



Environmental Risk from Land Use Changes in the Mangrove Ecosystem El Morro Island, North of Manabí – Ecuador

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Abstract

The El Morro Island Ecosystem, north of Manabí, Ecuador, is a tropical coastal ecosystem of high biological productivity, with mangroves and intertidal zones. This study evaluated the environmental risks associated with changes in land use and concentration of heavy metals in sediments, using a mixed approach that integrated multitemporal analysis, sediment analysis and community perception. WV02 (0.5 m) and Landsat 8 (30 × 30 m) satellite images were processed in QGIS 3.28, generating decadal maps (1985–2025) to identify trends in degradation, aquaculture expansion and their relationship with mangroves. 10 representative points of the mangroves were selected, considering proximity to sources of pollution and state of conservation. Surface sediments (0–100 cm) were analyzed by ICP-MS following EPA and ISO standards. Enrichment Factor (EF), Environmental Risk Code (ARC) and Geocumulative Pollution Index (Igeo) indices were calculated to evaluate anthropogenic influence and biological risk. The results show progressive loss of vegetation cover and expansion of shrimp farms: 30,102 ha deforested (1985–1995), an additional 10,719 ha (1995–2005) and 66,791 ha allocated to aquaculture activities. By 2025, the total vegetation was 22,204 ha. Cd and Hg were undetectable (<0.01 mg/kg) and Cr slightly exceeded the permissible limit at some points; the rest of the metals remained within safe ranges according to TEL, PEL, ERL and ERM. The EF indicated a predominance of natural processes (EF ≤ 1.99), except for Na with moderate enrichment (2 ≤ EF < 5). CRA and Igeo showed low mobility and no significant pollution.

Keywords: Multitemporal analysis, heavy metals sediments, enrichment factor (EF); environmental risk code (ARC); geoaccumulation index (Igeo)

1. Introduction

Mangroves are essential tropical ecosystems that are home to significant species biodiversity and provide numerous ecological services such as coastal protection and carbon sequestration (Golberg et al., 2020; Castillo et al., 2021). They cover a total area of approximately 152,361 Km² (Mereci et al., 2021), however, they face alarming degradation due to anthropic and natural factors (Jacquot et al., 2023; Saoum et al., 2024).

The conversion of mangroves to aquaculture areas is one of the main threats, altering the soil and increasing the concentration of metals in sediments (Nájera et al., 2021; Erazo & Bownan, 2021). It is estimated that between 2010 and 2020, an area of 10,000 km² was lost, due to aquaculture, agriculture, and urban expansion (Leal and Spalding, 2021). Rull (2023) states that if these trends continue, mangroves may disappear during this century as their long-term survival is at great risk.

Since 2016, annual deforestation rates in mangroves have remained between 0.16% and 0.39% per year (Rull, 2023; Martínez, 2022), with the expansion of shrimp aquaculture being responsible for 38% of the decrease in mangrove coverage (Morochó et al., 2022; Treviño & Murillo, 2021). In Ecuador, these ecosystems occupy 1,906 km² and have a rich diversity of species (Moreira, 2024; Pernía et al., 2019). However, mangrove forests have suffered a transcendental loss due to anthropogenic pressure causing environmental risk in the ecosystem of Isla el Morro north of Manabí, estimating a national loss of 70% by 2018 (Ministry of the Environment, Water and Ecological Transition [MAATE], 2020; Jaramillo, 2024; Rebolledo & Verduga, 2023).

Shrimp farming has deforested more than 40,000 hectares in total in the country, affecting biodiversity, local climate, and sediment quality (Holguín, 2023; Zhiminaicela et al., 2020). In the province of Manabí, mangrove deforestation was 4.80% during 2020 and in the north of the province 41.6% of the mangroves have disappeared in the last three decades (Pita, 2018; Morales et al., 2023; González et al., 2023). The ecosystem El Morro Island, known for its diversity of flora and fauna species and for the presence of mangroves in large quantities, is threatened by aquaculture expansion.

Currently, alternatives are emerging for the protection of these coastal ecosystems, such as the Sustainable Development Goals (SDGs), especially SDG 14 "Life Below Water" that seeks the conservation of oceans, seas and marine resources for sustainable development, highlighting among them mangroves, which are key to facing climate change (United Nations, 2018). This study focuses on analyzing the change in land use in the Isla El Morro ecosystem and its impact on the concentration of metals in the mangrove sediment.

2. Materials And Methods

Study Area

The El Morro Island ecosystem is located in the north of the province of Manabí, in the coastal region of Ecuador (Figure 1). The area has an area of 10,000,000 m² and has tropical ecological characteristics, standing out for the presence of mangroves and intertidal zones of high biological productivity. It is located at UTM coordinates: 613304 (west longitude) and 10028892 (north longitude), under the Universal Mercator (UTM) projection system, in zone 17N, based on Datum WGS 84.

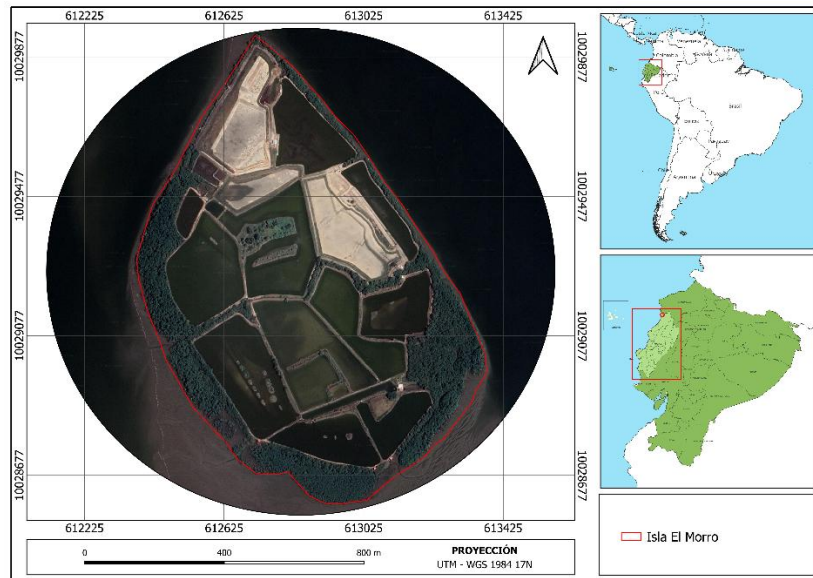


Figure 1. Location map of the El Morro Island Ecosystem

This research uses a methodology with a mixed approach, combining quantitative and qualitative analyses. Quantitative analysis includes evaluation of heavy metal concentrations and analysis of satellite imagery. The qualitative analysis was based on interviews with local actors and participatory observation (Chen et al., 2024; Zhao et al., 2022).

Land Use Change in the Isla el Morro Ecosystem (Multitemporal Analysis)

The identification of land use changes was carried out through a multitemporal analysis using satellite images of WV02 and with a spatial resolution of 0.5m and an accuracy $\pm 5m$, from the Maxar Technologies-Vivid Standard (EC01_25Q2) source, acquired on April 23, 2015. The supervised classification method was used, with Landsat 8 satellite images from the United States Geological Survey (USGS) platform with a resolution of 30x30m; in QGIS 3.28 software, maps were exported at a resolution of 500 dpi (dots per inch) (Saoum and Sarkar, 2024). Finally, a multitemporal analysis was carried out with the results obtained. Each map was made with the periodicity of 10 years, which allows a long-term comparison to be made. This comparative analysis identifies trends in the degradation and expansion of urban or agricultural areas and their relationship with change in mangrove ecosystems (Santos et al., 2012; Bagwan & Sopan, 2023).

Metal Concentration and Sediment Sampling Points

10 representative sampling points of the mangrove were selected (Figure 2), which were based on criteria of proximity to sources of pollution and conservation status (Environmental Protection Agency [EPA], 2001; United Nations Environment Programme [UNEP], 2019). Sediment samples were collected in the surface layer (0 – 100 cm) with stainless steel drill (United States Environmental Protection Agency [USEPA], 1996). The preservation and handling of the samples contemplated the criteria established in the ISO 5667-3 standard (International Organization for Standardization [ISO], 2018). The procedure for analyzing metals in sediments was performed using the inductively coupled plasma (ICP-MS) technique at the University of the Americas (UDLA) (USEPA, 1996; ISO 17294-2, 2016).



Figure 1. Sediment sampling

Determination of the Enrichment Factor (EF)

The Enrichment Factor (EF) was calculated to evaluate the anthropogenic influence on mangrove sediments. The EF (equation 1) was obtained by the relationship between the concentration of heavy metals in the sediment studied and the natural reference levels, using conservative elements such as aluminum or iron (Del Águila et al., 2005).

$$FE = \frac{\left(\frac{Metal}{Fe}\right)_{sedimento}}{\left(\frac{Metal}{Fe}\right)_{corteza terrestre}} [Eq. 1]$$

Where:

- **FE:** It is the enrichment factor, a measure that indicates the degree of concentration of a certain metal in the sediments.
- **(Metal/Fe) sediment:** It is the ratio between the concentration of metal and the concentration of iron in the sediments examined.
- **(Metal/Fe) crust:** It is the ratio between the concentration of metal and iron in the earth's crust.

Given the characteristics of the study area and its heterogeneity, it has been considered to use theoretical concentrations as background or reference values for the interpretation of the results (El-Amier et al., 2017; Muyulema et al., 2019). This is because the area is under the influence of anthropic activities, mainly related to shrimp farms. In this context, the theoretical average concentrations of metals in sedimentary rocks, proposed by Turekian and Wedepohl (1961), have been used as a reference.

Board 1. Theoretical reference concentrations of metals

Element		Reference concentration (mg/kg)
Aluminium	Al	80000
Cadmium	Cd	0,3
Chromium	Cr	90
Copper	Cu	95
Iron	Faith	47200
Magnesium	Mg	15000
Manganese	Mn	850
Sodium	Na	9600
Lead	Pb	20
Strontium	Mr	300
Mercury	Hg	0,4

Calculation of the Environmental Risk Code (ARC)

For its application, the procedure began with the selection of sampling sites, identifying strategic points within the mangrove ecosystem, considering areas close to industrial or agricultural discharges, areas with a history of contamination and regions of sediment accumulation. Surface sediment samples (0-100 cm) were then extracted and stored under controlled conditions for laboratory analysis (Salbu et al., 1988). Subsequently, heavy metals were analyzed, determining the concentration of elements such as: aluminum (Al), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), magnesium (Mg), sodium (Na), lead (Pb), strontium (Sr) and mercury (Hg); using analytical methods such as inductively coupled plasma mass spectrometry (ICP-MS) (Fuentes et al., 2019).

The CRA (equation 2) comprises five categories: no risk (< 1%), low risk (1-10%), medium risk (11-30%), high risk (31-50%) and very high risk (> 50%) (Fuentes et al., 2019). The analysis and interpretation of the results was carried out by comparing the values obtained with Canadian international standards of sediment quality, identifying critical areas with greater environmental risk and establishing priorities for mitigation actions (Ahdy and Youssef, 2011).

$$CRA = \left(\frac{CF1}{C_{total}} \right) \times 100 \text{ [Eq.2]}$$

Where:

- **CF1:** Metal concentration of the analyzed point.
- **Ctotal:** Total concentration of each metal in the sediment.

Geocumulative Pollution Index (GCI)

The Geocumulative Contamination Index (GCI) was applied to assess the degree of contamination in sediments, comparing heavy metal concentrations with reference values (Muller, 1979; Fernandino et al., 2015; Trujillo et al., 2023).

$$I_{geo} = \left(\frac{C_n}{1.5 B_n} \right) \text{ [Eq.3]}$$

- **Igeo:** This is the geoaccumulation index.
- **Cn:** Concentration of the metal in the sediment. S
- **1.5:** Correction factor for lithogenic effects.
- **Bn:** Geochemical concentration of the metal, reference values (Cd: 0.8 mg/kg; Cu: 36 mg/kg; Pb: 85 mg/kg, Zn: 140 mg/kg).

Comparison with national and international sediment quality standards

The results obtained in the concentration of metals in the mangrove sediment of the Isla El Morro Ecosystem were contrasted with the Unified Text of Secondary Legislation of the Ministry of the Environment (TULSMA), specifically Book VI, Annex 2, Table 2, establishes quality criteria for soils with respect to metals such as: Al, Cd, Cr, Cu, Fe, Mg, Na, Pb, Sr and Hg (TUSLSMA, 2015). At the international level, the values proposed by the Threshold Effects Level (TEL), Probable Effects Level (PEL) standards were used as guides. Additionally, the Effect Range Low (ERL) and Effect Range Median (ERM) criteria were used, which define the threshold levels of adverse effects for sediment quality in aquatic ecosystems since they allow determining levels of environmental risks (Simpson and Batley, 2016; García et al., 2018).

3. Results

Land use changes in the Isla el Morro ecosystem, North of Manabí

The change in land use was carried out through the multitemporal analysis from 1985 to 2025, it determined that there are changes in land use in the Isla El Morro ecosystem. Below are the thematic maps.

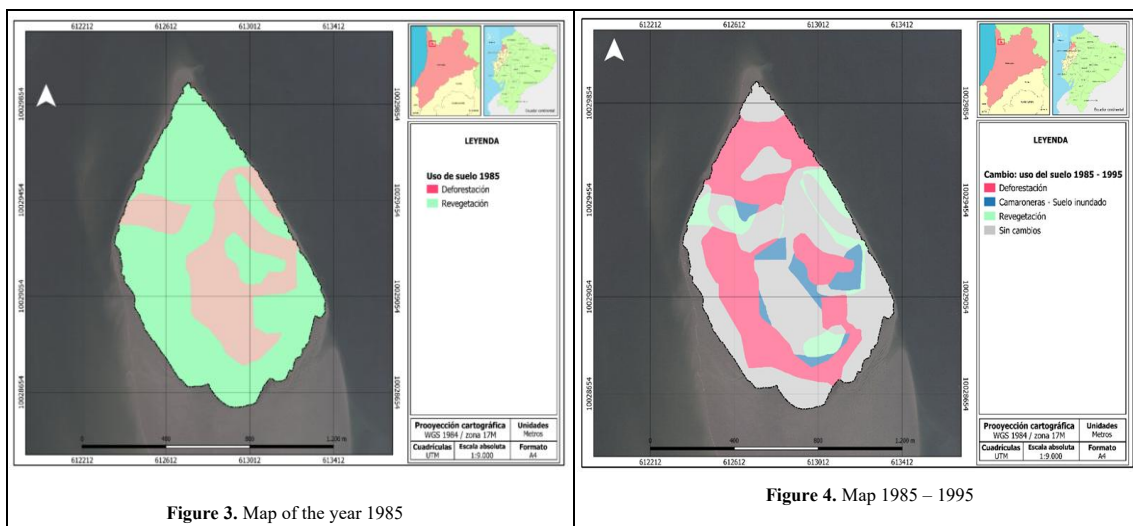


Figure 3. Map of the year 1985

Figure 4. Map 1985 – 1995

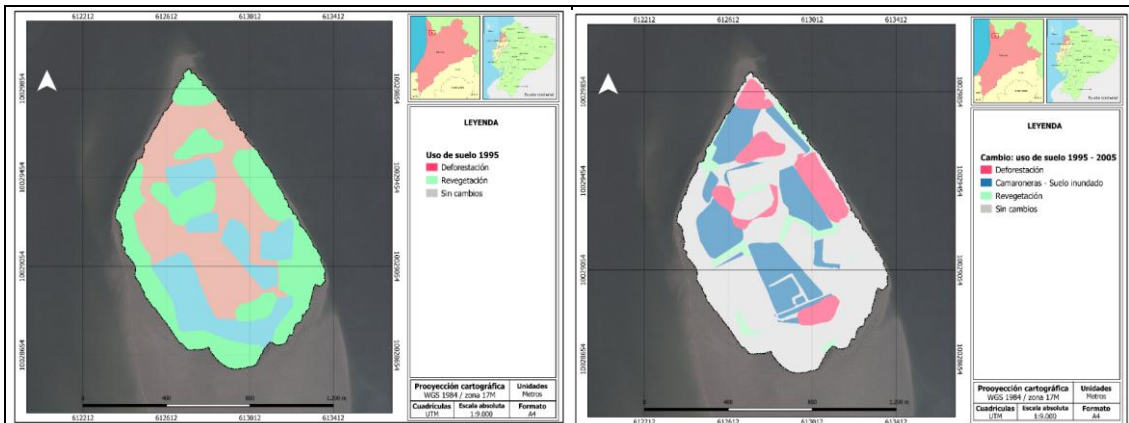
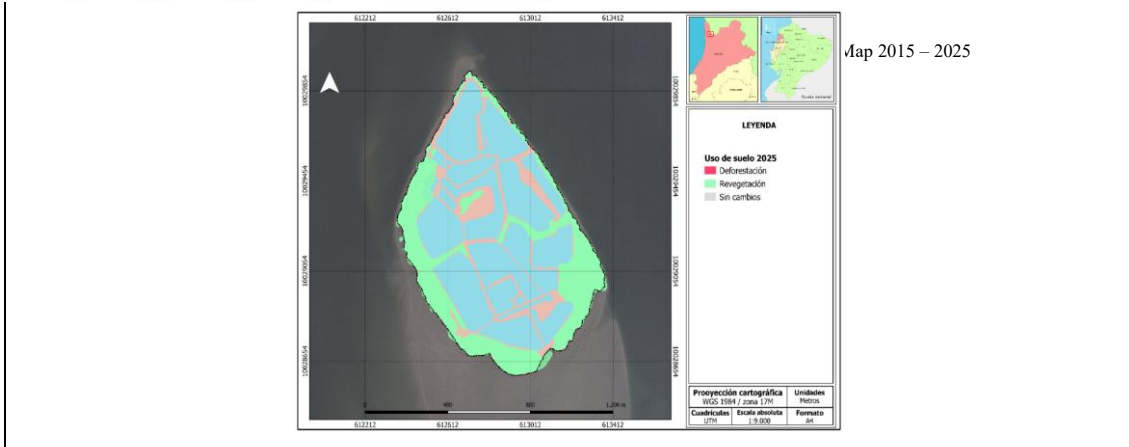
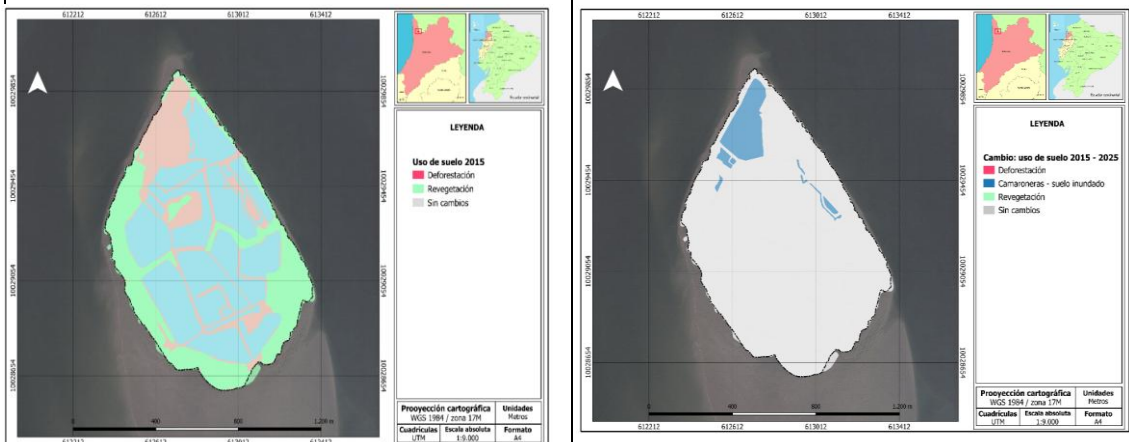
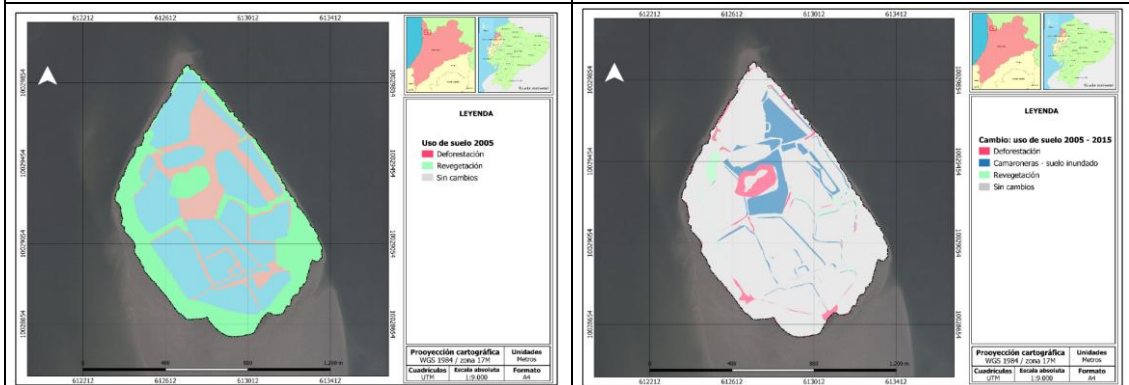


Figure 5. 1995 Map of the Year



Map 2015 – 2025

In the figures, the change in land use occurred between 1985 and 2025, the result of the multi-temporal analysis. Figure 3 presents the land use map in the Isla El Morro ecosystem in 1985 that shows the vegetation cover of 54,725 ha and 25,471 ha of deforested land, while Figure 4 shows that between 1985 and 1995 there was a loss of cover of 30,102 ha, where 6,311 ha were recovered by revegetation. however, 5,188 ha were affected by shrimp expansion and 38,595 ha remained unchanged.

Figure 5 shows the soil use map of the ecosystem during 1995, where there were 19,255 ha of shrimp farms, while bare soil covered 30,007 ha and vegetation extended over 30,934 ha. On the other hand, Figure 6 shows that between 1995 and 2005 there was a decrease in coverage of 10,719 ha, however, there were revegetation efforts that totaled 4,001 ha, on the other hand, the notable expansion in shrimp farms with a total of 19,637 ha and a total of 45,839 ha did not suffer alterations in land use.

Figure 7 of the 2005 land use map shows that 40,584 ha were used for shrimp farms, but 15,427 ha of undeveloped land and 24,185 ha were in the process of revegetation. Figure 8 shows the map of land use change between 2005 and 2025, indicating that there was a loss of 3,520 ha of vegetation cover, where 1,307 ha were recovered by revegetation process, the shrimp expansion entailed a total of 66,791 ha and 66,971 ha, did not present changes.

Figure 9 shows that a total of 41,502 ha are dedicated to shrimp farming in the ecosystem. On the contrary, a total vegetation of 22,204 ha, while the bare soil had a smaller area corresponding to 16,49 ha. Figure 10 of the land use change map illustrates that between 2015 and 2025, there is a decrease of 3,520 ha of vegetation cover, however, during the decade 1,307 ha were restored through revegetation, shrimp expansion occupied 66,791 ha and 66,971 ha remained unchanged. Figure 11 indicates a large shrimp expansion, covering a total of 47,079 ha. The bare soil covered 11,582 ha and the vegetation extended over 21,535 ha.

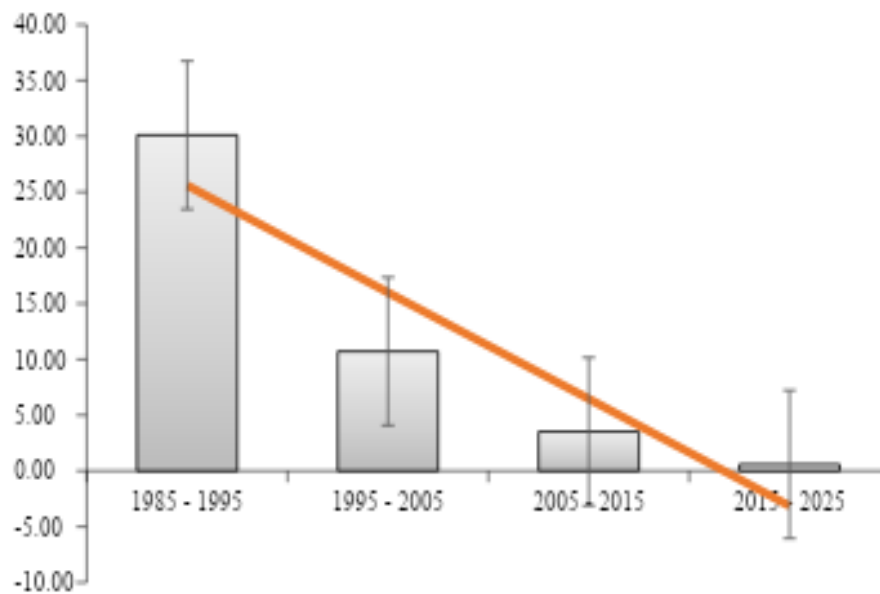


Figure 12. Land use change in the Isla El Morro ecosystem

Figure 12 shows that during the years from 1985 to 1995 there was a total of 30.10 hectares deforested, corresponding to 43.5%. For its part, during the years from 1985 to 2025, the total deforested areas corresponded to 35,871 hectares, equivalent to 60.6%.

Metal Concentrations Sampling Points

The sampling points (10) were distributed around the Isla El Morro ecosystem, as illustrated in Figure 13 and were randomly selected.

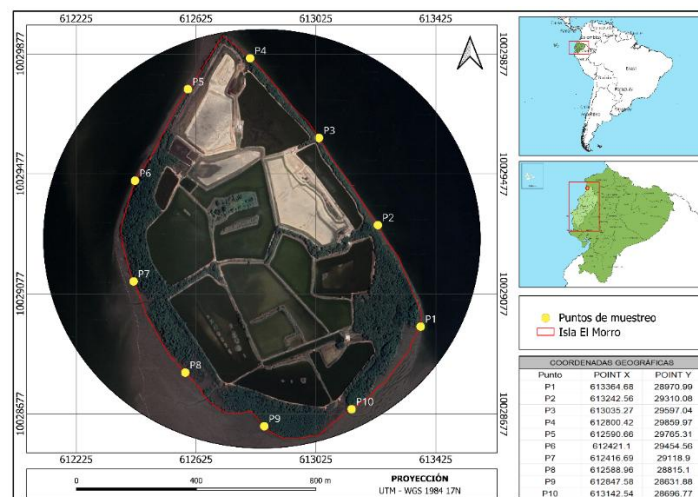


Figure 13. Map of sampling points in the Isla el Morro ecosystem

Total metal concentrations

The total concentrations of metals were evenly distributed. Table 2 shows the values of 10 monitoring points, taken as a reference around the ecosystem.

Board 2. Total concentrations of metals in sediment samples

Code	To the mg/kg	CD mg/k g	Cr mg/k g	Cu mg/k g	Faith mg/kg	Mg mg/kg	Mn mg/kg	Na mg/kg	Pb mg/k g	Mr mg/k g	Hg mg/k g
P1	16391,7 7	<0.01 *	43,35	23,96	17246,6	5078,6 1	321,5 7	7704,5 8	2,42	70,16	<0.01 *
Q2	15420,3	<0.01 *	40,62	21,54	16539,2	5392,4	188,1 2	8089,1 3	2,35	55,14	<0.01 *
Q3	8020,1	<0.01 *	23,17	11,02	10124,1 8	3004,7 9	78,32	4867,2 1	1,39	30,85	<0.01 *
Q4	9180,4	<0.01 *	29,78	14,89	13184,1 9	4168,7 6	129,2 2	6004,9 7	4,45	49,91	<0.01 *
Q5	14112,4 4	<0.01 *	38,85	20,47	15893,9	4981,6 5	169,0 1	8121	2,17	43,67	<0.01 *
Q6	13998,5 4	<0.01 *	35,74	18,92	15121,1 8	4690,9 9	151,7 4	7878,1 3	1,91	39,2	<0.01 *
P7	8705,62	<0.01 *	27,03	13,1	12145,7 7	3890,3 3	101,2 4	5784,9	1,64	36,51	<0.01 *
P8	7578,66	<0.01 *	20,99	10,3	9366,13	2915,0 8	67,54	4559,4 3	1,51	26,16	<0.01 *
P9	14754,8	<0.01 *	39,7	22,63	16980,1 2	5523,1 1	205,3 3	8246,8 7	2,49	53,1	<0.01 *
P10	16476,7 5	<0.01 *	42,38	23,72	17968,1 1	5589,7 8	196,4 7	8343,6 4	2,39	50,2	<0.01 *
LMP											
TULSM											
A											
Book VI, Annex 2, Table 2	N/A	0,5	20	30	N/A	N/A	N/A	N/A	25	N/A	0,1
Stocking	12463,9 4	-	34,16	18,06	14456,9 4	4523,5 5	160,8 6	6959,9 9	2,27	45,49	-
%CV	28%	-	23%	28%	20%	21%	44%	20%	36%	27%	-

*Lab Detection Limit

Note: A coefficient of variation (%CV) less than or equal to 30% indicates a homogeneous distribution; values greater than 30% reflect a heterogeneous distribution among the samples.

According to the established data, aluminum presented concentrations ranging from 7,578.66 mg/kg (P8) to 16,476.75 mg/kg (P10), with a general average of 12,463.94 mg/kg and a coefficient of variation of 28%, indicating moderate variability between sampling points. Cadmium and mercury were not detected at any of the sampling points, registering concentrations >0.01 mg/kg, which corresponds to the minimum detection limit of the laboratory. Because of this condition, it is not possible to accurately calculate the variation between samples. However, the absence of these metals in soils is environmentally favorable, considering their high toxicity and the risk they pose to ecosystems.

Chromium concentrations ranged from 20.99 mg/kg (P8) to 43.35 mg/kg (P1), with a mean of 34.16 mg/kg and a coefficient of variation of 23%. Copper showed concentrations ranging from 10.3 mg/kg (P8) to 23.96 mg/kg (P1), with an average of 18.06 mg/kg and a coefficient of variation of 28%. Iron was present in high concentrations, between 9,366.13 mg/kg (P8) and 17,968.11 mg/kg (P10), with a mean of 14,456.94 mg/kg and a coefficient of variation of 20%. Magnesium had concentrations between 2,915.08 mg/kg (P8) and 5,589.78 mg/kg (P10), with a mean of 4,523.55 mg/kg and a coefficient of variation of 21%. Manganese concentrations ranged from 67.54 mg/kg (P18) to 321.57 mg/kg (P1), with an average of 160.86 mg/kg. The coefficient of variation was 44%, indicating a high dispersion between the samples.

Sodium was found in concentrations ranging from 4,559.43 mg/kg (P8) to 8,343.64 mg/kg (P10), with a mean of 6,959.99 mg/kg and a coefficient of variation of 20%. Lead was present in low values, between 1.39 mg/kg (P3) and 4.45 mg/kg (P4), with an average of 2.27 mg/kg and a coefficient of variation of 36%, indicating high variability. Strontium showed concentrations between 26.16 mg/kg (P8) and 70.16 mg/kg (P1), with an average value of 45.49 mg/kg and a coefficient of variation of 27%, suggesting a moderate dispersion between points.

From the analysis of the eleven metals evaluated in the sediment samples of the Isla El Morro ecosystem, they determined that only chromium (Cr) exceeds the Maximum Permissible Limit (LMP) established in Ecuadorian environmental regulations, which is 20 mg/kg. The rest of the elements analyzed are within the allowed ranges.

Comparison with international environmental standards for sediment quality

The concentrations of heavy metals analyzed (cadmium, chromium, copper, lead and mercury) were compared with the Sediment Quality Guidelines (SQGs), specifically with the TEL (Threshold Effects Level) and PEL (Probable Effects Level) values, which represent thresholds of adverse effects on benthic organisms and allow establishing levels of ecological risk (Sánchez et al., 2018).

In addition, the ERL (Effect Range Low) and ERM (Effect Range Median) criteria were used as complementary integrated indices for a more accurate assessment of ecotoxicological risk. The results of this comparison are presented in the following table, which summarizes the percentage of compliance of the total sampling and metal analyzed.

Board 3. Comparisons with international sediment quality guidelines

Sediment Guidelines Metal	Concentration (mg/kg)				
	CD	Cr	Cu	Pb	Hg
TEL	0,6	37,3	36	35	0,17
PEL	3,53	90	197	91,3	0,49
ERL	5	80	70	35	0,15
ERM	9	145	390	110	1,3
Comparisons with TEL and PEL					
<TEL	100%	50%	100%	100%	100%
TEL ≤ Ci < PEL	0%	50%	0%	0%	0%
≥ PEL	0%	0%	0%	0%	0%
Comparisons with ERL and ERM					
< ERL	100%	100%	100%	100%	100%
ERL ≤ Ci < ERM	0%	0%	0%	0%	0%
≥ERM	0%	0%	0%	0%	0%

Note: TEL: threshold effect level, PEL: likely effect level, ERL: low effect range, ERM: medium effect range

All values of Cd, Cu, Pb and Hg are below TEL levels, suggesting a low probability of adverse effects on benthic organisms. In the case of Cr, half of the points (5 out of 10) had concentrations slightly higher than TEL, although well below PEL, which indicates that, if there is some presence of this metal, it does not reach levels that imply probable toxicity. In relation to ERL and ERM, 100% of the samples are below the ERL for all metals tested. This reinforces the previous interpretation: the levels found are within the ranges considered safe and do not exceed critical thresholds that indicate severe ecological risk or significant anthropogenic pollution.

Metal Enrichment Factor (FE)

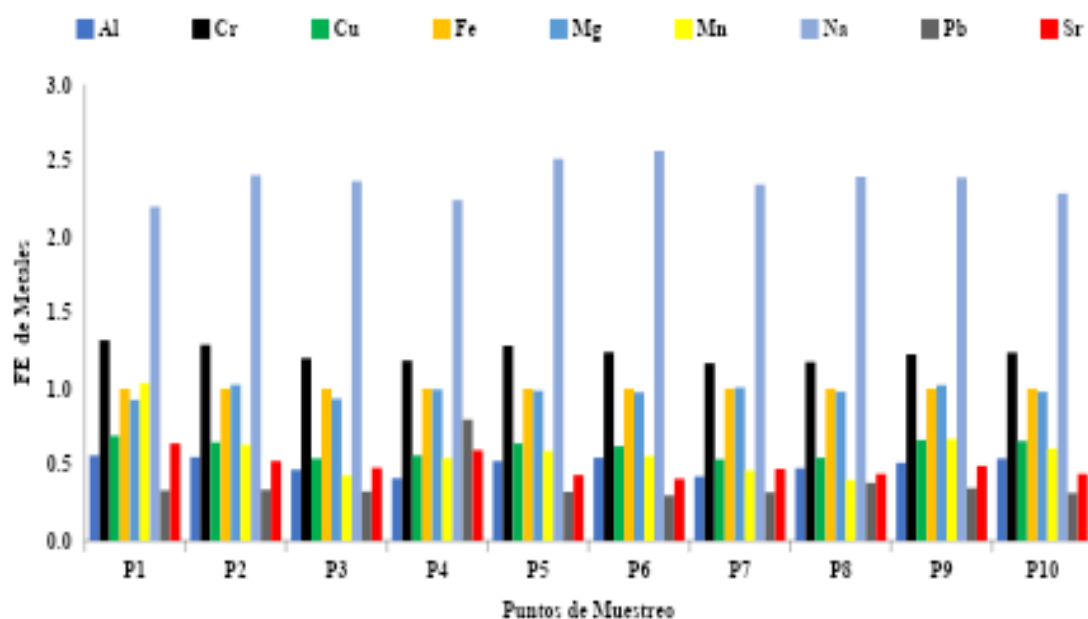


Figure 14. Metal enrichment factor in the sediment of the Isla El Morro ecosystem

Figure 14 shows the values of the Enrichment Factor (EF) of the elements analyzed (Al, Cr, Cu, Fe, Mg, Mn, Na, Pb and Sr), calculated for the soils at the ten sampling points evaluated.

Aluminum (Al) had an EF between 0.4 and 0.6 (0.5 ± 0.06), chromium (Cr) 1.2 and 1.3 (1.24 ± 0.06), copper (Cu) 0.5 and 0.7 (0.61 ± 0.07), iron (Fe) (1.0 ± 0.00), magnesium (Mg) 0.9 and 1.0 (0.97 ± 0.05), manganese (Mn) 0.4 and 1.0 (0.60 ± 0.18). Lead (Pb) 0.3 and 0.8 (0.37 ± 0.12) and strontium (Sr) 0.4 and 0.6 (0.49 ± 0.07).

The results of the Enrichment Factor (EF) obtained for the analyzed soils show that most of the elements, including Al, Cr, Cu, Fe, Mg, Mn, Pb and Sr, have values between 0.30 and 1.3; which is classified within the range of "From Depletion to Mineral Enrichment" ($EF \leq 1.99$). This indicates that the observed concentrations could be mainly due to natural weathering processes of the parent material, without there being a significant anthropic influence on its accumulation. On the other hand, sodium (Na) stands out for presenting a higher enrichment than the rest of the elements at all sampling points, with values ranging from 2.2 (P1) to 2.6 (P9) (2.40 ± 0.10), being classified within the category of "Moderate Enrichment" ($2 \leq EF < 5$), according to the criteria cited by Abdullah et al. (2020). This pattern suggests a possible influence of external sources, such as marine intrusion, natural accumulation processes associated with the salinity of the coastal environment of the ecosystem, or even localized anthropic contributions.

EF values were not calculated for Cd and Hg, as their concentrations were below the laboratory detection limit (<0.01 mg/kg), which prevents an accurate quantitative interpretation. However, this low detectability can also be interpreted as a negligible presence of these trace metals, which reinforces the low anthropogenic alteration of the study area.

Environmental Risk Code (ARC)

The percentages of labile metals, relative to their total concentrations, determined in the P1–P10 samples, showed the following CRA ranges: Cr (17-25%, 21%, $\pm 2\%$), Cu (5-23%, 14%, $\pm 6\%$), Mn (0.2-2%, $1 \pm 0.5\%$), and Pb (1-10%, $5 \pm 3\%$). According to the mobility and biological risk index, the metal Mn in P8 (0.2 %) is classified as risk-free, evidencing a minimum availability for incorporation into the biota. The low-risk category includes Mn in P1-P7, P9 and P10 (1-2%) and Pb in P1-P4, P5, P7 and P9 (1-4%), indicating limited mobility. The medium risk includes Cu at P1, P4, P5, P6 and P8 (13-19%), Cu at P2 and P9 (5-7%), Pb at P2, P6, P8 and P10 (5-10%), as well as Cr at all sampling points (17-25%) (Figure 15). No values corresponding to the categories of high or very high risk were recorded.

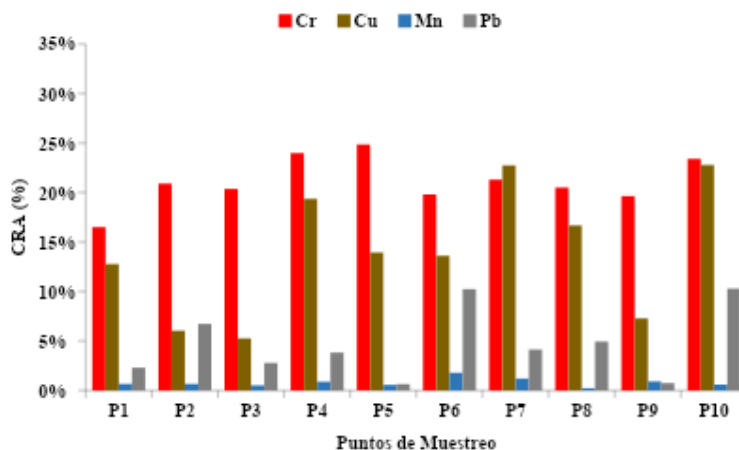


Figure 15. Environmental Risk Code (ARC) in sediment of the Isla El Morro ecosystem

Geoaccumulative Pollution Index (GCI)

The geoaccumulation index (I_{geo}) for the metals and metalloids analyzed presented the following ranges and averages: Al (-4.0 to -2.9; average -3.2 ± 0.3), Cr (-2.7 to -1.6; -1.9 ± 0.3), Cu (-3.8 to -2.6; -3.1 ± 0.4), Fe (-2.9 to -2.0; -2.4 ± 0.3), Mg (-2.9 to -2.0; -2.4 ± 0.3), Mn (-4.2 to -2.0; -3.0 ± 0.7), Na (-1.7 to -0.8; -1.1 ± 0.3), Pb (-4.4 to -2.8; -3.6 ± 0.5), Sr (-4.1 to -2.7; -3.3 ± 0.5) (Figure 16). These values indicate that all elements presented negative I_{geo} values, with averages within the range of non-contamination ($I_{geo} \leq 0$) (Abdullah et al., 2020).

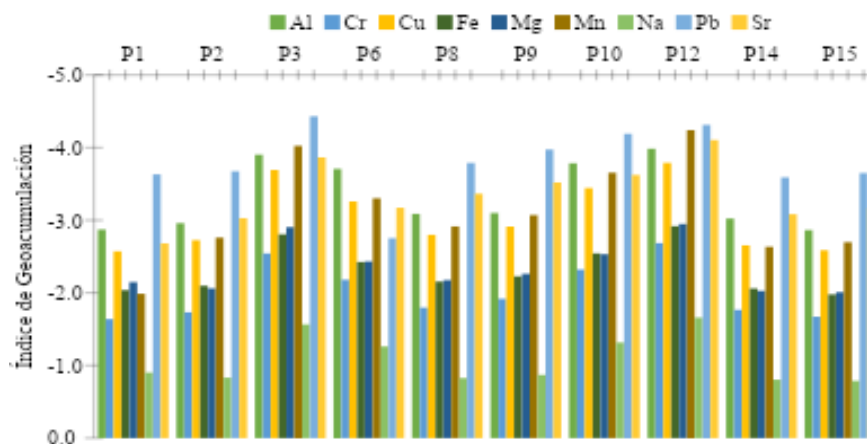


Figure 16. Sediment Geoaccumulation Index

Based on the results obtained, the following strategies are proposed:

Board 4. Conservation and reforestation strategies in the El Morro mangrove.

Strategic axis	Objective	Actions	Term	Responsible
Environmental education	Promoting education	To minimize 10% of the deforestation rate of the identified mangrove, it is proposed to implement environmental education talks on the creation of the nursery aimed at the community and visitors.	Annual	Authorities and community
Reforestation	Reforest the degraded areas to the north and south of the El Morro Island ecosystem	Create a community-managed nursery for the establishment of a local reforestation program, which will allow the recovery of vegetation cover and the conservation of biodiversity through environmental awareness.	Annual	Authorities and community

The results showed that 72.5% recognized a deterioration in the vegetation cover and 70% identified shrimp farms as the main cause of transformation, with an approximate area of 150 ha. Likewise, 68% indicated that they were aware of the risks of metal accumulation in sediments, while 82% would be willing to participate in environmental restoration programs. These data reflected that the community perceives the current state of the need through actions.

4. Discussion

In the Jambelí Archipelago, between 1991 and 2024, significant changes in land use change were evidenced, with a notable expansion of active shrimp farms that increased by 2,179.55 ha (Moran et al., 2025). For its part, in the canton of Sucre, province of Manabí, between 1970 and 2021 it has implied a drastic change in land use, especially due to the expansion of the shrimp industry, which has led to a drastic decrease in natural resources such as the flora and fauna of the mangrove, as well as in the restriction of access to resources for local communities (Moreira, 2024).

Mangroves are vital habitats in the intertidal zones of tropical and subtropical coasts (Fernández et al., 2014). Various studies focusing on heavy metal pollution from anthropogenic activities in mangroves (Moran et al., 2025; Moreira, 2024). Heavy metals easily enter coastal areas, are deposited in benthic sediments, and tend to become persistent and accumulate in biological systems, causing physiological changes in these ecosystems (Chai et al., 2017; Aljahdali & Alhssan, 2020).

In an investigation of heavy metal contamination in mangrove sediments in the Klang Estuary, Malaysia, the concentration of heavy metals such as Mn, As, Cu, Zn and Pb was evaluated. The results indicated that As and Pb concentrations exceeded the threshold effect level, unlike Mn, Zn and Cu which did not pose adverse biological impacts. In addition, the values of Igeo, CF and PERI showed a minimal risk of heavy metal contamination in the study area. On the other hand, Cu and Mn showed a medium environmental risk, unlike Pb and As that did not show any environmental risk (Elturk et al., 2019).

In addition, a study conducted on Hainan Island, China, investigated the concentration and distribution of heavy metals (Cr, Zn, Pb, Cu, As, and Cd) in different mangrove sediments with different land-use patterns along the coast of the entire island; The results showed metal contaminations in arable land, aquaculture ponds, riparian area, ecological area. These results revealed that different land uses not only modify the accumulation capacity of heavy metals in mangrove soils, but also contribute to different sources of heavy metal pollution (Li et al., 2022).

In another study on the determination of cadmium and lead sediment in the Estero Salado, Ecuador, an average concentration of Cd of 0.132 mg kg⁻¹ was obtained for zone M, while in zone P the concentration was 234 1.9±0.47 mg kg⁻¹, which exceeds the maximum limit allowed for sediments according to the International Standard of Canada (0.676 mg kg⁻¹). With respect to Pb, in zone M there were no significant differences between the four points sampled with a mean of 23.57 (3.87 mg kg⁻¹), while in zone P significant differences were shown between the four sampling points: P1=162.21 (9.277 mg kg⁻¹), P2= 97.81 (14.10 mg kg⁻¹), P4= 68.65 (11.23 mg kg⁻¹) and P3=47.03 (5.85 mg kg⁻¹) (Pernía et al., 2018). In another study carried out in the Estero Salado of the Gulf of Guayaquil during the years 2008, 2009 and 2014, the sediments revealed high concentrations of total mercury (THg) of 1.20 – 2.76 mg kg⁻¹ (Calle et al., 2018).

The study on "Heavy metals in forested mangrove sediments of the world's largest delta" evaluated seasonal variations, pollution status, ecological risks and sources of metals (Ni, Pb, Cr, Cu, Mn and Zn) in human-forested mangrove sediments in a deltaic region. The results indicated that the concentrations of heavy metals followed the order: Mn (464.7±53.47 µg/g) > Zn (62.32 ± 22.45 µg/g) > Ni (38.77 ± 8.03 µg/g) > Cr (38.77 ± 8.03 µg/g) > Cu

($35.74 \pm 6.73 \mu\text{g/g}$) > Pb ($7.38 \pm 7.14 \mu\text{g/g}$). Metal loads, with the exception of Cu and Pb, were higher during the dry season and lower in the wet season. The Igeo values showed low values (Igeo <0) for all metals, showing that ecosystem sediments in mangroves of the Cross River estuary are uncontaminated. As for the PERI values in the different sediment sites, they remained below 50, indicating negligible potential contamination (Rahman et al., 2024).

On the other hand, in a study on mangrove reforestation on Tanakeke Island in Indonesia, it was shown that ecological restoration and community participation can restore more than 400 ha of degraded land, with the implementation of ecological diagnostics and comprehensive planning where activities for the active participation of communities are carried out (Brown et al., 2014). Therefore, reforestation in mangroves depends not only on technical intervention, but also on community unity and local capacity building.

Anthropic pressure in coastal areas is shown to be fundamental as an essential factor in the reduction of mangrove vegetation cover, in addition to other studies carried out on the coast of Brazil indicate that activities such as the increase in urban shrimp farming expansion and aquaculture processes directly affect tropical areas (Hayashi et al., 2018). A study of the coastal region in the south of Kien Giang province (Vietnam) showed excessive loss of mangroves in urban areas (Tran et al., 2024), however, in Ecuador the highest deforestation was shown in mangroves located in spaces with high accessibility, specifically in Guayas and El Oro (Morocho et al., 2022).

The spatial gradient of metals indicates increasing from the interior areas to the mouth, driven by the mobilization and transport of particulate fractions during runoff episodes and by hydrodynamic selection along the estuarine channel (Drude et al., 2022). In studies of redox processes complemented by hydrogen sulfide sediments and the biogeochemistry of the rhizosphere, they control the retention and speciation of metals such as: Fe, Mn, Pb, Cu, Zn, etc., thus improving their movements and favoring the formation of poorly available phases that can accumulate differentially along the estuarine gradient (Mori et al., 2019). Research carried out in the Guayas estuary, Ecuador indicates that certain stations near the main channel have presented higher sedimentary concentrations of Ni and other metals compared to less flooded mangrove inland areas or with little fluvial-marine connection, suggesting dilution or mixing of seawater as a modulating factor, as well as retention in fine organic sediments (De Cock et al., 2021).

In addition, studies in Guanabara Bay (Brazil) indicate that in *Laguncularia racemosa* forests, trace metals tend to accumulate in forms with low removal potential and low risk of biological transfer, suggesting that physical and chemical retention in poorly mobile fractions modulates the availability for biota (Fe, Pb, Cu, Zn mainly (López et al., 2019). On the other hand, mangrove sediments indicate a high retention capacity of heavy metals thanks to their fine texture, high organic matter content, oxygen losses in deep layers (anoxic/sulfidic conditions), and associations with residual or oxidized phases of Fe-Mn oxides that limit the biological availability of metals, however, metals such as Ni, Cu and Zn, although mostly retained in less mobile phases, show correlations with biomarkers of oxidative stress in urban mangroves. (Espinosa et al., 2011).

In a study on the northern coast of Ecuador, it was shown that flows altered by shrimp farms show a 44% reduction in total organic matter and 53% in total nitrogen in sediments compared to flows with intact mangroves; this loss is associated with an increase in ammonium content and a change in the redox profile. which facilitates the mobilization of heavy metals that adsorb or are associated with organic fractions prone to dissolve under altered conditions (Rebolledo & Verduga, 2023). Similarly, land use from mangroves to crop soils or aquaculture ponds in the Zhangjiang estuary (China) increased the mobility of metals (especially Cd), altering the structure of soil aggregates and reducing the stability of mineral organic carbon, favoring the export of exogenous metals to adjacent waters (Wu et al., 2017)

The alteration of coastal land use not only modifies the physical structure of the mangrove, but also alters its geochemical balance and increases its environmental vulnerability. A study of the Arroyo Tifa estuary (Indonesia) revealed that the loss of mangroves and the alteration in soil composition lead to an imbalance in the stability of organic matter and the presence of metals. Likewise, the increasing anthropogenic activity in coastal mangroves increases the increase of metals in mangrove sediments, creating a sink source of pollutants (Sondermann et al., 2018).

5. Conclusion(S)

The expansion of shrimp farms has structurally and functionally transformed the mangrove swamp of the Isla El Morro ecosystem, causing a loss of vegetation cover of more than 60% in four decades. This finding evidences the human pressure on critical ecosystem services, highlighting the urgent need for evidence-based environmental management strategies to conserve the integrity of these tropical ecosystems.

The concentration of heavies in sediments of the Isla El Morro ecosystem indicates that, with the exception of chromium (Cr), which has slight excesses with respect to the permissible limit, the concentrations of all other metals are within safe ranges according to national and international standards (TEL, PEL, ERL, ERM). The Enrichment Factor (EF) indices show that most of the elements are in the category "From Depletion to Mineral Enrichment" ($EF \leq 1.99$), suggesting a predominantly natural origin, while sodium (Na) presents a moderate enrichment, probably associated with marine intrusion or natural coastal processes. The Environmental Risk Code (ARC) indicates low to moderate biological mobility of metals, with no high risk records, and the Geocumulative

Pollution Index (Igeo) confirms the absence of significant contamination.

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