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Multidecadal biogeomorphic dynamics of a deltaic mangrove forest in Costa Rica

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ABSTRACT

Térraba-Sierpe National Wetland (TSNW) is the largest wetland in Costa Rica located in the southeastern part of the country. The protected area comprises the Térraba-Sierpe delta covered with dense mangrove vegetation. We aim to analyze the geomorphological evolution of the coastal bars and the land use/cover change between 1948 and 2012 using aerial photographs and satellite images interpretation as well as field corroboration. We determined the geomorphological dynamics of three coastal bars (supratidal, intertidal, and subtidal), ten land uses/covers, and deforestation rates of six delta mouths for 64 years. In addition, we estimated a net periodic loss by deforestation between 1948 and 2012 exceeding 2562 ha, with an annual net loss of 40 ha per year. Moreover, these outputs quantify the anthropic impact over 40 years and give good evidence from an example of environmental policies implementation since the 1990s to protect these fragile tropical ecosystems.

1. Introduction

Located under the influence of marine and terrestrial processes, mangrove forests define a critical interface between terrestrial, estuarine, and near-shore marine ecosystems in tropical and subtropical regions (Polidoro et al., 2010). For instance, mangroves are under constant flux due to both natural and anthropogenic forces (Giri et al., 2011). Ecologically, mangroves are an ideal habitat for a diversity of animals during part of their life cycles due to the high abundance of food, shelter and low predation pressure (Nagelkerken et al., 2008). Moreover, these ecosystems provide valuable goods and services benefiting coastal communities, including coastal land stabilization and storm protection (Walters et al., 2008; Ostling et al., 2009). Therefore, the protection of coastal mangrove forests is key to provide invaluable and unique services to people and wildlife (Romañach et al., 2018). Nevertheless, since 1950 the mangrove biome has experienced an approximately 50% loss of habitat (FAO, 2007; 2015; Feller et al., 2010). Around 75% of world's mangroves are located in 15 countries, and less than 10% are under an existing protected areas network (Giri et al., 2011). Furthermore, many mangrove species are endangered or vulnerable along low latitudes (Polidoro et al., 2010).

Biogeomorphology explains the interaction between biotic and geomorphological processes (Stallins, 2006). It is a holistic earth-systems science, which gather biological, chemical and physical features of earth surface systems over a range of time, and space scales (Naylor et al., 2002). Understanding geomorphological process-landform interactions will be critical for characterizing wetlands as dynamic landscapes and improve its research and management (Lisenby et al., 2019). Increasing the analyzed timescales, the understanding of the dominant biogeomorphological processes dynamics can be enhanced in coastal environments (Ellison, 2019; Viles, 2019). Decadal scale climatic variability has direct alterations in sediment yield and erosion in coastal geomorphic systems (Viles and Goudie, 2003), and shore landscape dynamics affect coastal ecosystems such as mangroves (Viles et al., 2008). For an interdecadal timescale, remote sensing data have been used to assess mangrove changes (Giri et al., 2011; Restrepo and Cantera, 2013; Nardin et al., 2016; Galeano et al., 2017; Massuanganhe et al., 2018). Multidecadal remote sensing approaches have studied land use and cover changes in mangrove forests specially during the second half of the nineteenth century due to the technological resources increase (Tuholske et al., 2017; Vieilledent et al., 2018).

The high number of species and endemic organisms place Costa Rica as a megadiverse country with approximately 6% of the global biodiversity (Kappelle, 2016). Nonetheless, deforestation and landscape fragmentation dominated from the 1950s until the mid-1980s. Subsequently, a series of environmental policies reversed deforestation

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together with the rise of ecotourism and the development of more sustainable production alternatives reaching a forest cover of 51% of the country, currently (Keenan et al., 2015). This intense deforestation favor erosion and different sediment yield rates (152 ± 33·9 t km^{-2} $year^{-1}$ at 836 km^2 to 404 ± 141·7 t km^{-2} $year^{-1}$ at 4767 km^2) that reached Térraba-Sierpe delta (Krishnaswamy et al., 2001b). The tidal changes modeled the Térraba-Sierpe delta more intensely from the formation of six mouths: Coronado, Brava, Chiquita, Zacate, Guarumal and Sierpe (Acuña-Piedra and Quesada-Román, 2016). Different modifications have occurred during the last six decades such as the disappearance of Succession Island, Zacate and Coco islands washout, and the formation of a new barrier island as an extension of Guarumal Island (Cedeño et al., 2012; Quesada-Román and Acuña-Piedra, 2017). Moreover, Térraba-Sierpe delta have faced mangrove coverage changes due to agricultural activities as rice, oil palm, pasture for livestock, salt mines and shrimp ponds (Acuña-Piedra and Quesada-Román, 2017). During the last decades of coastal changes over the Térraba-Sierpe National Wetland, three different coastal bars (supratidal, intertidal, and subtidal), have shown a constant change that represent the alternating erosion/deposition pulses especially of Térraba basin dynamics (West, 1976; Ortiz-Malavassi, 2012; Silva et al., 2015; Acuña-Piedra and Quesada-Román, 2016). We hypothesize that coastal bar dynamics as well as land use/cover changes have negatively impacted the mangrove forests over six decades; nonetheless the implemented environmental policies since 1990s have benefited this fragile ecosystem. Hence, this study aims to analyze (i) the geomorphological evolution of three coastal bar types, (ii) the land use/cover change, and (iii) the environmental policy impact over 64 years (1948–2012) for the Térraba-Sierpe National Wetland (TSNW), southeastern Costa Rica.

2. Materials and methods

2.1. Study area

The TSNW is located at 8°52′ N and 83°35' W and drains into the Pacific Ocean (Fig. 1). The TSNW occupies an area of 24,360.5 ha. Our study includes only the mangrove area and the mouths that make up the delta, which is approximately 14,880 ha. Térraba-Sierpe delta results from a complex tectonic configuration. Conversely, the subduction of Cocos and Caribbean plates, the collision of the Cocos Ridge, and a regional faults system associated with the Panama microplate have different implications on local tectonics (Morell, 2015). A wide reverse fault with NW-SE direction limits at the NE with the Fila Brunqueña -of Miocene sedimentary and intense folding origin- and the delta (Marshall, 2007). Moreover, a series of normal and inferred faults with NW-SE orientations are across the delta. A series of sinistral faults with a positive relative vertical movement from the sea towards the delta limits the SE boundary (Denyer et al., 2003). The lithology is made up mainly of Tertiary basalts (~140-88 Ma), tholeiitic basalts of accreted oceanic islands (~70-40 Ma), and a mélange of the Osa-Burica accretion complex with Paleocene and Miocene age. Stratigraphically it is composed of Plio-Pleistocene sandstones, shales and littoral and sublittoral conglomerates (Denyer and Alvarado, 2007). Geologically, the upper layer of the delta is a Quaternary alluvial plain where permanent or temporary wetlands have a marine-coastal influence.

Térraba river is the biggest water basin in Costa Rica and its headwaters are located at 3820 m asl in Cerro Chirripó (Quesada-Román et al., 2019) and flows around 160 km until it reaches the TSNW (Fig. 2). Térraba river basin is composed of several protected areas but also

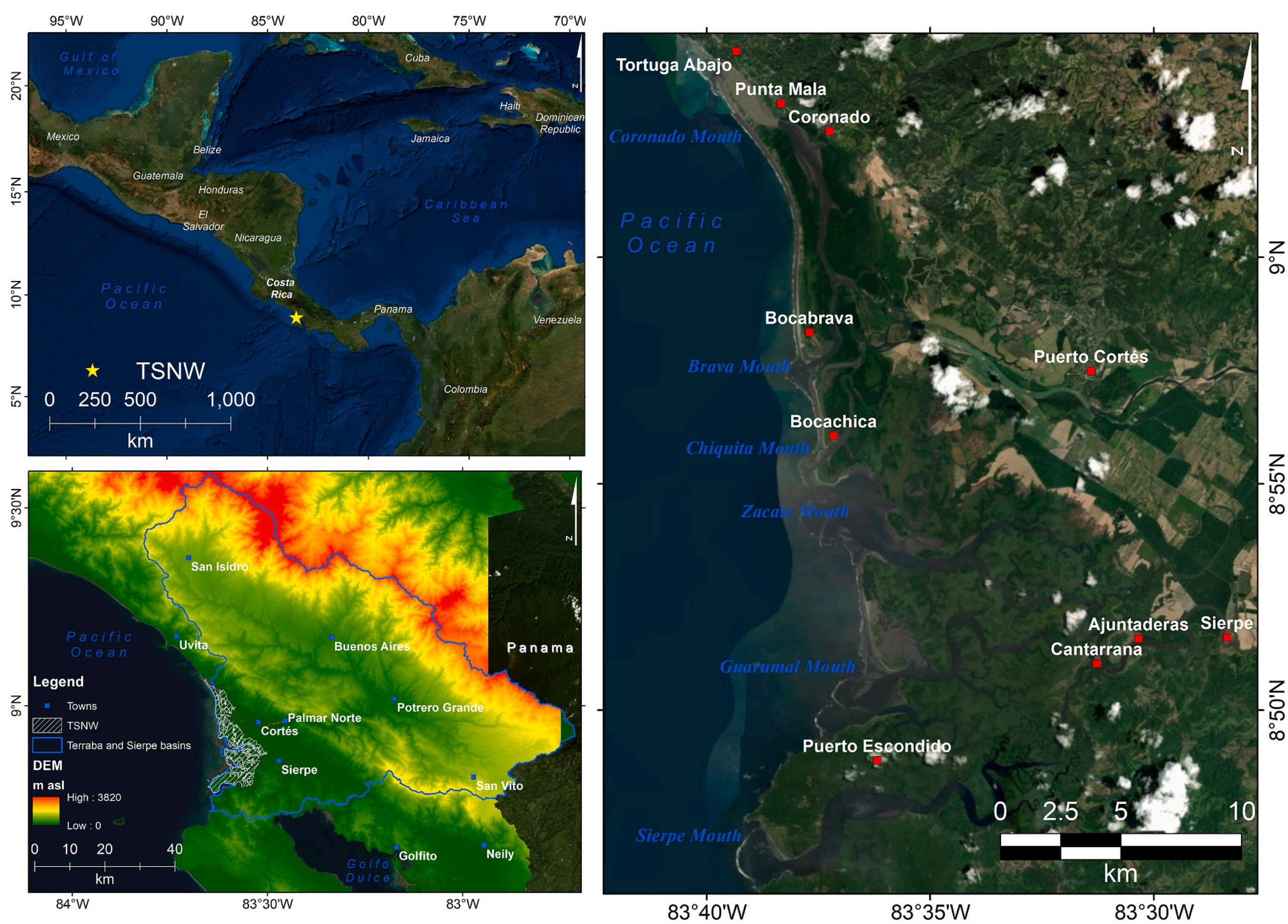

Fig. 1. Geographic location of the study area in the regional context (upper left); TSNW in the Térraba and Sierpe basins setting (lower left); six mouths and surrounding towns of Térraba-Sierpe National Wetland (right).

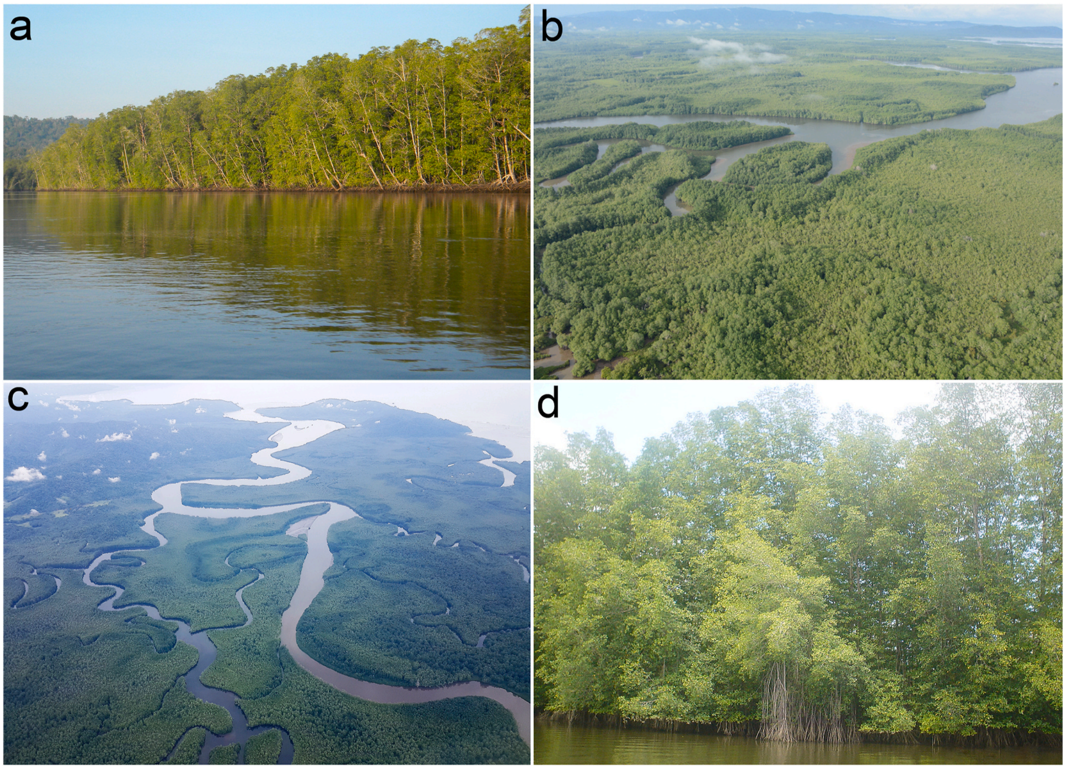

Fig. 2. *Rhizophora mangle* (a), Térraba-Sierpe channels, mangrove forests, and Violín Island in the upper part of the photo (b), Sierpe mouth (c), *Avicennia germinans* and *Rhizophora mangle* (d). Credits: Néstor Veas and Leonardo Quesada.

extensive pastures, coffee, pineapple, oil palm, sugar cane and seasonal crops land uses (Krishnaswamy et al., 2001). The latitudinal migration of the Intertropical Convergence Zone (ITCZ), El Niño-Southern Oscillation (ENSO), northeast trade winds, cold fronts, and tropical cyclones influence the local climate and precipitation patterns (Amador et al., 2010; Quesada-Román et al., 2020b). Annual rainfall sums between 3000 and 5000 mm with two rainfall maxima, the first in May and the peak in October. In July and August rainfall decrease during two to four weeks, the Mid-Summer Drought (Campos-Durán and Quesada-Román, 2017; Maldonado et al., 2018). Most of the rainfall occurs between May and November (rainy season) with a distinct dry season from December to April with annual average temperatures of over 22 °C (Amador and Alfaro, 2014). Within the country, 99% of the mangrove forests are found along the Pacific coast and a few patches in the South Caribbean (Cortés, 2016). Térraba-Sierpe delta is one of the best examples of mangrove habitat in Central America (West, 1976). Among mangrove forests and palm swamps there are four primary dominating species: *Rhizophora mangle*, *Avicennia germinans*, *Laguncularia racemosa*, and *Conocarpus erectus* (Ellison, 2004; Acuña-Piedra et al., 2018). Since the 1980s, protection of mangrove forests in Costa Rica commenced to be protected under environmental policies, management strategies, and ecological awareness (Kappelle, 2016).

2.2. Geomorphological mapping

We developed a geomorphological mapping divided in three phases: pre-mapping, fieldwork and post-mapping (Smith et al., 2011). During pre-mapping, we georeferenced three aerial photographs requested from the National Geographic Institute of Costa Rica of 1948, 1972 and 1992, which have a scale of 1:50,000, 1:20,000, and 1:60,000 respectively. In addition, we used a Rapid Eye satellite image of 2012 of 5 m spatial resolution from the Airborne Research Program of the National Center for High Technology of Costa Rica. The precision and resolution of these imagery has a mean of 25 m of uncertainty, which allow these analyses. We based our study area boundary according to the official limit of TSNW provided by the National Conservation Areas System (SINAC) only in the mangrove and coastal mouths areas. Coastal bars comprise unconsolidated bodies of sand or gravel in the nearshore fully or temporarily submerged below high tide level (Daidu et al., 2013; Otvos, 2020). Using ArcMap 10.3 we identified and mapped according to its texture, shape, color, and vegetation cover three types of coastal bars (subtidal, intertidal, and supratidal) at 1:3,000 digitalization scale. The method allowed mapping the genesis, dynamics, morphology, evolution, and age of the different landforms and its processes using various classic geomorphological methods and digital graphic techniques to develop the final cartographic product (Verstappen et al., 1991; Bishop et al., 2012; Quesada-Román, 2018; Quesada-Román and Pérez-Briceño, 2019). We performed the fieldwork during January 2016 to ground-truthed the different landform dynamics and limits using a preliminary morphogenetic map (Quesada-Román and Mata-Cambronero, 2020). Moreover, in order to confirm the coastal bars classification, we took eight soil samples of approximately 2 kg of each type of bar at 30 cm depth around Guarumal Island. Subsequently, in the laboratory we measured its texture using Bouyoucos and granulometric methods (USDA, 2004; Buol et al., 2011). During the final stage of post-mapping, we constructed the legend for the geomorphological maps according to Gustavsson et al. (2006). Three coastal bars (subtidal, intertidal, and supratidal) were identified along the 64 of analysis and were confirmed in both the field and the laboratory sediments analysis. Moreover, the determination of the different coastal bar areas allowed us to calculate and compare the erosional/depositional areas during the analyzed period. The optimal output scale given the extension of the delta is 1:25,000.

2.3. Land use/cover change and deforestation rates

We performed a land use and land-cover classification (LULC) is a multi-temporal analysis using the same aerial photographs and satellite image than the geomorphological evolution previous step. For this step, we digitalized aerial photographs at 1:2,000 scale (1948, 1972, 1992) and the satellite image at 1:3,000 (2012). As a result, we identified six land uses based on Corine Land Cover-Costa Rica Legend (CLC-R; Büttner et al., 2004; Rosales, 2016): rice, clean pastures and trees, natural spaces (sometimes with pastures), oil palm, bare or degraded lands, and mariculture ponds. More recent determined land uses/covers were validated with several fieldworks between 2014 and 2016. In addition, we identified five natural land covers: mangrove, swamps, coastal lagoons, sands and beaches. After, we made a deforestation analysis to establish mangrove coverage loss to understand the periodic net loss analysis and the rate of deforestation (FAO, 2015). Net Periodic Loss (NPL) refers to deforestation in each time:

$$NPL:\ MC1 - MC2 \quad \text{(Eq. 1)}$$

Where, MC1 corresponds to the mangrove coverage for the first years of analysis and MC2 refers to the coverage in the final year of the period analyzed.

The Net Annual Periodic Loss (NAPL) was obtained by average, which determines how much mangrove forest cover disappeared per year:

$$NAPL = NPL \,/\, t \quad \text{(Eq. 2)}$$

Where, NPL corresponds to the data obtained in the net periodic loss and the study time between the years compared.

The Deforestation Rate (DR) refers to the loss of vegetation cover to be replaced by another land use activity:

$$\%\,DR:\ (A2\ /\ A1)\,\hat{}\,(1\ /\ t2 - t1 - 1) \quad \text{(Eq. 3)}$$

Where, A1: initial forest area of mangrove (ha), A2: final area of mangrove forest (ha), t1: initial year, t2: final year (FAO, 2015).

3. Results

3.1. Coastal bars classification

According to the aerial images interpretation from 1948 to 2012, fieldwork verification and the laboratory results of the sediment texture and grain size we identified subtidal, intertidal, and supratidal coastal bars. Subtidal bars are result of the deltaic suspended sediments moved by the waves and tides towards the coast forming the first stage of deposition. During low tides these landforms can been observed and, in some cases, form small asymmetric ridges that appear above sea level. Moreover, their textures are mainly sand (~96%), from medium to coarse sand, classified as sandy soils absent of vegetation (Table 1). Accordingly, intertidal bars are the evolutionary result of the subtidal bars where an outcrop of the material accumulated above sea level begins, forming islands in some cases. More than 90% of the samples were sands, where fine and medium sands predominate, and a relative stability starts due to the slightly higher elevation as well as the incipient vegetation presence (Table 1). Therefore, supratidal bars are considered the final process in the consolidation of coastal bars. They manage to establish in parallel to the coastline with an origin based on saturation and the sedimentary basement fixation. These coastal bars showed variation in their texture content. Although the sands, as in the previous bars, were dominant as well as the fine sands, classified as sandy loam soils (Table 1).

3.2. Geomorphological dynamics

Térraba-Sierpe delta is compose by the changing coastal bars and the stable deltaic plains with slight or even unnoted changes along the studied six decades. For 1948, the delta had a surface area (deltaic plain + coastal bars) of 14,583.14 ha. The erosion dominated until 1992, with 14,035.63 ha by 1972 and 13,298.66 ha for 1992. However, for 1992 the information is incomplete because aerial photographs for the northern sector had significant cloud coverage. Conversely, from 1992 to 2012, 613.07 ha gained for the delta. When analyzing the coastal bars and the deltaic plain separately, we found that the bars begin to increase their area from 1972, reaching their greatest surface extension in 2012. Nevertheless, the deltaic plain begins a setback in the first 44 years (1948–1992) to start a continuous growth from 1992. It is important to highlight that although there was a terrain gain in the last period, the area of the wetland did not increase enough to match the area of 1948.

Every mouth had a specific dynamic between 1948 and 2012 (Fig. 3). Coronado mouth is the less modified by the erosive processes of the delta due to the spit formation where Térraba river flows to the Pacific Ocean (Fig. 3). This process indirectly protected the mouth from the erosive action of currents and tides. In 1948, this mouth had the three types of coastal bars. The subtidal had approximately 7 km length and 155–300 m width. Intertidal bars had a length of 4.5 km and a width between 50 and 350 m, and subtidal bars were 2.5 km long as well as 40–500 m wide. In 1972, subtidal bars dominated with a clear retreat of the intertidal and supratidal bars. In 1992, there is a lack of aerial photographs due to a large cloud spot and it is in 2012 when those sectors with subtidal bars (which were 40 years before) manage to consolidate with vegetation and become supratidal bars. Brava mouth has had a strong erosive and depositional dynamics that has caused several coastal changes. In 1948, it had an area covered with intertidal bars in the northern part of the mouth, with 4.2 km length and a width between 100 m and 220 m, as well as small sediment banks that form isolated subtidal bars. By 1972, intense erosion favors subtidal and intertidal bars formation that do not exceed 40 m wide. In 1992, in the northern section of the mouth, subtidal and intertidal bars manage to stabilize by vegetation, while in the southern region the landscape is fragmented, and a new mouth known as Nueva mouth originates. For 2012, the northern part gains terrain and a small coastal lagoon formed favoring the supratidal bars predomination.

Chiquita mouth by 1948 present a predominance of 500 m wide supratidal bars, followed by the intertidal bars with approximately 4 km in length. Contrarily, in the southern sector there was an evident stability due to the dense vegetation. For these reasons by 1972, the northern part was highly eroded, and the stability of the southern sector was lost. Over the next 20 years (1972–1992), coastal dynamics is oriented towards the consolidation of both the southern and northern parts. For 2012, there is a consistent increase of the three coastal bars during the last twenty years forming an ephemeral sand spit. Zacate mouth is one of the most dynamic mouths in the delta that has presented strong erosive processes causing significant land losses (Fig. 3). For 1948, sedimentation processes predominate with the three types of bars. For 1972, in the northern sector a rapid erosion close to the mouth of the Sierpe River isolated sediments forming a new bar. Contrarily, in the southern sector subtidal and intertidal bars occupied by mangrove vegetation stabilized. In 1992, Zacate mouth shows similarity with 1972, where erosion in the northern sector continued to appear and the bar is still in the process of consolidation meanwhile in the southern

Table 1
Grain size analysis of the different coastal bars in Térraba-Sierpe National Wetland.

Coastal bar	Sand (%)	Silt (%)	Clay (%)	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Soil texture
Subtidal	96.33	1.67	2.00	25.38	38.10	36.52	Sandy
Intertidal	95.00	2.33	2.67	3.89	41.05	55.06	Sandy
Supratidal	78.00	13.50	8.50	1.47	21.81	76.72	Sandy loam

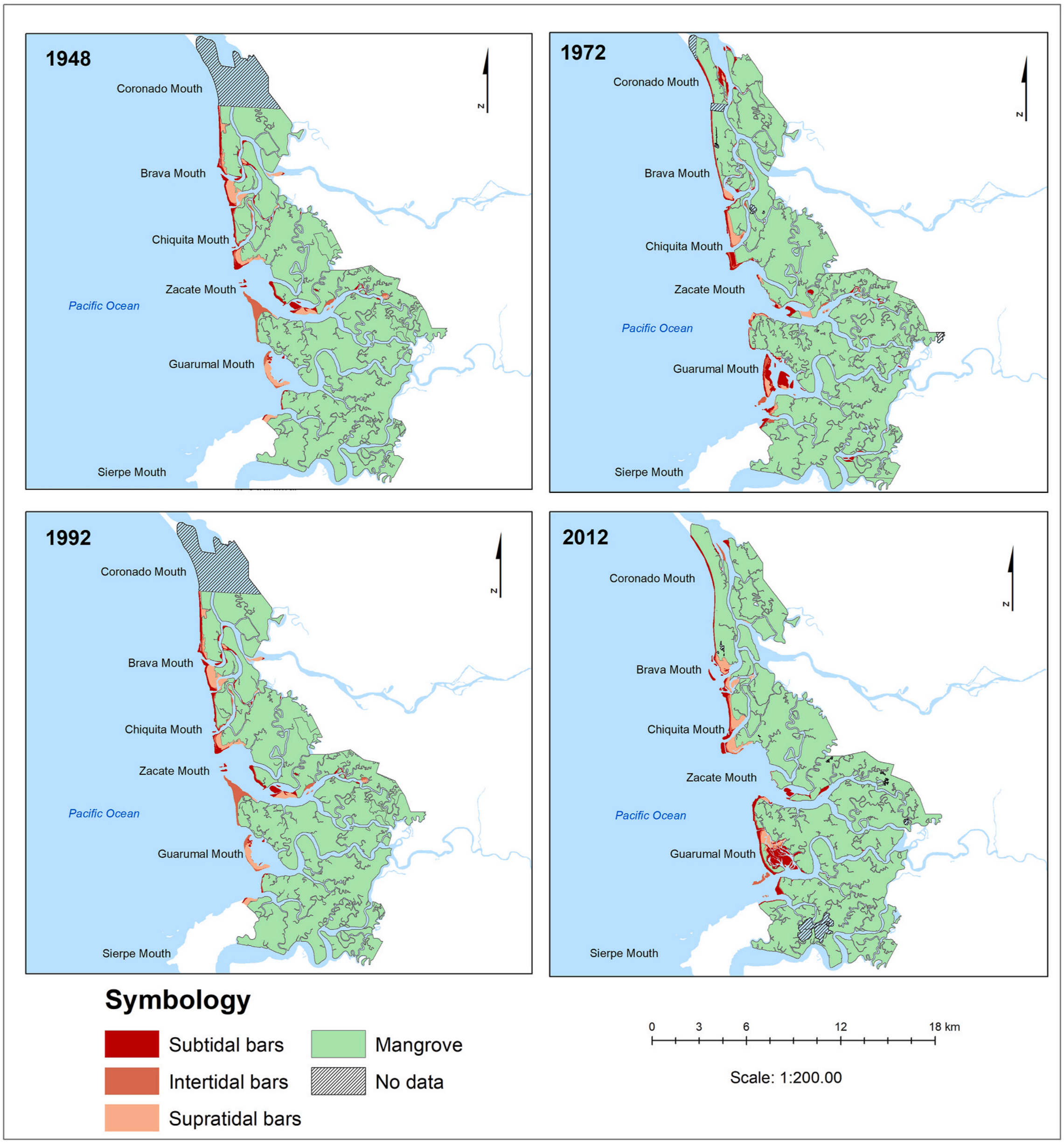

Fig. 3. Geomorphological evolution of coastal bars over 64 years in the different mouths of Térraba-Sierpe delta on Térraba-Sierpe National Wetland.

zone the consolidated terrain increases associated with the swell trajectory. In 2012, this mouth continues to lose terrain in the northern part and the bar near the mouth of the Sierpe River consolidated due to the presence of dense vegetation. As for the southern sector, erosion did not develop in the consolidated terrain, but the mentioned intertidal bar disappeared completely.

Guarumal mouth is a peculiar case compared to the other mouths because in the northern part an island formed in a period of 40 years (Fig. 3). However, in the southern part a north-south direction bar formed with a solid vegetation cover that functioned as a deposit barrier. By 1972, an island with an important presence of intertidal and supratidal bars with a north-south direction, as well as subtidal bars, totaling 120 ha, began to form in the northern sector. At the same time, the southern sector started depositional dominant processes. In 1992, in the northern sector the materials that make up the island continue to consolidate, although losing area corresponding to subtidal bars and in turn taking an arched shape with a northeast direction. In the case of the southern sector, the island shows a pattern of stability without significant presence of bars. Finally, by 2012 the northern sector manages to consolidate itself as a firm island with a northwest direction called Guarumal Island reaching 177 ha. A strong deposit of subtidal bars connects during low tide the island with the delta plain. The southern sector remains stable in terms of sedimentation dynamics. Finally, Sierpe mouth is the most stable one without significant observed changes. During the 64 years of analysis, presented only some small variations in the wetland meanders that are usual processes of the deltas were presented (Fig. 3).

3.3. Land use/cover change and deforestation rates

Land use and coverage had different dynamics during the studied 64 years (Table 2; Fig. 4). In 1948 mangrove vegetation summed 11,256.23 ha. Concomitantly, swampy areas covered 3,019.91 ha. For instance, natural coverage or wetland vegetation (mangrove + swampy areas) was 14,276.14 ha, a 92% of the delta. Other less dominant classes such as areas without information (862.99 ha), beaches and sands (248.59 ha), wooden pastures (7.72 ha), bare and degraded lands (18.73 ha), clean pastures and trees (31.96 ha) totaling more than 58 ha of

Table 2
Land use and coverage changes during 64 years in Térraba-Sierpe National Wetland.

LULC/Year	1948	1972	1992	2012
Mangrove	11,256.23	10,189.55	8934.45	8955.34
Swampy areas	3019.91	2628.08	2325.01	2758.01
No information	862.99	272.53	1201.88	235.98
Beaches and sands	248.59	938.21	870.12	917.86
Wooden pastures	7.72	152.46	98.52	104.12
Natural spaces	31.96	185.15	671.11	618.11
Clean pastures and trees	0	74.71	217.16	243.89
Bare and degraded lands	18.73	0.74	30.7	1.18
Rice	0	3.92	23.57	56.2
Mariculture ponds	0	0	128.02	263.26
Oil palm	0	0	0	12.64

agricultural land uses for that year. In 1972, mangrove coverage decreases and covers 71% of the delta (a reduction of 1066 ha compared to 1948). There is also a decrease in swampy areas with a loss of 391.83 ha compared to 1948. Therefore, the total area occupied by the wetland vegetation is 12,817.63 ha, equivalent to 89% of the total area. Likewise, agricultural land uses increase and become more than 400 ha, equivalent to 3% of the surface of the wetland. The identified uses were wooden pastures (227.17 ha), clean pastures and trees (185.15 ha), bare or degraded lands (0.74 ha), and a new activity, rice cultivation (3.92 ha; Table 2).

Between 1972 and 1992, wetland vegetation continues decreasing (8,934 ha). Moreover, the swampy areas become more than 2,325 ha. Consequently, natural coverage was 11,259.46 ha, summing a decrease of more than 1,500 ha compared with 1972, representing an 88% of the delta. Agricultural land uses continued to increase growing more than 700 ha during these twenty years. Specifically, natural spaces grew (671.11 ha), as well as clean pastures with trees covering (315.68 ha), rice cultivation (23.53 ha), discovered land (30.70 ha), and a new activity of mariculture ponds (128.16 ha). Among 1992 and 2012, wetland vegetation managed to recover (13,911.73 ha), more than 450 ha. On the contrary, land use activities continued to increase (130 ha) under a less expansive process to the previous years. Oil palm (Fig. 5c) as a new agricultural activity started with 12.64 ha. The other uses reported

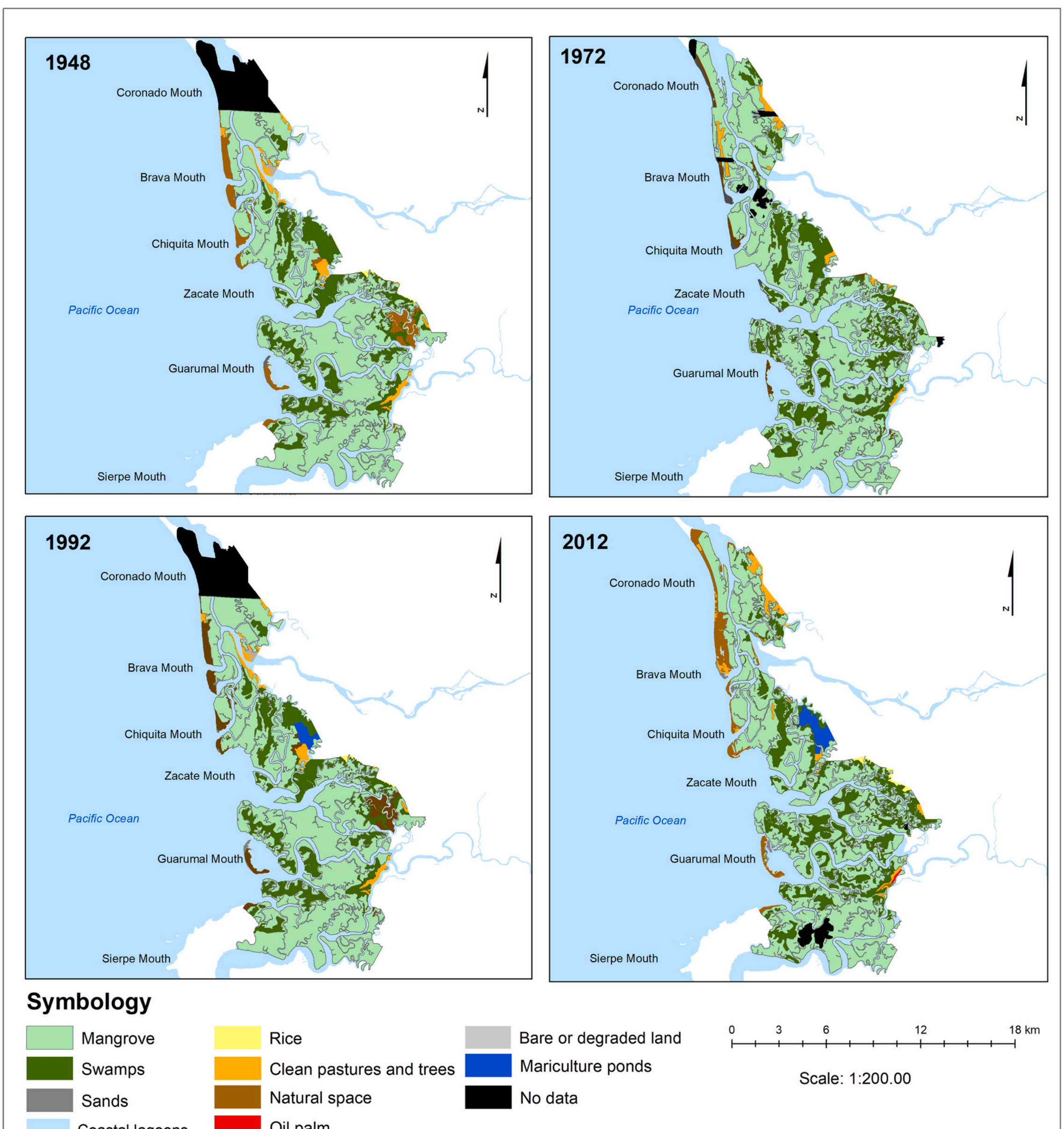

Fig. 4. Land use/change over six decades in the different mouths of Térraba-Sierpe delta on Térraba-Sierpe National Wetland.

intensifications such as wooden pastures (104.12 ha), rice cultivation (56.20 ha; Fig. 5b), mariculture ponds (263.26 ha; Fig. 5a). Contrarily, there was a decrease of the bare or degraded lands (1.18 ha).

The Net Periodic Loss (NPL), Net Annual Periodic Loss (NAPL), and the deforestation rates for 64 years in the TSNW were calculated (Table 3). From 1948 to 1972, NPL is around 1458 ha and the annual net loss was approximately 60 ha per year during the 24 years of this period. The deforestation rate for this period was 0.46%. From 1972 to 1992, the deforestation on average there was a disappearance of 77 ha per year, with an NPL of more than 1,550 ha, and a deforestation rate of 0.64%. As of 1992–2012, there was a recovery of mangrove coverage of more than 450 ha and the net annual loss of 22 ha per year.

4. Discussion

We determined the geomorphological evolution of three coastal bars (supratidal, intertidal, and subtidal), the land use/cover change, and the deforestation rates of the Térraba-Sierpe Natural Wetland (Costa Rica) between 1948 and 2012 based on aerial photographs and satellite images interpretation coupled with field corroboration.

4.1. Interdecadal timescale evolution of deltaic mangrove

Different tectonic, geological, climatic, ecological, fluvial and coastal dynamics have modeled the different coastal bars presented in the Térraba-Sierpe delta. Coronado mouth stability along almost six decades is associated with a system of active reverse faults that cross the region. The raised block is on the Fila Brunqueña side meanwhile the sunk side is in the wetland, that has favored material deposition (Morell et al., 2018). This is probably a reason why the Térraba river main mouth (Coronado) is in this sector of the delta. The stable behavior of Sierpe mouth in the southern extreme of the delta is due to the presence of Violin Island. This isle is made of Cretaceous tholeiitic basalts of accreted oceanic islands (~70-40 Ma) of 6.5 km in length, 2 km wide, and 250 m above sea level (Morell, 2016). This island functioned as a barrier against ocean currents during the Térraba-Sierpe delta formation (Denyer and Alvarado, 2007). Tectonic control is a well-known condition that influences delta morphologies with differential subsidence or uplift rates producing asymmetry patterns (Méndez-Linares et al., 2007; Korus and Fielding, 2015).

Table 3
Annual net periodic loss and deforestation percentage of the mangrove forest in the Térraba Sierpe National Wetlands from 1948 to 2012.

Deforestation/Periods	1948–1972	1972–1992	1992–2012	1948–2012
Net Periodic Loss (ha)	−1458.5	−1558.1	453.8	−2562.4
Net Annual Periodic Loss (ha)	−60	−77	22	−40
Deforestation Percentage	0.46	0.64	0.19	0.3

Coastal bars dynamics are highly related with the ENSO oscillations in similar latitude and climatic conditions of Colombia (Restrepo and López, 2008). Moreover, Térraba-Sierpe delta has a river dominated shape (Galloway, 1975). Our results indicate that during the period 1972–1992 erosion dominated most of the delta mouths, this is probably related with a couple of warmer decades influence by El Niño conditions (NOAA, 2020). During El Niño in the Pacific coast of Costa Rica, dry conditions prevail lowering the fluvial contribution and producing more erosion (Waylen and Laporte, 1999). Meanwhile, during la Niña phenomena there is a fluvial flow increase and consistently river sedimentation in the Térraba Delta Sierpe (Méndez et al., 2019). This condition probably influenced aggradation in the period 1992–2012, where a strong La Niña affected the region during 2010–2012 (NOAA, 2020). Local sea level rise and the swell pattern control the coastal bars predominant NW growth (Lizano, 2015; Silva et al., 2015). This wave action perhaps is another variable that modifies the coastal bars (Anthony, 2015), but the influence of the sediment supply and dynamics of rivers Térraba and Sierpe, definitely has the major weight in the delta dynamics. Our coastal bars evolution results agree with West (1976) who registered the coastal changes between 1960 and 1972. Consistently, Ortiz-Malavassi (2012) analyzed changes of TSNW coastal line between 1973 and 2005. Moreover, current global sea-level rise and compaction of recently deposited sediments could increase coastal flooding in river deltas (Syvitski et al., 2009). Similar sea level changes and ENSO influences on other tropical deltas have been observed previously using satellite images in Colombia (Restrepo and López, 2008), radiocarbon dating during the Holocene in Egypt (Marriner et al., 2012), aerial photographs during 1997 El Niño event in Tanzania (Erftemeijer and

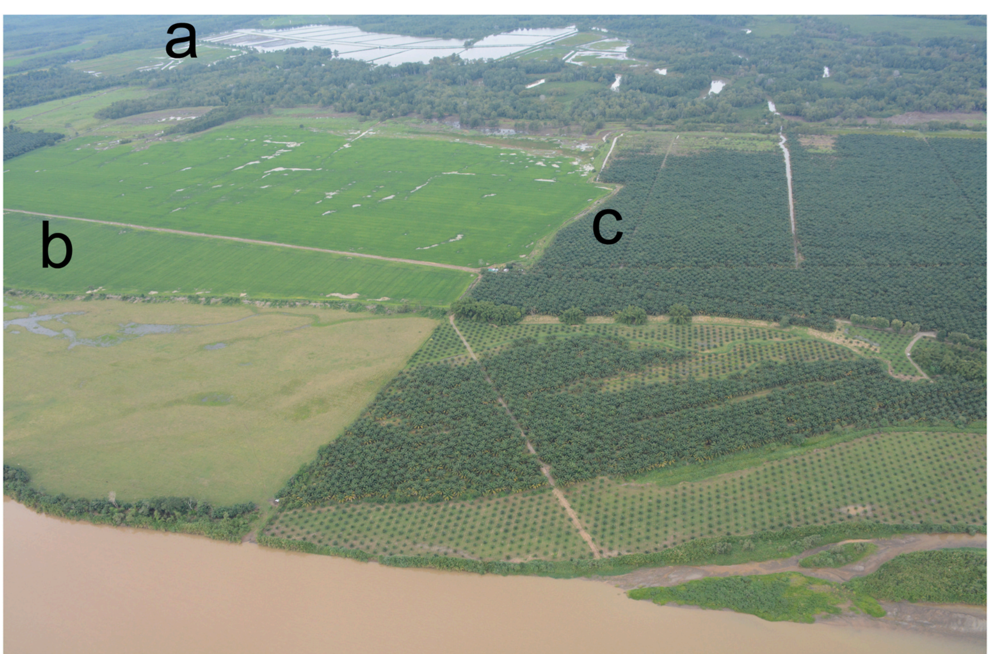

Fig. 5. Agricultural land uses impacting Térraba-Sierpe National Wetland: mariculture ponds (a), rice fields (b), oil palm (c). Credits: Néstor Veas.

Hamerlynck, 2005), and C^{14} in Papua New Guinea (Goni et al., 2006).

Coastal bars can evolve from subtidal, intertidal and supratidal bars, thereafter different vegetation species colonize and stabilize them depending on their stage. On the initial stage, some of the subtidal bars are covered by grasses, such as the *Uniola pittieri*, a plant that reaches up to 150 cm tall predominant on sandy beaches (Hammel et al., 2003). In addition, other species as vines such as *Canavalia rosea* and *Entada polystachya* tend to colonize wetlands during the intertidal phase (Cortés, 2016). Moreover, in some sectors *Rhizophora mangle* and *Rhizophora racemosa* settle with isolated individuals within the supratidal bars (Acuña-Piedra et al., 2018). Our grain size and textures results were consistent with the vegetation colonization and stabilization stages of the three coastal bars. Barrantes-Leiva and Cerdas-Salas (2015) also determined a dependency between the presence of specific sediment type and mangrove species. Sequential colonization of different mangrove species has also been identified in other tropical deltas with interdecadal timescale evolution. A study in the Save River Delta in Mozambique during 50 years revealed that geomorphic modifications on the deltaic wetland control the mangrove trees colonization (Massuanganhe et al., 2018). Moreover, a significant correlation amid percent of sand in bottom sediments and density of mangrove forest was determined in the Mekong Delta in Vietnam (Nardin et al., 2016). Another example of deltaic mangrove changes was reported from 1969 to 2003 in Patía River in Colombia, where mangrove colonization, die-off and defoliation are linked with differentiated sediment accumulation rates (Restrepo and Cantera, 2013).

4.2. Upstream dynamics and land use changes

During the Last Glacial Maximum (LGM), glacial or periglacial action modeled the highest elevations of Térraba basin at Cordillera de Talamanca (Quesada-Román and Zamorano-Orozco, 2019a). The results are well-preserved cirques, arêtes, moraines, till deposits and glacial lakes above 3000 m asl (Quesada-Román et al., 2019, 2021). Subsequent LGM deglaciation favored the formation of an extensive alluvial fans sequence in the Pacific side of Cordillera de Talamanca (Quesada-Román and Zamorano-Orozco, 2019b; Camacho et al., 2020; Quesada-Román, 2021). These alluvial fans and floodplains along the General Valley concentrate, due to a late agricultural colonization since the 1940s, agricultural activities such as farming sugarcane, coffee, pineapple, as well as intensive and extensive livestock (León, 1948; Cedeño et al., 2012; Quesada-Román and Díaz-Bolaños, 2019; Cedeño-Fonseca et al., 2020). Consistently, the decade of 1960s was when most deforestation took place in southern Costa Rica, given its late agricultural colonization (Quesada-Román, 2013; Zahawi et al., 2015; Quesada-Román and Mora, 2017).

The combination of agricultural colonization and explosive land use changes provoked strong erosion rates after 1950s (Krishnaswamy et al., 2001, 2018). In addition, the impact of tropical cyclones and earthquakes on upstream waters provoke constant landslides (Quesada-Román et al., 2018; Quesada-Román and Zamorano-Orozco, 2018) and floods (Quesada-Román, 2016, 2017; Quesada-Román et al., 2020a, 2021) that increase the sediment yield in the basin. Accordingly, these sediment flux responses in the Térraba-Sierpe delta agree with our results between 1970s and 1990s. Guarumal island formation in the TSNW is a clear example of the anthropic influence over the interdecadal climatic variations (Ortiz-Malavassi, 2012).

Results similar to Térraba-Sierpe delta varying dynamics have been reported in several other tropical and subtropical deltas where upstream land use changes and its subsequent sediment yields have molded it morphologies. Such dynamics have been identified in the Niger River Delta (Nigeria), where during the last seven decades, the anthropic modifications have molded the delta shoreline with alternating advances and retreats (Dada et al., 2018). Moreover, the land use changes during the last three decades in the Vietnamese Mekong delta have demonstrated higher subsidence rates especially the uses that required more groundwater (Minderhoud et al., 2018). Similarly than our results in Térraba-Sierpe delta, an alternation of erosion and accretion patterns were identified between 1985 and 2015 in the coastline of Bangladesh associated with the intense land use change in the water basins that fed the Meghna river delta in Bay of Bengal (Ahmed et al., 2018).

Ecogeomorphological analysis of the coastal deltaic floodplains of the Mississippi River Delta showed that since the 1930s the processes of progradation and degradation of some of the delta lobes responded to upstream land use modifications and flood pulses linked with La Niña events (Twilley et al., 2019). Consistently, sedimentation rates of Minjiang River delta in China have varied from the 1950s to 2014 due to the anthropic land use changes (i.e., agricultural and a reservoir construction; Ai-jun et al., 2020). Magdalena River in Colombia contributes approximately with 9% of the total sediment load discharged from eastern South America. This disproportionate sediment yields are associated with intense land use changes along the principal cities and agricultural regions of the country, which is constantly modelling its delta since colonial times (Restrepo et al., 2006). Worldwide, the second half of the nineteenth century experienced an agricultural activity boom, an observed trend in other deltas (Evans, 2012). Great geomorphological transformations in recent decades have been affecting coastal regions, especially in a change of the erosion/sedimentation rates (Goudie, 2018). Humans have been influencing the geomorphology of deltas particularly over the last century (Ibañez et al., 2019). Consistently, over the past 30 years deltas globally have experienced a net land gain of 54 ± 12 km^2 per year (Nienhuis et al., 2020).

4.3. Mangrove abating and environmental policies impact

Térraba-Sierpe National Wetland lost 2,562 ha over 64 years. Recently, López-Angarita et al. (2018) found similar deforestation rates in Panamá and Colombia as our results. Regionally, the Mangle Corridor near the Gulf of Fonseca between El Salvador and Nicaragua lost 30% of the original mangrove between 1970 and 2010 (Alfaro, 2011). Furthermore, 40% of mangroves species of Central America is threatened with extinction (Polidoro et al., 2010). As a whole, the world lost 136,914 km^2 of mangrove areas between 1980 and 2000, with the Americas having the highest annual rate of loss (Valiela et al., 2001). Between 1980 and 2005, 20% of total mangrove global coverage vanished (FAO, 2007).

Costa Rica has made much environmental effort in order to reverse the high deforestation rates and protect its natural resources (Kappelle, 2016; López-Angarita et al., 2016). By 1978, the Ministry of the Environment and Energy established the National System of Conservation Areas (SINAC). At the international and regional level, countries have adopted several policies such as the Central American agreement for the protection of the environment in 1989, Ramsar Convention on Wetlands in 1991, Convention of Biological Diversity in 1992, Mesoamerican Biological Corridor in 1997, Central American policy for the Conservation and Rational Use of Wetlands in 2002, Marine Corridor of the Eastern Tropical Pacific in 2004. Moreover, at the national level Costa Rica implemented the Forestry Law in 1996 which limits the exploitation and logging of mangroves, among other forestry coverages. In addition, in 1998 the Biodiversity Law was enacted which made all wetlands protected areas, dedicated to the conservation and protection of biodiversity, soil, and water resources. Furthermore, all exploitation was prohibited, permitting only research and recreation. By 1998, all wetlands were protected areas and most Ramsar sites had management plans. Moreover, the National Strategy for Wetlands in 1993, the National Wetland Program in 1999, and the National Policy for Wetlands in 2001 were implemented. These environmental policy/laws, in addition to eco-tourism, a sensitive environmental consciousness, and protecting secondary forests from conversion, transformed Costa Rica into a reforestation hotspot of the neotropics (Nanni et al., 2019). At present, Costa Rica has 27,840.47 km^2 of protected areas, representing a 54% of its continental territory.

Térraba-Sierpe National Wetland was declared a Protected Area with the category of wetland site in 1994, and the international granting as a Ramsar site in 1995. In 2013 the General Management Plan of the TSNW was officially approved. This tool has contributed to increase the mangrove coverage, establishing protection measures, but also allowing and regulating the tourist activity and fishing. In addition, this plan proposes the reduction of non-natural uses areas in order to recover the wetland areas with environmentally friendly reforestation practices (Acuña-Piedra and Quesada-Román, 2017).

Mangrove rehabilitation/restoration projects are managed by different scientific and socio-political agendas and need to be responsive to these multiple stakeholders and agents who hold different values (Ellison et al., 2020). TSNW is characterized by the extraction of piangua (cockles; *Anadara tuberculosa* and *Anadara similis*), fishing, intensive agriculture (oil palm, rice, livestock), and a flourishing tourism that offer tours through the mangroves, sport fishing and diving (SINAC-PNUD-GEF, 2017). Térraba-Sierpe National Wetland has a plan for the exploitation of the piangua. The plan was built with the participation of the public institutions as well as with members of the existing cockles extractors associations (SINAC-PNUD-GEF, 2018). Along the tropics, efficient integrated ecosystem services management could preserve benthic biodiversity in mangrove ecosystems (Ellison, 2008).

As a Ramsar Site, Térraba-Sierpe National Wetland has an adaptation actions plan to climate change (SINAC-PNUD-GEF, 2018). Wildfires commonly occur during the dry season, and in recent years these processes are increasing their occurrence. This plan gave capacitation to forest guards dealing with wildfires and facilitated the installation of informative banners to avoid ignition activities. Moreover, Térraba-Sierpe National Wetland management defined maximum and minimum navigation speeds in the channels of the Ramsar Site, and thus prevent the erosion of edges and the consequent sedimentation of channels. Signs were created to indicate to the boats the speed reduction to 40, 20 and 10 km/h, depending on the area of the wetland, as well as signaling for areas where you can only navigate with paddle and the use is not allowed of motorboats.

Camacho-Navarro et al. (2017) found that the wetlands located near the boundaries of the Térraba-Sierpe National Wetland show the transformation from wetland to palm, through several stages. First, it is ditched to eliminate excess water, then cattle are introduced, and it continues to drain. Later, the land is prepared, with machinery, for the sowing of rice; possibly this machinery opens deeper drains to continue drainage. Finally, palm is planted for its production. The process of change, wetland-grass-rice-palm takes an approximate period of five years. Therefore, continuous monitoring, heavier fines and even prison procedures are necessary and urgent measures for the effective management of this wetland.

Costa Rica has an extensive tradition of ecotourism. The southern Pacific of Costa Rica is one of the most pristine areas of the country and tourism is growing very fast during the last decades. A good signal is the local population ecological awareness due to the environmental policies and educational programs since mid-1990s. Moreover, a more scientific tourism can be developed understanding the relationships between landforms and mangrove dynamics through geotourism (Quesada-Román and Pérez-Umaña, 2020). Térraba-Sierpe National Wetland it is a potential site to develop a geopark in order to promote and manage its geological, geomorphological, ecological and cultural heritage (Pérez-Umaña and Quesada-Román, 2018). Térraba-Sierpe mangrove ecosystem management depend on promote a good communication among local communities, private sector, and public institutions in order to seek the more sustainable balance between natural resources exploitation, economic revenues and conservation strategies.

Along the low latitudes, the loss of mangrove species will have devastating economic and environmental consequences for coastal communities (Polidoro et al., 2010). Until the 1990s several countries started to adopt international, regional and local environmental policies, which favor the mangroves conservation and management (López-Angarita et al., 2016). At present, coastal wetlands policies should promote the adaptation and a collaborative, multilevel, and decentralized system to achieve the integration of local population in decision-making (Mojica-Vélez et al., 2018). In addition, mangroves management is highly challenging given the multiple sectors with jurisdiction over them such as fisheries, forestry, agriculture, tourism, or transport (López-Angarita et al., 2018). Therefore, mangrove ecosystem management, conservation, and restoration experiences in different parts of the world have showed that local, state and national level government as well as local communities' commitment is key to successful projects (Gilman et al., 2008; Romañach et al., 2018).

5. Conclusions

We determined the interdecadal morphodynamics evolution of the Térraba-Sierpe delta between 1948 and 2012. During this period, we classified and characterized three coastal bar types (supratidal, intertidal, and subtidal), ten land uses/covers, and deforestation rates of six delta mouths of the Térraba-Sierpe Natural Wetland. These results showed the key role of biogeomorphology explaining landform dynamics and biotic processes in mangroves. Moreover, these outputs highlight how upstream and catchment scale land use/cover change implications along a multidecadal scale is critical to understand the coastal alterations. The reconstruction and monitoring of coastal wetlands land use/cover change along several decades is an important tool for decision makers and stakeholders in environmental and land use planning. During the last decade, the intense land use transformation (mangrove-grass-rice-oil palm) is putting in risk the borderlands of the TSNW. This issue should be continuously monitored, also implementing heavier penalties for the effective management of the wetland. Effective mangrove ecosystem management in TSNW should stimulate constant communication and decision-making processes amid local people, public institutions, and private sector to develop a sustainable equilibrium among natural resources exploitation, economic profits and conservation schemes. Besides, the crucial decision of Costa Rica implementing environmental policies clearly showed that recovering mangrove forest is possible and provided an example for the international community. Local communities and every government level commitment is critical to mangrove ecosystem management, conservation, and restoration projects along tropics and subtropics.

Author agreement statement

We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We understand that the Corresponding Author is the sole contact for the Editorial process. He is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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