





Article

Mangrove Forests Evolution and Threats in the Caribbean Sea of Colombia

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Abstract: Colombia has approximately 379,954 hectares of mangrove forests distributed along the Pacific Ocean and the Caribbean Sea coasts. Such forests are experiencing the highest annual rate of loss recorded in South America and, in the last three decades, approximately 40,000 hectares have been greatly affected by natural and, especially, human impacts. This study determined, by the use of Landsat multispectral satellite images, the evolution of three mangrove forests located in the Colombian Caribbean Sea: Malloquín, Totumo, and La Virgen swamps. Mangrove forest at Malloquín Swamp recorded a loss of 15 ha in the period of 1985–2018, associated with alterations in forest hydrology, illegal logging, urban growth, and coastal erosion. Totumo Swamp lost 301 ha in the period 1985–2018 associated with changes in hydrological conditions, illegal logging, and increased agricultural and livestock uses. La Virgen Swamp presented a loss of 31 ha in the period of 2013–2018 that was linked to the construction of a roadway, alterations of hydrological conditions, illegal logging, and soil urbanization, mainly for tourist purposes. Although Colombian legislation has made efforts to protect mangrove ecosystems, human activities are the main cause of mangrove degradation, and thus it is mandatory for the local population to understand the value of the ecosystem services provided by mangroves.

Keywords: mangrove; coastal dynamic; salinization; *Rhizophora mangle*; *Avicennia germinans*; *Laguncularia racemosa*

1. Introduction

Mangrove forests are composed of unique plant species, that is, halophilic trees and shrubs that have specific morphological, physiological, and reproductive characteristics that enable them to survive in a critical interface among terrestrial, estuarine, and near-shore marine ecosystems in tropical and subtropical regions around the world. They are considered one of the most productive natural ecosystems on earth because of their relevant ecosystem services and ecological functions, such as being a nesting habitat for fishes, birds, marine mammals, crustaceans, amphibians, and reptiles. They also act as effective nutrient filters, support numerous rural economies, and protect coastal communities from storms and floods by acting as windbreaks and wave barriers, reducing coastal erosion [1–7]. Last but not least, mangrove forests, due to their great biomass (above- and below-ground) and capacity of

accumulation of sediments, are able to store more carbon (on average $22 \pm 6 \text{ Tg year}^{-1}$) than terrestrial forests, making them one of the most carbon-rich ecosystems in the tropics, with an estimated value of USD 194,000 per hectare per year [8].

Mangrove forests currently occupy less than 14 million hectares, representing <1% of the world's coastal areas, of which more than two-thirds are located in 18 countries: Indonesia, Brazil, Australia, Mexico, Nigeria, Malaysia, Myanmar, Bangladesh, Cuba, India, Papua New Guinea, Colombia, Guinea Bissau, Mozambique, Madagascar, the Philippines, Thailand, and Vietnam [1,3]. It is estimated that approximately 35% of mangrove forests disappeared during the last two decades of the 20th century, mainly due to their direct conversion to different land uses [1,6,9,10] such as aquaculture, agriculture, urbanization, and impacts due to alterations in the hydrology of river basins and changes in fluvial sediment inflow, among others [3,5,7,11,12]. Although the rate of mangrove forest loss has decreased significantly in the last two decades, it is still worrying, with rates of up to 3.1% per year in some countries—this could lead to a loss of their functionality in less than 100 years. In addition, only 6.9% of the world mangroves are protected, and hence it is mandatory to establish new areas of protection in an effort to reduce the rate of loss [1,4,10,13]. It is estimated that between 0.02 and 0.12 Pg per year of carbon have been released into the atmosphere as a consequence of mangrove degradation, which represents 10% of the total emissions resulting from deforestation [7]. Therefore, global net loss of mangroves would require the successful rehabilitation of about 100,000 ha per year unless the necessary measures were taken to halt current mangrove losses [14]. Further, mangroves work as a transitional intertidal ecosystem that is particularly vulnerable to the effects of climate change, mainly those linked to rising sea level, surface water warming, warming and changes in the composition of the atmosphere, and changes in rainfall, among others [5,12]. In different regions of Latin America and the Caribbean, climate change is considered to be the main driver of environmental impacts on mangroves [12]. Natural and anthropogenic stressors may interact in an additive or synergistic manner, which could lead to accelerated and massive alterations of these ecosystems [11]. However, mangrove forests are considered as a highly resilient ecosystem that has the capacity to adapt and adjust to changing conditions [6], and hence it can play a fundamental role in the design of climate change adaptation strategies.

Mangrove forests observed in Latin America and the Caribbean represent around 26% of the total amount recorded at world scale. They cover an area between 3.58 and 4.54×10^6 ha, of which 80% is found in six countries: Brazil, Mexico, Cuba, Colombia, Venezuela, and Honduras [12]. On the western side of South America, the largest mangrove forest cover is found in the tropical zone of the Colombian Pacific coast and in northern Ecuador [15]. Colombia is characterized as being the only country of South America with coasts in the Pacific Ocean and the Caribbean Sea with an extension of 1200 and 1800 km, respectively. Differences in precipitation and tidal range between both coasts favor the existence of almost continuous strips of mangroves along the Pacific coast, whereas in the Caribbean this ecosystem is closely linked to freshwater sources [16].

Overall, Colombia has a mangrove forest cover of around 379,954 ha, with 292,724 and 87,230 ha respectively located on the Pacific and Caribbean coasts [15,17,18]. They show a total amount of eight species: *Rhizophora mangle*, *Rhizophora harrisonii*, *Rhizophora racemosa*, *Laguncularia racemosa*, *Conocarpus erectus*, *Avicennia germinans*, *Avicennia harrisoni*, *Pelliciera rhizophorae*, and *Mora oleifera*.

On the Caribbean coast of Colombia, in the Department of Atlántico (Figure 1), there are currently around 613.3 hectares of mangrove forests located in different municipalities [19] and, along the coast of the Department of Bolívar, they currently occupy a surface of around 7000 hectares [20]. This paper determines the evolution, during the last decades, of the most extended and representative mangrove forests on the Colombian Caribbean coast between Barranquilla and Cartagena de Indias (departments of Atlántico and Bolívar)—Mallorquín, La Virgen, and Totumo mangrove swamps (Figure 1). This study took into consideration both natural changes (due to coastal erosion/accretion, etc.) and those produced by anthropic activities [21], which have influenced the evolution of the aforementioned mangrove forests, in order to design adequate plans for their environmental improvement and sound

conservation strategies. The present paper investigates their evolution and their human (deforestation, road construction, etc.) and natural impacts (salinity variations, coastal erosion, etc.) on three mangrove forests located at the departments of Atlántico and Bolívar, located in the Caribbean coast of Colombia (Figure 1). Such areas are characterized by five mangrove species that are common along the Colombian Caribbean Sea [21]: *Rhizophora mangle*, *Avicennia germinans*, *Laguncularia racemosa*, *Conocarpus erectus*, and *Pelliciera rhizophorae*.

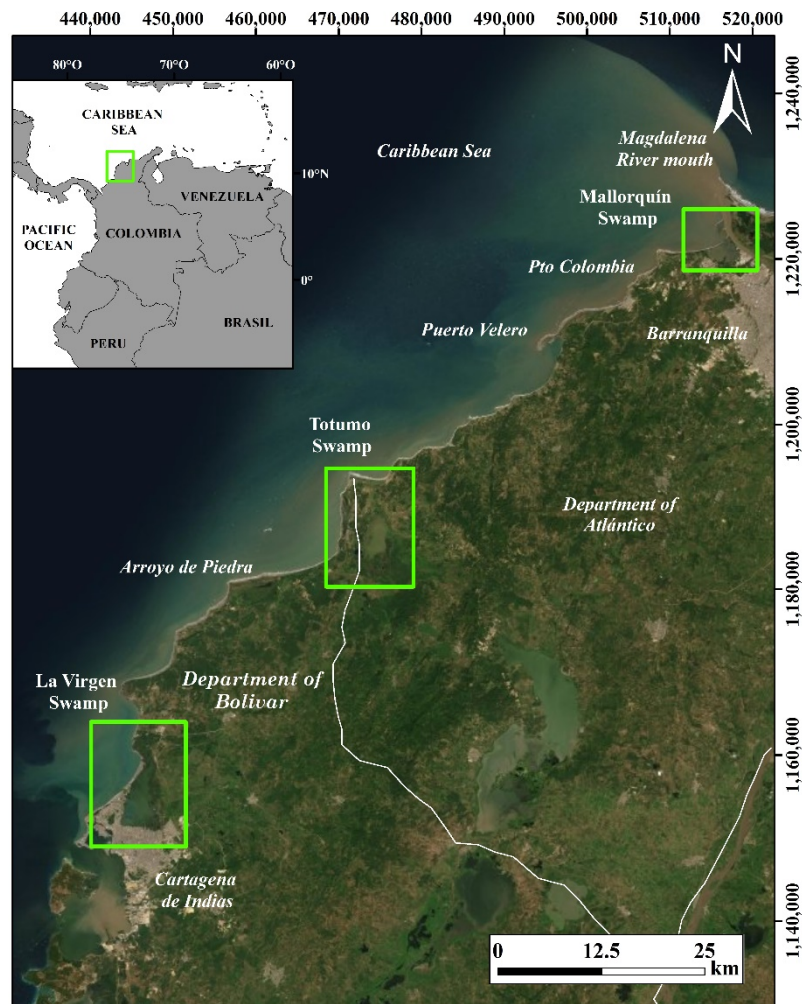


Figure 1. Location map with studied mangrove forests.

2. Study Area

The Caribbean coast of Colombia is a tropical environment with seasonal variations in rainfall (Figure 2) from the dry season (December–March) and the transitional seasonal (April–July) to the rainy season (August–November) [22,23].

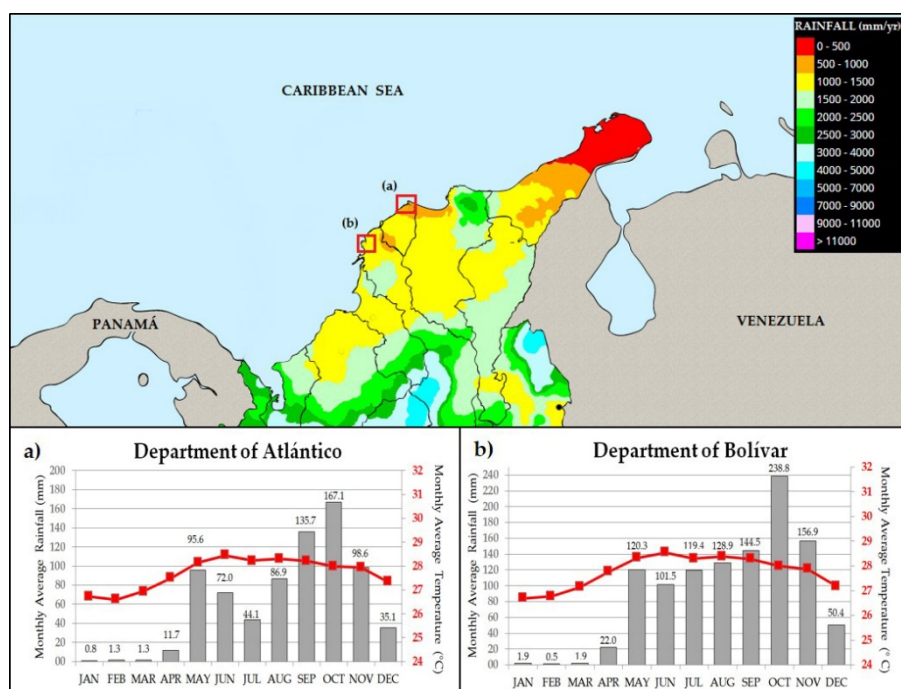


Figure 2. Rainfall and temperature variations at Colombian Caribbean coast (data recorded in the 1980–2010 period- IDEAM [24]): (a) Department of Atlántico; (b) Department of Bolívar.

The main regulator of rain cycles throughout the Colombian territory is the Intertropical Convergence Zone [25,26]. This low pressure equatorial system follows the synchronization of the sun [27] and a southern movement (between 27.5° S and 27.5° N), having the largest amount of solar energy received by the planet [28]. Other oscillations, such as Maiden and Julian, as well as the variability associated with the El Niño and La Niña phenomena (Southern Oscillation—ENSO) in the Pacific, contribute especially to the intensity of the precipitation anomalies on the Colombian Caribbean coast [26]. Tide has mixed semi-diurnal periodicity and microtidal variability, with maximum values of 60 cm [22]. Wind average velocity is <12 m/s, with the strongest winds blowing from the northeast in December–March and weakest values associated with easterly approaching winds, usually blowing in September–November. The dominant sea surface current is the *Caribbean current* that flows during almost all the year from east to west; an opposite current, the *Darien* or *Colombia* current, flows from Panama northeastward [29]. Significant wave height is between 1 and 2 m and wave climate is dominated by swell waves approaching from the northeast from November to May, and sea (smaller) waves, approaching from the northwest, west-southwest, and southwest, during the remainder of the year. Predominant longshore sediment transport is southwestwardly directed and a minor reversal takes place during rainy periods when southerly winds achieve more importance, giving rise to short erosive waves [30]. Coastal erosion is essentially linked to the impact of hurricanes and cold fronts—the former events impacting the coast from June to November, and latter events from January to March [31].

Mallorquín Swamp is located in the northwest part of the Department of Atlántico (Figure 1), on the western bank of the Magdalena River, close to Barranquilla. It is a shallow estuarine coastal lagoon with an area of around 650 ha, surrounded by floodplains and sand dunes. Three species of mangroves have been reported in Mallorquín Swamp: *A. germinans*, *R. mangle*, and *L. racemosa* with a maximum average height of 15.7 m. The most abundant species is *A. germinans* (71%), followed by *L. racemosa* (21%), and finally *R. mangle* (8%) [32]. Salinity range was 9‰–22‰ in surface water and 14‰–50‰ in interstitial water, that is, at a depth between 50 and 100 cm [32]. The mangrove leaves had cuts and perforations associated with herbivory. The presence of climbing plants was also observed—they generate overweight and strangulation of stems and branches [32]. The system has been affected by coastal erosion, increased

sedimentation processes, and anthropogenic activities linked to the urbanization of nearby areas and contamination processes due to solid waste and sewage discharges [33–37].

Totumo Swamp (Figure 1), located between the departments of Bolívar and Atlántico, is composed by a main body of water with an approximate extension of 1361.06 ha and presents several mangrove patches on the borders of the swamp. Totumo Swamp presents average salinity values from 0.1‰ to 2‰, and thus it is considered a fresh water body [38]. The vegetation adjacent to Totumo Swamp belongs to the dry tropical forest and very dry thorny scrub. Lastly, along the swamp flood plains, an abundant vegetation of *Typha dominguensis* was observed [38]. The swamp is partially protected by a 5 km long spit, namely, Galerazamba spit, made up of a wide beach with a gentle slope from 2° to 5°, which has undergone major morphological changes since its initial description by Francisco J. Fidalgo in 1805 [39–41]. The spit encloses inland lagoons (e.g., La Redonda) that are fed by rainfalls, as well as directly by the sea during the stormy season. La Redonda lagoon, inside the Galerazamba spit, has an average salinity of 23‰, suitable for mangrove development [38]. On and nearby the spit, there are several mangrove areas composed of *L. racemosa* (77%), which is located on the edge of the lagoon, and *C. erectus* (23%), which is found at the mouth of the swamp. Mangroves have a shrubby growth, with maximum average heights of 6.1 m for *L. racemosa* and 5.7 m for *C. erectus*. The vegetation is currently under anthropogenic pressure, mainly due to the expansion of the agricultural frontier that has been increasing in recent years, negatively impacting the mangrove forest by illegal logging and successive land reclamation. Presently, the original brackish vegetation is changing towards a typical freshwater vegetation ecosystem because of the reduced inputs of marine waters due to the construction of gates (that are usually closed) at the lagoon inlet entrance [19,38].

North of Cartagena de Indias (Department of Bolívar, Figure 1), there is one of the most important coastal wetland of Colombia, namely, **La Virgen Swamp**, which has an approximate surface of 20 km² and a mangrove forest cover of around 824 ha, with a main drainage network consisting of 8 streams in the rural area and 20 channels in the urban perimeter of Cartagena de Indias. Four species of mangrove have been reported in La Virgen Swamp: *A. germinans* (67%), *R. mangle* (30%), *L. racemosa*, and *C. erectus* that, together, make up 3% of the swamp. *R. mangle* is located on the internal border of lagoons and channels; *A. germinans* is found in the less intervened sites, reaching the limit with the tropical dry forest; *L. racemosa* is mainly found on the edges of abandoned ponds; and *C. erectus* is only found at the border between the mangrove forest and the mainland vegetation [42]. Salinity varies considerably, and its most frequent peaks are in the range of 0‰ to 35‰ [42]. The average height of the mangrove plants varies from 1 to 10 m, according to the forest sector [21,43].

The area is subject to various threats such as illegal logging; artificial filling; and terracing for the implementation of fish farming, waste disposal, urbanization, and pollution; for example, La Virgen Swamp receives about 60% of the Cartagena de Indias wastewaters, around 114,000 m³/day. Further, because of the reduced capacity of water exchange between the lagoon and the Caribbean Sea, several problems have arisen in the last decades, such as eutrophication, increased salinity, and fish mortality [20,44,45].

3. Methodology

The methodology applied to assess the mangrove area changes was supported by multi-date remote-sensed data. Using satellite images, it is possible to identify, calculate, and monitor mangrove areas, as well as the surfaces affected by erosion processes [46–49].

3.1. Data Used

To determine the extent of mangrove ecosystems, we used Landsat 5 and 8 multispectral satellite images (TM—thematic mapper, and OLI—operational land) with a spatial resolution of 30 m in their optical channels available at the United States Geological Survey [50]. The dates of the images varied between 1985 and 2018 (Table 1). The dataset was composed of the OLI sensor bands, already subjected to a complex algorithm of adjustment of the atmospheric effects that was based on parameters estimated

from the same sensor bands and the application of the model of the second simulation of the satellite signal with the code known as solar vector spectrum (6SV) [51].

The images presented a good resolution due to the lack of cloudiness and atmospheric disturbances. Similarly, Google Earth Pro images and thematic cartography available in DIMAR-CIOH [52], INVEMAR [53], and a layer from the Humboldt Foundation cartographic base were used.

3.2. Digital Images Analysis

The manipulation of Landsat images was carried out using ARGIS 10.4. Initially, the coordinate system was defined by processing the georeferencing according to the parameters defined for land mapping in Colombia with the Magna Sirgas Datum Bogotá coordinate system.

The analysis, interpretation, and quantification procedures of the images used were performed using band composition, as well as the normalized difference vegetation index (NDVI), which was calculated using the following equation:

$$\text{NDVI} = (\text{IVP} - \text{V}) / (\text{IVP} + \text{V}) \quad (1)$$

where IVP and V represent the reflectance values in the near-infrared and red infrastructure bands, respectively. The NDVI varies from -1 to $+1$, with negative values and zero representing areas without vegetation [54]. The procedure for delimiting the areas identified as mangrove forests was carried out by manual vectoring on the classified images. This method requires a great deal of interpretation and is time consuming, as each polygon must be determined individually.

Ortho-rectified satellite images were also used to map shoreline position. Shoreline migration was analyzed in ARGIS 10.4 by the Digital Shoreline Analysis System—DSAS 5.0 [55].

Table 1. Details of multispectral remote sensing data and other documents used in this study.

Location Area	Sensor and/or Document	Spatial Resolution (m)/or Scale	Year/Month/Day of Acquisition	Source	Cloud Cover (%)
Mallorquín Swamp	Landsat 5-OLI	30	1985/01/24	USGS	<5
	Landsat 5-OLI	30	1998/05/20	USGS	<5
	Landsat 8-OLI	30	2013/04/01	USGS	<5
	Landsat 8-OLI	30	2018/12/05	USGS	<10
Totumo Swamp	Landsat 5-OLI	30	1985/01/24	USGS	<5
	Landsat 5-OLI	30	1998/09/20	USGS	<5
	Landsat 8-OLI	30	2013/05/13	USGS	<5
	Landsat 8-OLI	30	2018/12/05	USGS	<5
La Virgen Swamp	Landsat 5-OLI	30	1985/01/24	USGS	<5
	Landsat 5-OLI	30	1998/09/20	USGS	<5
	Landsat 8-OLI	30	2013/05/13	USGS	<5
	Landsat 8-OLI	30	2018/12/05	USGS	<5
All areas	Unidentified	4	All years	Google Earth Pro	<5
	Lidar-Spot ¹	1:50,000	All years	DIMAR-CIOH	Unidentified
	Layer Colombia ² Mangrove	1:5,000,000	2005	INVEMAR	Unidentified
Mallorquín Swamp/Totumo Swamp	Spot-Aster ³	30	1986	INVEMAR	Unidentified
			2004	INVEMAR	Unidentified

¹ Atlas Geomorfológico del Caribe Colombiano [52]. ² Sistema de información para la gestión de los manglares de Colombia SIGMA [56]. ³ Ordenamiento Ambiental de la Zona Costera del Departamento del Atlántico [53].

3.3. Field Visits

Detailed field visits were made to the three mangrove forests investigated in this study in order to determine actual predominant plant species, their distribution, their conditions (leaf characteristics and plant average height), and the typology of anthropic activities (road emplacement, expansion of urbanized areas, disposal of waste materials, illegal logging, etc.) and their effects on the environment. Characteristics of mangroves in past investigated time spans were essentially reconstructed from unpublished reports carried out by environmental departmental authorities and research institutes.

4. Results and Discussion

4.1. Mangrove Swamps Evolution

The evolution of three most relevant mangrove forests along the Department of Atlántico and Bolívar, that is, the Mallorquín, Totumo, and La Virgen swamps, is presented in the following sub-sections.

4.1.1. Mallorquín Mangrove Swamp

The mangrove forest of Mallorquín Swamp presented small changes in the period of 1985–1998, a reduction of around 51 ha from 1998 to 2013, and an increase of around 34 ha during the 2013–2018 period (Figure 3, Table 2).

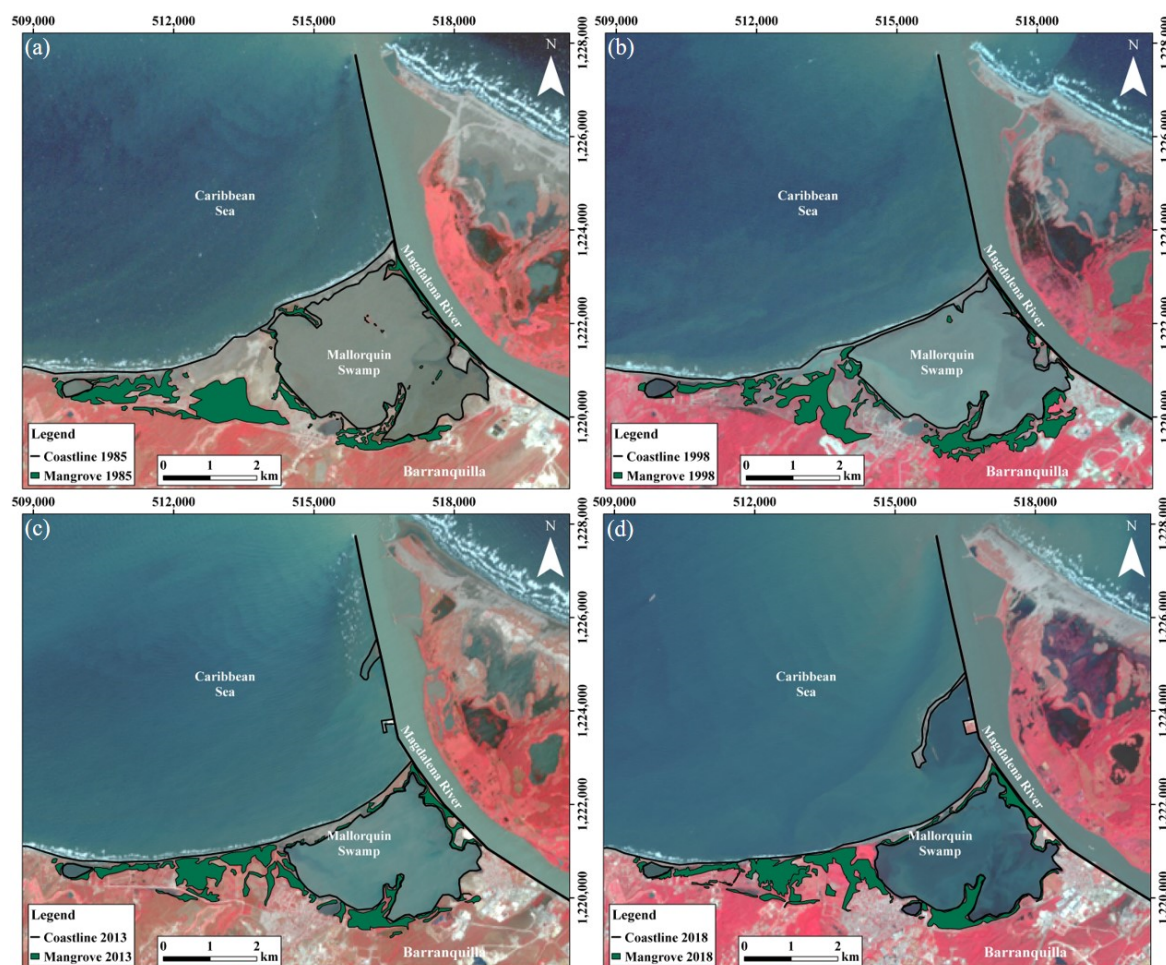


Figure 3. Evolution of the mangrove forest (green) in the Mallorquín swamp (a) 1985, (b) 1998, (c) 2013, and (d) 2018.

Table 2. Variation of the mangrove forest cover (ha) in the Mallorquín, Totumo, and La Virgen swamps.

Year	Mangrove Cover (ha)		
	Mallorquín	Totumo	La Virgen
1985	302	496	725
1998	304	215	685
2013	253	229	941
2018	287	195	910

Until the beginning of the 1940s, the swamp had an estuarine regime constituted of different coexisting and connected systems, that is, the Cantagallo, Mallorquín, La Playa, and Manatías swamps, which presented a wide variety of ecosystems and fishing areas [57,58]. After the construction of the western jetty at the Magdalena River mouth, during the 1925–1935 time span, the sand bar that encloses Mallorquín Swamp suffered—between 1939 and 1987—an erosion rate of 65 m/year, finally acquiring its current configuration. The swamp recorded a strong hydrologic imbalance due to a deficit in fresh water supplies that were essentially limited to the León stream and direct rainfall [53,59]. The deficiency in water supplies significantly affected the different ecosystems, impacting the fishing activities and the mangrove forest health [57,58].

Concerning the period from 1985 to 1998, fairly unrepresentative changes were reported, that is, a very small increase (Table 2) as a result of the mangrove loss observed at the sand bar that encloses the swamp and the mangrove cover increase recorded in the southern part of the swamp (Figure 3a,b). Despite such small changes, the swamp reflected a stressful environmental condition, mainly due to the diminution of hydrodynamic processes. The effects of such an unfavorable situation continued in following years, and were more evident at the beginning of the 2000s.

In this same period, the area of Mallorquín Swamp was reduced considerably. The bar migrated landward on average 29.5 m/year, resulting in a period of relevant morphological changes and loss in mangrove cover.

Changes in the hydrodynamic conditions, as observed since the end of the 1980s by Galvis et al. [19,60], were linked to the few continental and marine water supplies, because of the reduced fresh water supplies from the León stream and the lack of permeability of the western jetty at the Magdalena River mouth. This brought to the modification of the mangrove ecosystem, and *A. germinans* and eurihaline vegetation became the predominant species compared with *R. mangle*, reflecting a process of salinization that continued in following years, reaching interstitial salinity values from 20‰ to 30‰, as reported by Galvis et al. and Ulloa-Delgado et al. [60,61]. However, the loss of *R. mangle* was not only associated with the salinity increase but also with erosion processes that led to the loss of trees and beach surfaces, which made the implantation of new *R. mangle* propagules impossible.

In the period from 1998 to 2013, around 51 ha of forest were lost (Table 2) as a result of urban area expansion in the southern part of the swamp [19,61], where illegal forest cutting by local inhabitants, accumulation of solid waste materials, and artificial infilling works were observed (Figure 3b,c). On the other hand, mangrove growth was recorded in the sand bar because of the reduction of coastal erosion (Figure 4) that allowed bar stabilization and propagules implantation and growth.

The most exploited species was *L. racemosa*, used for the construction of huts to provide shade for tourists visiting local beaches. As for solid waste materials, which prevent the proper development of seedlings and pneumatophores and hence favor a decrease in the self-healing capacity of the forest [62], they essentially came from the Magdalena River that drains a basin of 257,430 km², wherein 724 municipalities are located, representing 80% of the Colombian population [63]. Further mangrove losses were related to the diminution of fresh water supplies, especially during the 1997–1998 period in which Colombia was greatly impacted by the El Niño phenomenon that led to a generalized decrease of rainfall and river discharges. During the most critical dry period (October 1997 to January 1998), the flow of the Magdalena River fluctuated between 45% and 70% in its lower basin [64], considerably decreasing its water contribution to Mallorquín Swamp and the consequent increase of salinity. The

very narrow strip of *R. mangle* observed in 1998 in the southern, northeastern, and northwestern parts of the swamp was later replaced by a monospecific forest of *A. germinans*, with the presence of few individuals of *L. racemosa* and *C. erectus* and xerophytic plants (*Prosopis juliflora*, *Capparis odorantissima*, *Sarcostema* sp., and *Stigmaphyllon* sp.) [61]. In general, the forest presented mature individuals, but of little height (average: 3.86 m) and with leaves characteristic of xerophytic plants [61]. Such a trend continued in 2005, as reported by INVEMAR [53] and GTA [57], but slightly decreased in 2007 when salinity achieved values between 20‰ and 35‰ that allowed *A. germinans* to survive [65] and led to a slow recovery in the general mangrove forest cover [53]. In addition, in 2007, reforestation programs were initiated by the fishing communities with the support of local environmental authorities [53]. The stabilization of the hydrological conditions and the reforestation programs had positive effects that were observed in the following period investigated.

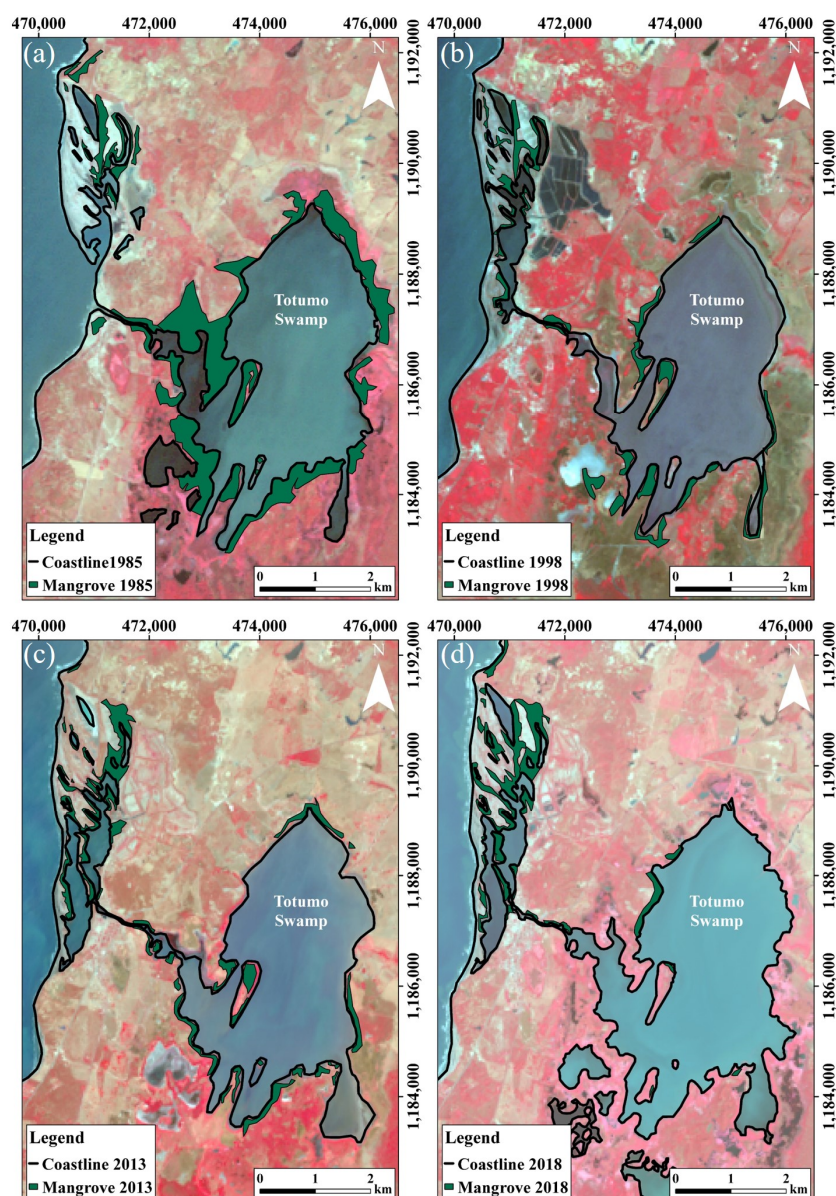


Figure 4. Evolution of the mangrove forest (green) in the Totumo swamp: (a) 1985, (b) 1998, (c) 2013, and (d) 2018.

In the period from 2013 to 2018, an increase in mangrove coverage of around 34 ha was located on the west part of the sand bar and in the southern part of the swamp (Figure 3c,d). In this period, the

stability of the sandy bar was observed, as a consequence of the growth of a spit, as being connected to the Magdalena western jetty, located to the north of the swamp. This new formed feature protected the bar from incoming waves (Figure 3c,d).

Additionally, the recovery of the mangrove could be related to the reforestation campaigns carried out by different entities [53] and the maintenance of the different channels that communicate the swamp with the Magdalena River. In 2016, the Corporación Autónoma Regional del Atlántico (Local Environmental Authority) carried out activities aimed at the environmental recovery of the swamp by directly cleaning the channels and by installing meshes in the boxculverts to reduce waste materials entering in the channels communicating the swamp with the Magdalena River [58]. Presently, an ongoing project is being developed to declare Mallorquín Swamp a protected area [66].

4.1.2. Totumo Mangrove Swamp

The mangrove forest of Totumo Swamp presented a reduction of ca. 280 ha in the period from 1985 to 1998, an increase of ca. 13 ha in the period from 1998 to 2013 and a loss of ca. 33 ha during the period from 2013 to 2018 (Figure 4 and Table 2).

The large loss of mangrove cover recorded in the first period (from 1985 to 1998) was related to the transformation of the forest into a freshwater vegetation ecosystem [38]. Most relevant changes were recorded in the northern part of the swamp (Figure 4a,b). Totumo Swamp communicated with the Caribbean Sea through a natural inlet that allowed the entry of salt water, generating ideal conditions for the growth of mangrove [38,53]. However, in the 1970s, gates emplaced at the inlet entrance, 20 m in width, greatly limited sea water entrance, turning much of Totumo Swamp into a freshwater system (Figure 4) [38,67], which receives supplies from numerous streams, such as Punta Antigua, Lata, Calabria, and Bombo [61]. As a result, during the rainy season, salinity was close to zero and, during dry seasons (i.e., January–May and July–September), salinity increased up to 15‰ [68]. Mangrove plants presented shrubby and stunted forms and did not exceed 2 m in height. There were observed specimens of *R. mangle*, *L. racemosa*, *C. erectus*, and *A. germinans*, the latter being the most abundant. A considerable decrease of *R. mangle* was observed at the mouth of the swamp, and *Typha dominguensis* was recorded on the west bank, alternating with *C. erectus* with rhizomes on the roots, stems, and lower branches [61].

An increase of around 13 ha in mangrove surface was recorded in the period from 1998 to 2013 as a result of mangrove growth on the western side of the swamp, on the Galerazamba spit, as well as a decrease on the eastern side (Figure 4b,c).

Galerazamba spit has undergone relevant morphological changes since its original description by Francisco J. Fidalgo in 1805 [39–41]. Anfuso et al. [69] reported spit evolution from 1947 to 2013, recording an accretion of around 0.7 km² and a down drift (i.e., southward) migration of about 80 m. Hence, the increase in the mangrove area was directly related to the growth of the spit that enclosed numerous small lagoons, among which the larger one was La Redonda Swamp, fed by rainfalls and by the sea during stormy season [39,40].

On the eastern side of the swamp, INVEMAR [19] observed in 2004 that the mangrove cover was reduced to a strip of approximately 5 to 10 m in width, mainly composed of *C. erectus* and *L. racemosa*. At this area, the natural mangrove cover was progressively displaced by pastures and macrophytes and human activities as livestock and agriculture [53]. On the southwestern side of the swamp, only a very narrow line of *C. erectus*, with plants about 7.5 m high, was recorded; no natural regeneration or flowering of mangroves was observed [19].

The mangrove forest of Totumo Swamp degraded in the period from 2013 to 2018, with a loss of around 33 ha (Figure 4c,d). The decrease was mainly observed on the eastern side, whereas the western side showed only a small increase associated with mangrove growth in the lagoons at Galerazamba spit. The overall reduction in mangrove cover was undoubtedly related to the loss of water exchange with the Caribbean Sea. This turned Totumo Swamp into a freshwater ecosystem, wherein water is nowadays mainly used for agricultural and livestock activities. The economic interests linked to the

maintenance of such activities retain the gates at the inlet entrance that was closed to prevent seawater entrance, thus prohibiting the restoration of the original swamp ecosystem.

4.1.3. La Virgen Mangrove Swamp

La Virgen mangrove forest presented a reduction of around 40 ha in the period from 1985 to 1998, an increase of around 255 ha in the period from 1998 to 2013, and again a reduction of around 34 ha in the period from 2013 to 2018 (Figure 5, Table 2).

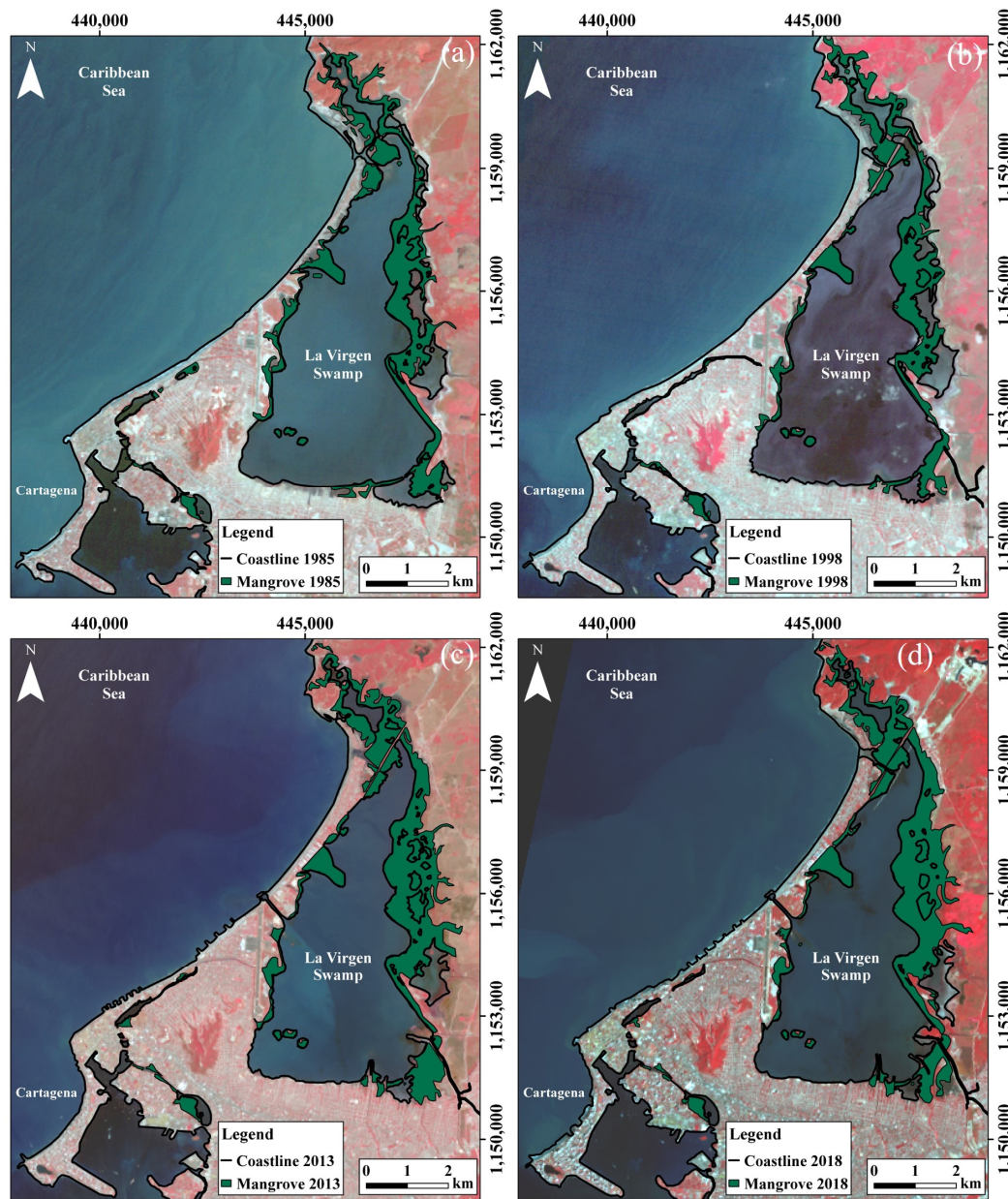


Figure 5. Evolution of the mangrove forest (green) in La Virgen swamp: (a) 1985, (b) 1998, (c) 2013, and (d): 2018.

The mangrove forest of La Virgen presented a reduction of approximately 40 ha in the period from 1985 to 1998 (Table 2). This reduction was mainly observed in the northern part of the swamp (Figure 5a,b) and was associated with different factors that were reported since 1984 by CARDIQUE [70], among them are (i) the accumulation of waste materials, mainly plastics, observed especially at the

roots of *R. mangle* [21]; (ii) the illegal logging—for the construction of houses by the communities living on the banks of the swamp—of *L. racemosa*, which consequently suffered a relevant pressure, with mortality values of 92.9%; and (iii) the land filling for urban infrastructure emplacement, such as the construction of a connection runway to the local airport and the roadway Cartagena-Barranquilla, among others [45,70]. In the following years, the mentioned roadway greatly affected water exchanges between the swamp and the Caribbean Sea, reducing the existing inlets to a single point located at La Boquilla [43,71]. Therefore, water exchange capacity was significantly reduced, limiting the oxygenation process and altering the constant flow of sediments and organic material, mainly due to the periodic infilling of the inlet, which generated problems such as eutrophication, increased salinity, and fish mortality [44]. In addition, the road construction at the border of the mangrove forest will probably lead to the replacement of native vegetation by other vegetation types, as observed in Punta Mala Bay, Panama [72]. During this investigated period, along and nearby the mentioned roadway, the construction of many resorts and hotels also took place, which was done to satisfy the tourism market demand, as well as the implementation of aquaculture activities (e.g., cultivation of tarpon fish) [71].

In the southern sector, the loss of mangrove areas occurred mainly through landfill processes and, consequently, substitution by urbanization (Figure 5).

Concerning the period from 1998 to 2013, an increase of 255 ha was observed essentially along the eastern border of the swamp (Figure 5b,c). This mangrove surface increase was linked to the execution of a project, at the end of 2000, which stabilized the La Bocana area to guarantee the permanent water entrance from the Caribbean Sea. The project consisted in the emplacement of different structures at the inlet entrance and along the feeding channels (sand traps, gates, etc.) that favored the recirculation of water within the swamp, improving the level of oxygenation and salinity; in this way, the lagoon recovered the natural ecosystem services [73]. INVEMAR [19] recorded an increase of mangrove vegetation in 2004, which was dominated by *R. mangle* and *A. germinans* (that together accounted for 97% of the total amount), followed by *L. racemosa* and *C. erectus*. *L. racemosa* was rare and was usually found on the edges of abandoned ponds, whereas *C. erectus* was the least frequent and was only located at lagoon borders, along with the mainland vegetation. In addition, in 2004, a reforestation program was carried out, wherein 401,564 plants (of four species of mangroves) were planted in an area of 44.3 ha [19]. Summing up, the reestablishment of the hydrodynamic of the swamp and the implementation of reforestation programs seemed to be the main reasons for the increase in mangrove coverage between 1998 and 2013.

Concerning the last investigated period, from 2013 to 2018 (Figure 5c,d), the swamp presented a reduction of mangrove forests of approximately 30 ha, essentially due to the conclusion of the construction, in 2015, of the Cartagena-Barranquilla roadway, as well as a new roadway that included the emplacement of a viaduct 5.39 km in length, 4.73 km of which passes over La Virgen swamp [74]. The environmental assessment prior to the construction of the viaduct stated that the structure would impact around 52 ha of swamp surface and 41 ha of mangroves [75]. The National Environmental Licensing Authority (ANLA) authorized in 2015 the logging of 1673 trees, among which 1158 were mangrove trees [75]. The construction company has to compensate such actuations by creating a new green area of 177 ha, which could in the next few years increase the total forest coverage [75]. In 2015, the Institute Humboldt and the Foundation Omacha observed, as is the case in the northern zone of the swamp, there is only *R. mangle* (64%) on the banks and *A. germinans* (33%) on the mainland, whereas four species of mangrove were recorded in the eastern sector: *A. germinans* (65%), *R. mangle* (33%), *C. erectus* (0.6%), and *L. racemosa* (0.3%). Inside the forest, there were no permanent flooding events, and hence *A. germinans* dominated (with 97%), and both *C. erectus* and *L. racemosa* were rare and interspersed with *A. germinans* [76]. Further losses of mangrove coverage in the period between 2013 and 2018 were observed in the southern and southeastern areas of the swamp that have been progressively filled in and occupied by human illegal settlements and aquaculture ponds that are generally linked to the illegal occupancy by people displaced by violent events from different territories in Colombia and in Venezuela [43,45]. These different factors could together be the cause of the

mangrove loss recorded in the analyzed time frame. Nowadays, the swamp shows around 775 ha of mangroves, including *R. mangle*, *A. germinans*, and *L. racemosa* [45].

4.2. Environmental and Natural Concerns

Oceanographic, climatic, and geomorphological aspects; soil conditions; level and duration of flooding; salinity; and sediment load determine the structure and floristic composition of mangrove forests [77].

Salinity is one of the most important abiotic factors influencing the structure, seedling establishment, and function of mangrove ecosystems, and small changes in salinity can lead to abrupt ecological changes [6,78]. Most mangrove species can grow in fresh water, but growth is stimulated under saline conditions, with optimal seawater concentrations ranging from 5‰ to 50‰, depending on the mangrove species [78,79]. High salinity soils limit seed germination and reduce plant growth [80]. The low rates of water loss from the leaves, as a strategy for surviving under hypersaline growth conditions, limit rates of carbon gain affecting the plant growth; as a result of this, individuals of low stature and stunted growth (scrub mangroves) are observed [79]. Therefore, the degree of tolerance to salinity determines the dominance of species within the mangrove forest. Mangrove forests dominated by *R. mangle* can cope with wave strength and salinities close to those of sea water (about 35‰), those dominated by *A. germinans* can tolerate and develop under salinity conditions of 60–65‰ and sandier substrates. Although *L. racemosa* tolerates salinities similar to *R. mangle*, it requires a more open canopy, which allows a greater availability of light for regeneration, and therefore is generally associated with disturbed areas [77]. The effect of the increased salinity on the mangrove species was clearly observed in Mallorquín Swamp, which suffered a loss of diversity—*A. germinans* and *R. mangrove* were replaced by *A. germinans* of low stature and a few individuals of *L. racemosa* [19]. The same condition was also described by Sánchez et al. [65] in a mangrove forest located in the municipality of Puerto Colombia (Colombian Caribbean Sea). The authors detected that in soils with high salinity (76‰ at 0.3 m), the dominant species was *A. germinans*; meanwhile, *R. mangle* was absent or very scarce. A similar trend, that is, the predominance of *A. germinans* associated with a few individuals of *L. racemosa*, was also observed in the forest along the Indian River Lagoon (Florida, USA), which is developed on high salinity soils due to low sea water inputs and high evaporation rates [79]. Mangrove mortality due to hypersalinity conditions was reported in the Ciénaga Grande de Santa Marta (Colombia), where sites with dead or dwarfed vegetation had an average soil salinity of 74‰, with values between 52‰ and 100‰. Basal area and forest biomass volume were inversely correlated with soil salinity [81]. Currently, the Mallorquin swamp presents salinity values between 14‰–50‰ in interstitial water, which allow the growth of *A. germinans*, *R. mangle*, and *L. racemosa* [32]. In addition, new sandy bodies are being formed in front of Mallorquín Swamp, where mangrove seedlings are observed (Figures 3d and 6a). This could generate ideal conditions prone to the increase of this mangrove forest. However, the presence of solid waste is one of the main problems that this forest presents; therefore, cleaning and educational campaigns should be carried out in the surrounding communities and also should be devoted to the tourists that visit the forest (Figure 6b).



Figure 6. (a) Mangrove seedlings growing in the new sand bar, and (b) plastic waste observed in the mangrove forest of Mallorquín Swamp.

The mangrove, as a facultative halophyte plant, can tolerate fresh water conditions for a limited time but not during its entire life cycle [82,83]. The flowing of seawater into the mangrove forest system reduces the possibility of survival for plant species that are not salt tolerant [82]. The mangrove forest of Totumo Swamp was transformed on its eastern side into an ecosystem dominated by freshwater plants (*Typha dominguensis* and *Eichhornia crassipes*) due to the loss of seawater input that brought salinity to zero (Figure 7a); meanwhile, mangrove remnants were recorded on its western side that is characterized by brackish water conditions (Figure 7b). La Virgen Swamp was affected mainly by the construction of a road that impedes the normal exchange of water with the Caribbean Sea. The swamp receives about 60% of the city wastewater, which has an approximate volume of 114,000 m³/day [44,45]. The lack of communication with the Caribbean Sea generated an increase in wastewater concentration, generating eutrophication processes that affected the mangrove forest.

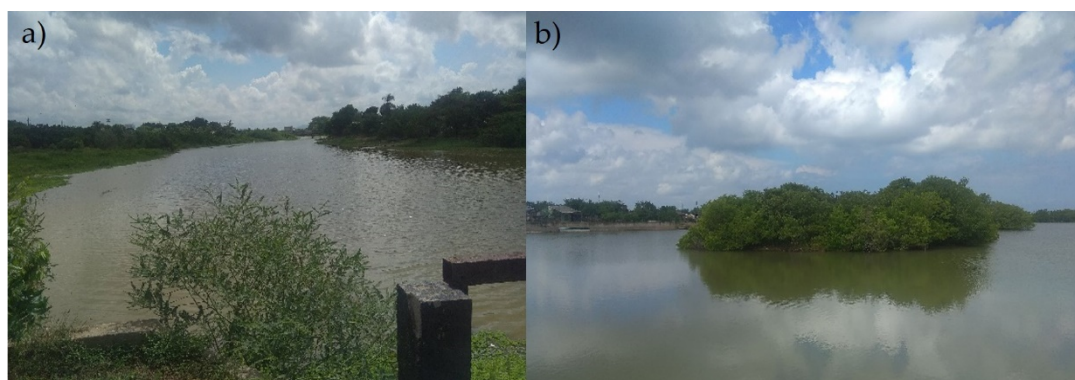


Figure 7. (a) Eastern side of Totumo Swamp characterized by fresh water conditions; (b) mangrove remnants (*Rhizophora mangle*) in the western side of Totumo Swamp characterized by brackish water conditions.

Deforestation is considered one of the main anthropogenic causes of mangrove degradation [84]. Colombia has the highest annual rate of deforestation in South America, showing values between 1.1% and 0.6% for 1980–1990 and 2000–2005 periods versus average values of 0.69% and 0.18% observed in South America [85]. In Colombia, mangrove areas have been converted mainly into agricultural land, ponds for aquaculture, and urban development (mainly for tourism). Illegal logging has been reported for the three mangrove forests investigated in this paper (Mallorquín, La Virgen, and Totumo), but each one was associated with different activities.

In Mallorquín Swamp, the logging was particularly linked to an increase in urban growth, mainly in the southern part of the swamp (Figure 3d). In La Virgen Swamp (Figure 8a) urban growth for

tourism, road construction (Figure 8b), aquaculture, and the use of wood for house building were the main factors associated with the felling of the mangrove forest. In Totumo Swamp, the expansion of the agricultural frontier and the increase in livestock activity on the margins of the swamp were the main factors associated with the felling of the mangrove forest. With respect to land uses in Totumo Swamp, they include extensive livestock farming (5209.43 ha), annual or seasonal crops (53.75 ha), pasture cultivation (3049.85 ha), and aquaculture (155.82 ha) [38].

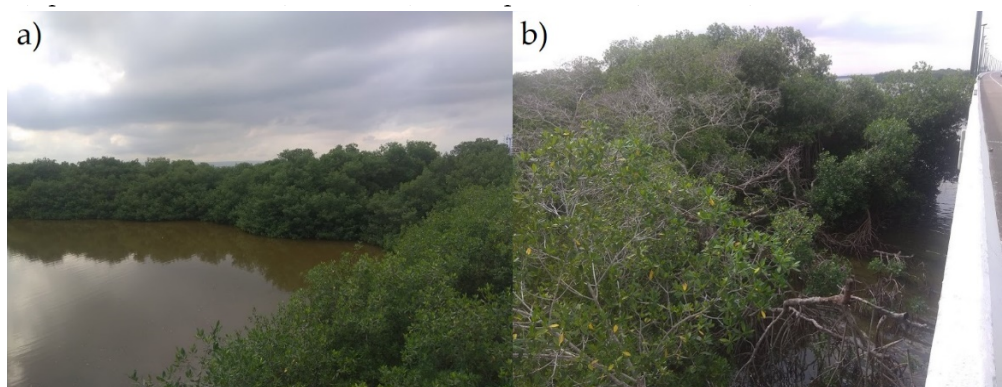


Figure 8. (a) Mangroves (*R. mangle*) in good condition in the west sector of La Virgen Swamp; (b) mangrove cutting due to the construction of the viaduct over La Virgen Swamp.

Deforestation modifies the mangrove phytogeographic landscape and reduces its biological diversity [84]. Deforestation not only decreases the number of mangrove specimens, but also produces ecological effects on the forest, such as stunted and shrubby growth, canopy opening, stem mortality, decreased regeneration of harvested species, and changes in species composition, among others [86]. The extraction of woody and non-woody products has degraded many areas of mangroves, resulting in the development of plants of low height and thin diameter [85], as reported mainly in the Mallorquín and Totumo swamps. Mangrove deforestation is linked to the lack of adequate methods to assess their economic value; this has led people to consider them as worthless wastelands and as unhealthy risk areas that should be adapted to alternative and more lucrative uses [84].

Mangrove forests are also subject to natural disturbance related to changes in the amount and seasonality of rainfall. This is one of the most relevant factors in the Colombian Caribbean coast, an example being the intensification of the El Niño phenomenon, which generates decreases in the productivity of mangrove forests dominated by *R. mangle* and, in the long term, their replacement by *A. germinans* [77]. This was observed in the mangrove forest of Mallorquín Swamp that, due to alterations in its hydrology caused by anthropic activities (e.g., construction of the western jetty at the Magdalena River mouth) and natural phenomena such as a relevant reduce of precipitations due to El Niño (1997–1998), recorded not only alterations/degradation in its cover, but also in its composition becoming a monospecific forest consisting only of *A. germinans*.

Mortality events associated with climate extremes (e.g., tropical cyclones and El Niño and La Niña phenomena) could increase in the coming years because mangroves are important sentinels of global climate change processes [87].

5. Conclusions

The results obtained in the framework of this paper show how, during different periods of time, mangrove forests at localities investigated in the Colombian Caribbean Sea have been impacted by diverse and complex anthropogenic activities and natural disturbances. Although natural disturbances such as the El Niño phenomenon have greatly affected, at times, the cover and the structure of mangrove forests, human activities were the main cause of degradation and loss. Alterations in the hydrology of swamps, which lead to increases or decreases in salinity, urban growth, illegal logging,

expansion of agricultural frontiers, and road construction, were the main causes associated with the loss of mangrove cover.

Although losses of mangrove covers were observed in all investigated sites, it is worth noting that different activities carried out by local environmental authorities, together with local inhabitants, favored mangrove forest cover stabilization and, at places and times, led to an increase, such as in the Mallorquín and La Virgen swamps. In Totumo Swamp, different economic interests, essentially linked to agricultural activities, prevented mangrove forest recover. At many places, illegal activities such as logging continue to affect the mangrove forests investigated in this paper, and thus it is mandatory for the Colombian environmental authorities to develop strategies aimed not only at protecting and recovering these ecosystems, but also at raising awareness among the local inhabitants concerning the ecological value of these ecosystems, as well as their importance in coastal adaptation and mitigation function of climate change-related processes.

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