighted, especially for urban growth in the area (Figure 4). This contrasts with the reductions in total area and landscape percentage for the AL, WB, and MG classes (Figure 2). The aforementioned variations demonstrate a dynamic characterized by gains and losses in total area between the same classes and the natural and anthropic components over the past 22 years.

Therefore, land use in the study area during 2001, 2015, and 2023 represents the transformation of an area categorized as a state ecological reserve. This demonstrates how anthropic activities and natural components are undergoing constant changes, which were evident over a period of less than 10 years.

At the landscape level, the metrics showed the greatest variation between 2001 and 2023. However, the highest values for total area and NP were recorded in 2015 (Table 6). In 2023, these metrics decreased: the total area was reduced to 3750.93 ha, with a reduction of 920 patches, and the total edge to 354,150 m. However, the highest value for NNED was recorded in 2015. The Shape and Shannon Diversity indices showed minor variations across the three reported years, remaining within a range of 1.58–1.68, with a maximum value in 2001.

Table 6. Landscape-level metrics in the environmental system (ES).

Year	Total Area (ha)	NP	Total Edge (m)	Shape Index	EDNN (m)	Shannon Diversity Index
2001	4074.03	3025	656,640	1.24	89.96	1.68
2015	4530.51	2292	697,020	1.25	98.63	1.58
2023	3750.93	2105	354,150	1.27	96.68	1.60

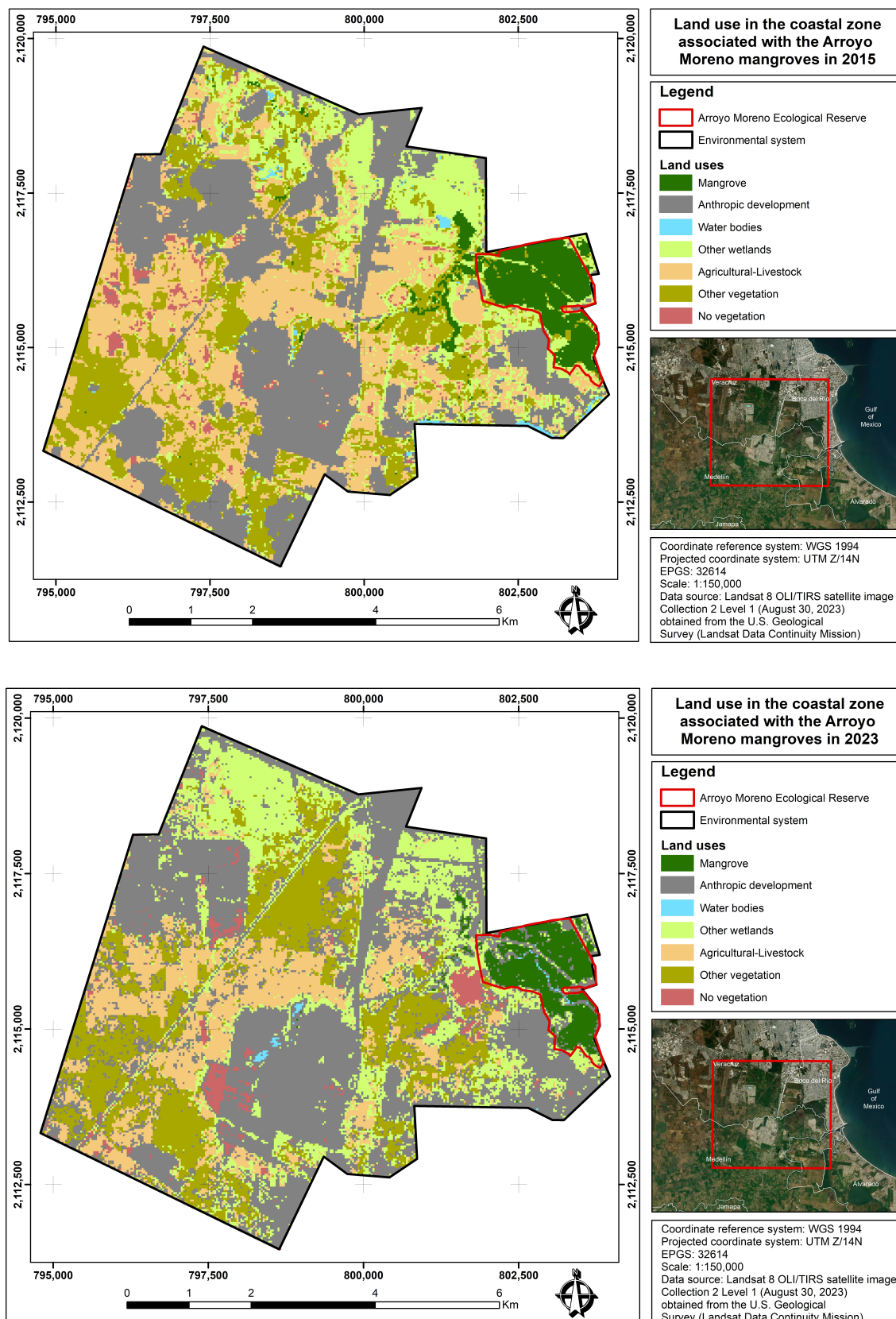


Figure 3. Land use changes in the Environmental System (ES) of the Arroyo Moreno riparian mangrove and Tembladeras ecological reserves Veracruz Mexico in 2015 (Up) and 2023 (Down).

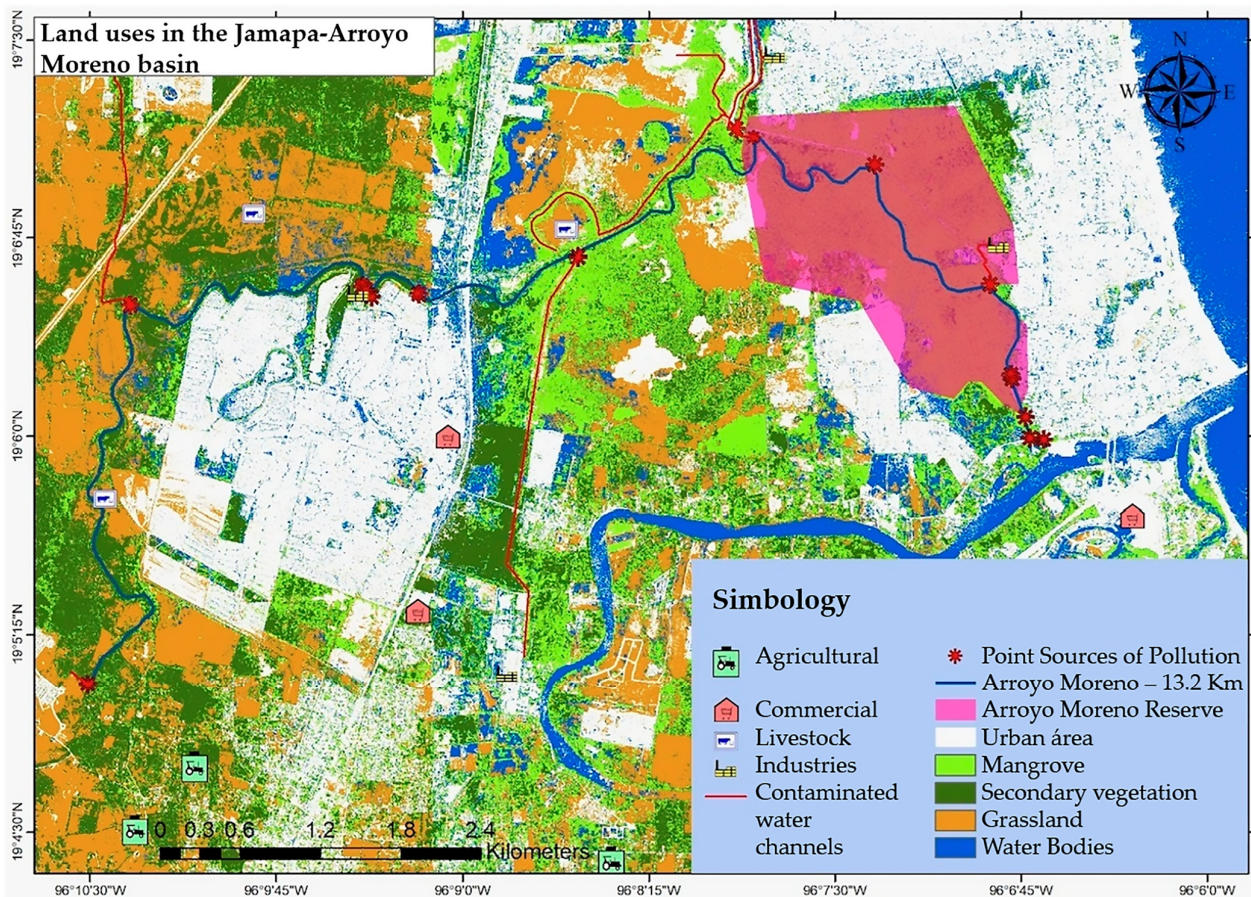


Figure 4. Identification of land uses and point sources of pollution in the Jamapa-Arroyo Moreno basin, Veracruz, Mexico. Authorship: Luis Antonio Peña Dorantes.

4. Discussion

4.1. Patch-Level Characterization

This research is the first to be conducted in the area, covering a 20-year historical period and incorporating different levels of analysis and landscape metrics. Analysis of landscape metrics in the study area showed that the minimum detectable patch area was 0.09 ha; however, although the areas with pixels below the detection threshold could be considered, they may not have been correctly considered due to the marked decrease in WB classes. Through the review of the land use areas presented in Figure 4, it was identified that the Arroyo Moreno ecological reserve and the wetlands associated with anthropic development in the area overlap.

Furthermore, the environmental system (ES) includes an ecosystem such as the Arroyo Moreno riparian mangrove, which has unique hydrological conditions, such as a significant input from the Arroyo Moreno River and minimal marine influence. The Arroyo Moreno and Tembladeras Ecological Reserves represent areas of considerable biological and ecological importance, serving as refuges for diverse species of fauna and flora [19,27].

Despite their importance, research in these areas has been limited, focusing primarily on the analysis of flora and fauna diversity [18,19]. Likewise, there is minimal information on land use change and trends for the ecosystems comprising the Arroyo Moreno riparian mangrove and the Tembladeras wetlands [29]. One of the most recent investigations was conducted by Peña-Dorantes et al. [31] who reported the presence of 15 points sources of pollution (PSP), which were detected using artificial intelligence, obtained similarity percentages of up to 92%.

The results obtained for the total area in the three periods analyzed showed fluctuations, with the 2015 period showing the highest values for almost all analyzed periods. However, the upward trend is notable for the anthropic component classes, such as AD and OV. Likewise, during this same period, a trend in land use changes in the AL class is evident, generating a significant increase that tripled the area for the AD class. The total area value is a metric that helps define coverage trends by exploring the spatiotemporal characteristics of landscape fragmentation, and the ecological implications for ecosystems [40,46,48]. Changes in mangrove area worldwide during the period 1996–2016 are primarily caused by anthropic disturbances, which led to significant degradation and loss of these ecosystems [25,49].

Coinciding with the impact of the total area from the patch-level analysis, a significant reduction in the maximum values of the total area is evident for the natural component classes such as MG and WB. However, the value of their average area remained the same for these classes, and only the OW class showed an increasing trend in maximum size. These changes in the classes of other wetlands can be related to ecological succession, driven by the reduction in area for the MG and WB classes, the latter of which is considered the most impacted.

The decrease in area and, therefore, their fragmentation has substantial implications for the conservation of mangrove ecosystems. Edge effects can be considered even more significant in ecosystems such as mangroves; they can be more influential in sites where the area-to-perimeter ratio is higher for smaller, irregularly shaped patches, compared to large or regularly shaped patches [30,46,47].

4.2. Class and Landscape-Level Characterization

Over the 22-year analysis period, this study identified an increase in the number of fragments and a decrease in their size primarily for the natural component land use classes. Meanwhile, the anthropic land-use classes showed an increase in both their size and number of fragments.

Various studies report different NP and area values, mainly associated with the specific conditions of the different studies, but they agree on the impact of fragmentation generated in these ecosystems. Kanniah et al. [1] reported an increase in the NP from 130 to 402 ha, as well as a reduction in the average size of mangrove patches from 105 ha to 27 ha. Valdez-Leal et al. [50] reported a NP of 1052 in an area of 172,491.09 ha, indicating that larger fragments contribute more to species conservation. Herbeck et al. [51] indicated the fragmentation of mangrove areas, from 230 larger patches to 2134 smaller ones, which generates a serious impact on the functionality of the ecosystem. Then, more isolated areas, increasing the overall irregularity and separation across the area, which could have an ecological impact [52].

In the study area, the NP showed the greatest changes in the WB and AL classes; while the MG class also showed a decrease in the number of patches and a reduction in total area, indicating that mangrove patches are becoming increasingly isolated. The presence of smaller and isolated patches is closely related to fragmentation, where the effects generated in an ecosystem include greater isolation, distortion of the shape complexity, contributing to an increase in the edge effects, an impact on ecological stability by reducing species populations (loss of biodiversity) and processes such as migration and gene flow, and even causing microclimatic alterations [1,10,39,53–58].

Various types of effects of fragmentation on biodiversity have been reported [52,59–61]. Emphasized that the sensitivity of organisms to fragmentation is influenced not only by their degree of habitat specialization but also by their dispersal capabilities [58].

Protected natural areas (NPAs) are subject to diverse pressures that influence both within and outside the area [3,41,54,56,62]. However, the NPA remain one of the most critical tools for biodiversity conservation [53]. A relationship between plot size and frequency can be identified, with an increase in the number of small plots, a decrease in the number of medium-sized plots, and very few large plots [55,56].

Regarding SH, the values obtained for the study period indicate that although the area is smaller, its shape can be considered regular; according to McGarigal and Marks [42], values close to or equal to 1 indicate that the polygons are circular and compact. Therefore, more circular fragments tend to experience fewer edge effects and less external interference [1,10,30,40]; the intensification of the edge effect in modified landscapes can increase landscape contrast and accelerate degradation processes [57,58,63].

The use of multiple metrics offers a more complete understanding of ecosystem changes, such as fragmentation; however, the NP value alone has limited interpretive value, as it does not provide information on patch area, distribution, or density [42]. Meanwhile, metrics such as mean patch size and average distance between the closest patches are easily interpretable and ecologically relevant as they correlate closely with the total ecosystem extent [25,64].

In the case of metrics such as ENND, an increase in its value may indicate the aggregation of multiple fragments that were previously very close [43,52]. In the study area, it was identified that the DA class of the anthropic component presented the greatest average distance between fragments, indicating a greater closeness of the fragments, related to the increase in the area for this class. In contrast, Mendoza et al. [65] reported that, fragment size reductions were directly related to increases in inter-fragment distance.

Coastal zones worldwide are under constant pressure from human activities, including diverse productive uses, urban growth, and pollutant discharges [1,30,50]. According to the Monitoring the Mangroves of Mexico initiative [66] and Díaz-Gallegos et al. [67], mangrove coverage in Veracruz declined between 1976 and 2020, despite the expansion of state-level Natural Protected Areas (NPAs).

Urban expansion within the study area of this research represents one of the pressures with the greatest impact on the riparian mangroves Arroyo Moreno and wetlands of Tembladeras (Table 7). According to the Veracruz Metropolitan Area Planning Program, the three municipalities within the study area have experienced continuous population growth over the past 50 years. They also indicated that the population increase was 2.30 times during the period 1980–2021; while the urban area increase was 9.48 times during the period 1980–2021, and the total land gain during the period 2000–2021 was 10,500 hectares of urban land [68].

Table 7. Population growth in the municipalities of the environmental system (ES).

Municipality	1980	1990	2000	2010	2020
Metropolitan Area of Veracruz (MAV)	468,764	580,016	708,400	834,256	939,046
Boca del Río	61,883	144,549	135,804	138,058	144,550
Veracruz	305,456	328,607	457,377	552,156	607,209
Medellín	25,436	29,298	35,171	59,126	95,202

Source. Territorial Planning Program for the Metropolitan Area of Veracruz (TPP ZMV) [68]. Note: The next National Population and Housing Census in Mexico will be conducted in 2030.

Population growth in the region has generated a pollution problem of water pollution in the watershed and in the Arroyo Moreno has been highlighted, primarily due to the discharge of untreated wastewater, originating primarily from residential areas [1,30]. Wu et al. [69] indicated that the analysis of causal factors has a key effect and influences landscape ecological risk, such as distance from roads and cities, light pollution, and

precipitation. Therefore, landscape ecological risk can be influenced by both natural conditions and human activities in a region [69,70]. In the study area, the primary threat to mangrove ecosystems is urban development, while agricultural and livestock activities have shown a significant decline in their impact.

Furthermore, the pressure exerted by anthropic expansion has become increasingly evident, particularly due to the proximity of the Arroyo Moreno–Tembladeras ES to areas undergoing urban development and land use change. The orthomosaics covering a total of 70 hectares, corresponding to the eastern section of the Arroyo Moreno Reserve (REAM) and the northern part of the Tembladeras Reserve, demonstrate notable proximity to anthropic development within their respective zones of influence.

Landscape-level indices provide quantitative information on landscape composition and configuration, including the proportion of each land cover, the area, and the shape of landscape elements [39,71]. In the case of the study area, landscape-level characterization did not show changes as pronounced as those observed at the class level. However, it did reveal a reduction in total area, indicating a potentially negative long-term trend.

Shannon Diversity values showed consistent behavior at the class and landscape levels during the years 2001, 2015, and 2023. Because this index falls under the category of diversity metrics, its stability suggests that there was no substantial increase in the composition or predominance of specific land covers in the landscape [42,43]. However, a reduction in total area and NP was observed by 2023.

The monitoring the spatial distribution and area changes of mangroves facilitates deeper exploration of their ecological transformations and resource dynamics [72]. Understanding the dynamics of an environmental system such as Arroyo Moreno–Tembladeras must consider not only a multi-temporal analysis of changes in land use [73,74], but also include information on the levels of human intervention and pressures exerted on the landscape and at the level of the hydrological basin.

5. Conclusions

The Environmental System (ES) comprising the ecological reserves of Arroyo Moreno and Tembladeras is under constant pressure from anthropic activities, primarily due to its location within a rapidly expanding urban area. The use of various landscape metric indices proved to be a valuable tool for identifying trends in landscape transformation. One of the indices indicated that, despite vegetation cover conservation in certain areas, the number of mangrove fragments increased most of which were smaller than one hectare. There has been a marked increase in anthropic development in the immediate vicinity of the Arroyo Moreno–Tembladeras ES. This trend has negatively affected the integrity of the natural landscape, contributing to fragmentation, a decrease in patch size, and a reduction in the number of mangrove fragments.

Given the significant anthropic pressures resulting from urban expansion, it is imperative to implement long-term conservation strategies and mitigation measures to address ongoing fragmentation and land-use change within the ES. Establishing buffer zones could serve as an effective medium-term strategy, facilitating the interaction of ecological components with adjacent land uses. Ultimately, sustained conservation efforts will be critical to preserving ecosystem functionality, maintaining biodiversity, and securing the environmental services provided by these ecosystems.

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