Conservation State of the Mangrove Forests of Bonaire, Caribbean Netherlands

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The photograph shows a channel in the mangrove forests of Lac Bay, Bonaire.

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Contents

Summary

In the Caribbean Netherlands, mangrove forests are found exclusively on Bonaire. where they hold critical ecological value and are protected under several international and regional frameworks, including the Ramsar Convention and the SPAW Protocol. Bonaire hosts four mangrove species, with the red mangrove (*Rhizophora mangle*) being dominant. The largest mangrove system is located in Lac Bay (~222 ha), with smaller patches in Lagun, Pekelmeer and other areas amounting to a total of ~236 ha. These forests offer essential ecosystem services, including coastal protection, carbon storage, and support for biodiversity and ecotourism. Despite their importance, mangroves on Bonaire face several threats, including siltation from terrestrial runoff, climate change, and more recently, large-scale influxes of *Sargassum* spp. brown algae. While the mangrove cover in Lac Bay remained relatively stable at approximately 239 ha between 1961 and 1996, a 6.6% decline was recorded between 1996 and 2022. In Lagun, the situation is even more severe, with nearly 46.2% of the mangrove area lost between 2014 and 2020. These declines are mainly attributed to backwater siltation, but also to anoxic conditions caused by decaying *Sargassum* spp. at the seaward fringe of the mangrove forests. As a result, the conservation status of Bonaire's mangroves is classified as 'unfavourable-inadequate', which signals a need for continued and expanded conservation actions. Effective conservation efforts should be aimed at restoring water depth and circulation in the backwaters of Lac Bay and Lagun. This can be achieved by mechanical removal of accumulated sediment from the backwaters, reopening existing and historical tidal creeks to enhance tidal flow, and strategic placement of oil booms to block *Sargassum* spp. influxes into the mangrove forests. Other priorities include reducing overgrazing by free-roaming livestock in the hinterlands, reforesting the overgrazed hinterlands with native tree species, and building and maintaining water retention structures in these areas. Furthermore, implementing legislation to prevent excessive urban development and industrial activity in the watersheds of Lac Bay and Lagun is crucial to reduce downstream inflow of toxins, sediments, nutrients, and pathogens through surface runoff and groundwater. In conclusion, the situation on Bonaire underscores the importance of addressing land-based pressures, monitoring mangrove ecosystem health, and scaling up restoration efforts to prevent further degradation.

1 International protection status

Within the EU, most coastal habitat types are protected under the European Habitat Directive, mainly due to their ecological importance for migratory shorebirds. The Caribbean Netherlands also contains various coastal habitats, including mangrove forests. An indication of the international protection status of mangrove forests within the Caribbean Netherlands can be derived from the WWF-classification for the Neotropical Ecoregion, which states: Critical/Endangered (WWF, 2017).

Within the Caribbean Netherlands, mangrove forests of considerable size occur only in the southeastern part of Bonaire, where they border the shores of Lac Bay. The entire Lac Bay lagoon and the mangrove forest it contains has been declared a protected Ramsar site, signifying its international importance in terms of natural characteristics (Debrot, Meesters and Slijkerman, 2010). The Pekelmeer in the south of Bonaire, which also contains some patches of mangrove forest, has also been declared a Ramsar site (Geelhoed et al., 2013). The mangrove forests of Bonaire are dominated by the red mangrove (*Rhizophora mangle*) and the black mangrove (*Avicennia germinans*), while the white mangrove (*Laguncularia racemosa*) and button mangrove (*Conocarpus erectus*) are also known to be occasionally present (Davaasuren and Meesters, 2012; Casal et al., 2024). These four species are listed in Annex III of the Specially Protected Areas and Wildlife (SPAW) protocol of the Cartagena Convention and are all protected under the Eilandsbesluit Natuurbeheer.

2 Characteristics

2.1 Description

Mangrove forests are evergreen forests that are formed by trees that have adapted to live in the warm intertidal areas of the world wherever waters are sufficiently calm and where there are sufficient sediments for them to take root (Leal and Spalding, 2022). These forests are found globally across the tropics and subtropics, where they grow in estuaries, deltas, lagoons and sheltered shores. Here, they provide important ecosystem services including enhanced biodiversity, coastal protection, mitigation of climate change through carbon sequestration, and provisioning of breeding and nursery grounds for many fisheries species (Nagelkerken et al., 2008; Leal and Spalding, 2022; Casal et al. 2024). Furthermore, they act as nutrient, sediment, and pollutant traps, thereby protecting adjacent habitats, such as seagrass beds and coral reefs, from these stressors.

The main global threat to mangrove forests is habitat loss due to aquaculture, agricultural production, coastal development for housing and tourism, and overexploitation (logging) (Polidoro et al., 2010). As a result, mangrove forests declined by 35% worldwide between 1980 and 2000 (Millennium Ecosystem Assessment, 2005), and kept declining globally but at a slower rate of 3.4% between 1996 and 2020 (Bunting et al., 2022). Compared to global trends, mangrove forests in the Caribbean have suffered even more damage over the last two decades, with a decline of 7.9% between 1996 and 2020. This decline is mainly attributed to coastal development, demographic growth, and climate change (Bunting et al., 2022), and more recently also to the impact of massive influxes of holopelagic *Sargassum* spp. brown algae (Chávez et al., 2020; Mücher & van der Geest, 2024). Work by Rull (2023) suggests that if current rates of mangrove loss in the Caribbean continue, mangroves will go extinct from this region over the next three centuries. The effects of climate change on mangrove forests is less well understood. However, a recent review of the scientific literature on this topic by Trégarot et al. (2024) showed that altered rainfall regimes (i.e. reduced rainfall) and increased frequency and intensity of extreme weather events have the most negative impact on mangrove forest cover in the Caribbean.

In the Caribbean Netherlands, four species of mangroves are found: *R. mangle*, *A. germinans*, *L. racemosa* and *C. erectus*, of which the red mangrove *R. mangle* is the most common (Davaasuren and Meesters, 2012; Casal et al., 2024). Mangrove forests exhibit strong species-specific zonation patterns, which can be attributed to species-specific preferences with regard to salinity, tidal flooding, and land elevation. These species-specific zonation patterns can be accurately distinguished and mapped using satellite spectral photography, as was shown for the mangrove forest in Lac Bay by Casal et al. (2024). *R. mangle* grows in frequently or permanently flooded areas near the seaward margins of the mangrove forest in Lac Bay, while *A. germinans* grows at higher elevation areas with low water content, as found in the northern backwaters of Lac Bay (Casal et al. 2024).

2.2 Relative importance within the Caribbean

In 2017, the total area of mangroves in the Lesser Antilles of the WWF Neotropical Ecoregion (ID: NT1416) was estimated at 20,636 hectares, spread over 263 different sites. The largest mangrove forests were found in Antigua and Barbuda, Guadeloupe, Martinique, and the US Virgin Islands (WWF, 2017). The total extent of mangrove forest on Bonaire is currently approximately 236 ha (Mücher and Verweij, 2020; Casal et al., 2024; Mücher & van der Geest, 2024), which is 1.1% of the total mangrove area in the Lesser Antilles that was estimated in 2017, thus making its relative importance within the Caribbean limited.

3 Ecological aspects

3.1 Habitat

Mangrove habitat is characterized by a vegetation of evergreen mangrove trees that mainly occur in the intertidal zone, along sheltered and shallow-water coastlines in the (sub) tropics. Table 1 provides a more detailed overview of the environmental requirements for mangrove forests to persist.

***Table 1**. Outline of the main abiotic conditions necessary for the development of mangrove forests where white, orange and green reflect unsuitable, slightly suitable, very suitable condition, respectively*

Salinity	Very fresh	Moderately fresh	Slightly brackish	Moderately brackish	Strongly brackish	Saline (30-50 ppt)	Hypersaline (> 50 ppt)
Temperature	<15 °C	15-20 °C	20-30 °C	30-37 °C	>37 °C		
Water depth	Deep (>2 m)	Shallow (1-2 m)	Lower intertidal zone	Mean sea level	Higher intertidal zone	Terrestrial	
Wave action	High	Intermediate	Low	None			

The aerial roots of mangroves stabilise the seabed and provide a substratum on which many organisms depend. Above the water, the mangrove trees and canopy provide important habitat for a wide range of species, including birds, insects, reptiles and mammals (e.g. bats, primates). Below the water, the mangrove roots provide substrate for epibionts (e.g. tunicates, sponges, algae, bivalves), while the space between roots provides shelter and food for motile fauna such as prawns, crabs and fishes (Nagelkerken et al. 2008). Mangrove litter is transformed into detritus, which forms an important basis of the mangrove food web, in addition to plankton, epiphytic algae and microphytobenthos. Due to the high abundance of food and shelter, and low predation pressure, mangroves form an ideal breeding and nursery habitat for a variety of animal species, including (commercially important) crab, prawn and fish species (Nagelkerken et al. 2008). Mangrove forests are often also characterized by a dense concentration of mosquitoes, particularly the Crabhole Mosquito, *Deinocerites sp*. Other salt-tolerant and drought-resistant species found in mangrove areas include plants like *Sesuvium portulacastrum*, *Batis maritima*, and *Salicornia perennis* (Perennial Glasswort). Piscivores birds, such as herons, and insectivorous birds are often abundant, while mangrove forests are also known to provide important roosting sites for doves and parakeets (Harms and Eberhardt, 2003). Table 2 provides an overview of typical species that can be found in mangrove forests in the Caribbean Netherlands.

***Table 2**. Typical species inhabiting mangrove forests in the Caribbean Netherlands.*

Common name	Scientific name	IUCN category	Taxa	Category[1]
Red mangrove	*Rhizophora mangle*	LC	Plants	Cab
Black mangrove	*Avicennia germinans*	LC	Plants	Cab
Yellow warbler	*Setophaga petechia*	LC	Birds	Cb
Green heron	*Butorides virescens*	LC	Birds	Cb
Grey snapper	*Lutjanus griseus*	DD	Fish	Cb
Rainbow parrotfish	*Scarus guacamaia*	NT	Fish	Cb

[1] Typical species categories are as follows: Ca = constant species indicating good abiotic conditions; Cb = constant species indicating good biotic structure; Cab = constant species indicating both good abiotic conditions and good biotic structure; K = characteristic species; E = exclusive species.

3.2 Ecosystem services

Ecosystem services provided by mangrove forest in the Caribbean Netherlands include climate regulation by carbon sequestration, provisioning of habitat and food for many species of fish, birds, marine mammals, and invertebrates, provisioning of honey, timber, fuel, and medical resources, nursery and breeding grounds for commercially fished species (e.g. grey snapper, great barracuda, and Caribbean spiny lobster), opportunities for ecotourism (e.g. guided canoe and/or bird watching tours), and trapping of land-based sediment, nutrients and pollutants, thereby protecting adjacent key habitats (i.e. seagrass beds, coral reefs), from these stressors.

4 Current distribution and reference values

In the Caribbean Netherlands, mangrove forests are exclusively found on Bonaire, where they occur along the shores of Lac Bay, but occasionally also along the shores of Lagun, Pekelmeer and various salina's. Based on the most recent literature, it is estimated that the total extent of mangrove forest on Bonaire is approximately 236 ha (value based on satellite image from 2014; Mücher and Verweij, 2020), of which 222.3 ha is located in Lac Bay (value based on satellite images from 2021 and 2022; Casal et al., 2024), 1.4 ha is located in Lagun (value based on satellite images from 2020; Mücher & van der Geest, 2024) and the remaining ~12.3 ha can be found along the shores of Pekelmeer and various salina's in the south of Bonaire (Mücher and Verweij, 2020). Apart from the study by Mücher and Verweij (2020), there are no historical reference values for the total extent of mangrove forests on Bonaire, but they do exist for Lac Bay. Table 3 provides an overview of the extent of mangrove forest (ha) in Lac Bay reported for different years and shows that total mangrove cover in Lac Bay remained rather stable between 1961 and 1996 (range 238 - 239 ha) after which it has reduced from 239 ha in 1996 to 222.3 ha in 2021/2022.

***Table 3**. Overview of the extent of mangrove forest (ha) in Lac Bay (Bonaire) reported for different years.*

Reference	Mapping year	Technique	Mangrove cover (ha) Lac Bay
Erdmann and Scheffers, 2006	1961	Aerial photo	239
Erdmann and Scheffers, 2006	1996	Aerial photo	238
Mücher & van der Geest, 2024	2014	Satellite (Pleiades)	221
Casal et al., 2024	2021/2022	Satellite (Sentinel-2)	222.3

5 Assessment of National Conservation State

5.1 Trends in the Caribbean Netherlands

Aerial and satellite maps of mangrove distribution in Lac Bay dating back to 1961, show largescale mangrove die-offs in the backwaters of Lac Bay. Simultaneously, the mangroves migrate seaward and the lagoon becomes shallower due to both endogenous production and exogenous input of sediment (Wagenaar-Hummelinck and Roos, 1970; Erdmann and Scheffers, 2006; Debrot et al., 2019, Casal et al., 2024). Infilling is facilitated by mangroves that typically sequester most sediments on their landward margin and thereby are forced to migrate seawards. Over time, this process has resulted in isolated shallow hypersaline waters in the backlands of Lac Bay that used to be inhabited by mangroves, but are no longer suitable for mangrove growth and survival (Wagenaar-Hummelinck and Roos, 1970, Erdmann and Scheffers, 2006; Debrot et al., 2019, Mücher & van der Geest, 2024). Despite this ongoing process of seaward mangrove expansion and landward mangrove loss, the total extent of mangrove forest (ha) in Lac Bay remained rather stable between 1961 and 1996, ranging between 238 - 239 ha (Table 3).

5.2 Recent developments

In the past decades, the mangrove die-offs in the backwaters of Lac Bay outpaced the seaward expansion of mangroves, which has resulted in a 15.7 ha (6.6%) loss of mangrove habitat in Lac Bay between 1996 and 2021/2022 (Table 3). Part of this loss could also be attributed to the massive influxes of pelagic *Sargassum* seaweed that have intermittently invaded Lac Bay since 2018 (van der Geest et al., 2024). These influxes most likely caused mangrove die-offs at the seaward fringe of the forest, due to the anoxic conditions resulting from the large amount of accumulating and degrading *Sargassum* near the shore (see Fig. 1), and may also have suppressed seaward expansion of the mangroves (van Tussenbroek et al., 2017; Mücher & van der Geest, 2024). In Lagun, 46.2% (1.2 ha) of the total area coverage in 2014 (i.e. 2.6 ha) was lost by 2020, which most likely could also be attributed to run-off related siltation of the backwaters of Lagun in combination with the direct impact of recent *Sargassum* influxes (Mücher & van der Geest, 2024).
To improve water circulation in the hypersaline backwaters of Lac Bay, where 15.4 ha of mangrove forest was lost between 2014 and 2020 (Mücher & van der Geest, 2024), a dedicated group of volunteers from Mangrove Maniacs started to restore historic tidal creeks (i.e., channels) and maintain existing tidal creeks, by removing excess sediment and mangrove regrowth. Recent field measurements show that the tidal connection between the lagoon and the backwaters of Lac Bay is still limited, but that the tidal creek restoration on average increased the tidal inflow volumes into the backwaters with about 12% (Gijsman et al., under review). To reduce run-off related infilling of Lac Bay, budget has also been allocated to building water retention structures in the watershed of Lac Bay. In addition, Mangrove Maniacs has built mangrove nurseries, which have been used for small-scale mangrove outplant initiatives in degraded and coastal areas on Bonaire. Survival rates of planted mangrove seedlings varied between species and across sites, but were overall low. Survival rates of red mangrove outplants were 27.5% and 29.6% in Lac Bay and the southwest coast of Bonaire respectively, while they were 8.4% for black mangrove outplants in the backlands of Lagun (Haanskorf, 2024).

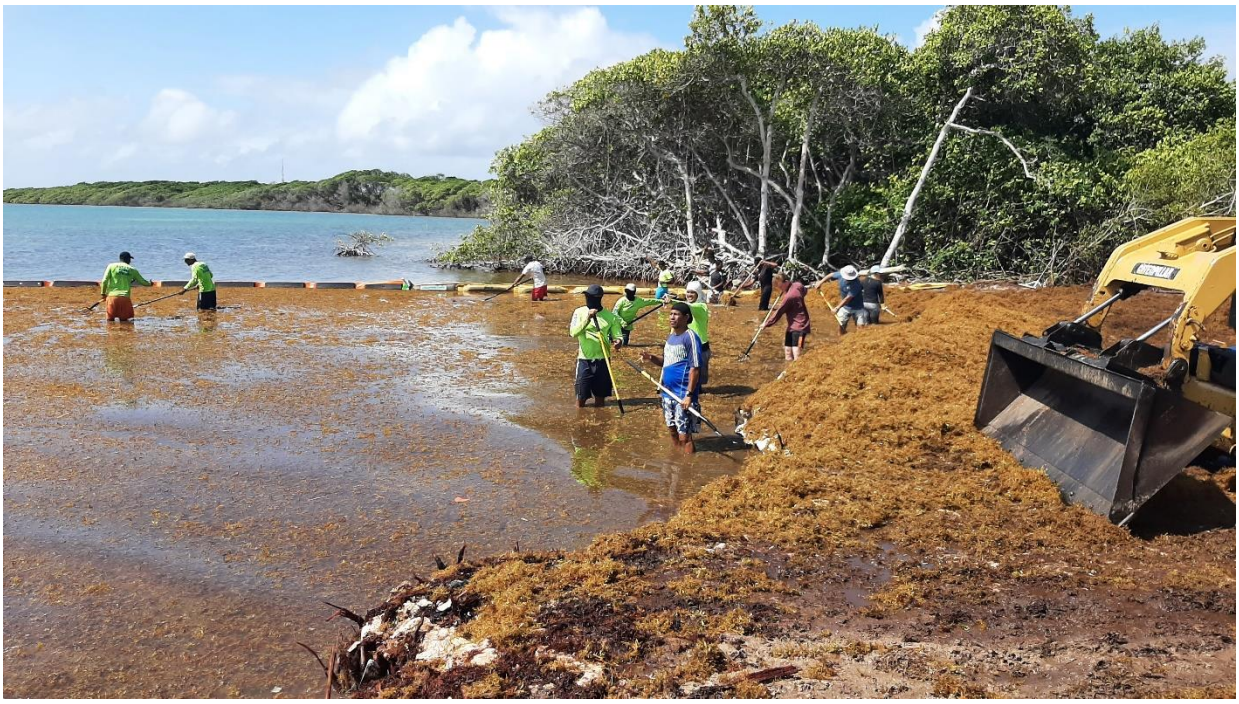

Figure 1. *Sargassum clean-up activities in Lac Bay on 10 March 2022. Note the mangrove-die offs at the seaward fringe of the forest, which most likely are the result of the anoxic conditions caused by the large amounts of decaying Sargassum near the shore. (photo credits: Matthijs van der Geest).*

5.3 Assessment of distribution

The total mangrove area in the Lesser Antilles in 2017 was estimated at 20,636 ha, spread over 263 different locations, which may seem favourable. However, in the Caribbean region as a whole, 7.9% of the mangrove forests have been lost between 1996 and 2020, which equals a loss rate of 0.32% per year (Bunting et al., 2022). Likewise, in Lac Bay, 6.6% (15.7 ha) of the of the total mangrove area coverage in 1996 (i.e. 238 ha) was lost by 2022, which equals a loss rate of 0.25% per year (Table 3). However, of the total mangrove area coverage in Lagun in 2014 (i.e. 2.6 ha), 46.2% (1.2 ha) was lost by 2020, which equals a very unfavourable loss rate of 6.6% per year (Mücher & van der Geest, 2024).

5.4 Assessment of surface area

While the area coverage of mangroves in Lac Bay used to be rather constant at approximately 239 ha between 1961 and 1996, it is currently estimated to be approximately 222.3 ha, which is only 93% of its former coverage (Table 3). Moreover, almost half of the mangrove area that was present in Lagun in 2014, was lost by 2020 (Mücher & van der Geest, 2024). These recent losses in mangrove cover can mainly be attributed to mangrove die-offs in the backwaters of Lac Bay and Lagun, due to ongoing siltation (Mücher & van der Geest, 2024). Although limited, *Sargassum*-induced mangrove die-offs at the seaward fringe of the forests most likely also played a role (Mücher & van der Geest, 2024).

5.5 Assessment of quality

5.5.1 Abiotic conditions

The relatively rapid siltation resulting from erosion and runoff of terrestrial sediment from the degraded and overgrazed hinterland is still the main cause of the loss of abiotic conditions suitable for mangrove growth and survival (Debrot et al., 2019; Mücher & van der Geest, 2024). In addition, the recent decomposition of large quantities of *Sargassum* at the seaward fringe of the mangrove forests also cause abiotic conditions that are detrimental to mangrove growth and survival (Mücher & van der Geest, 2024).

5.5.2 Typical species

Due to the siltation and influx of *Sargassum*, typical species for the mangrove forest are lost, such as the dominant red and black mangroves. The distribution of these species is thus an important indicator for the health of the forest. Using five Sentinel-2 images from 2021 and 2022, Casal et al. (2024) estimated the extent of mangrove forests in Lac Bay to be on average 222.3 ha, of which 136.0 ha were classified as red mangrove and 77.1 ha as black mangrove. The remaining unclassified mangrove area (~9 ha) most likely was dominated by white mangroves, although this needs validation in the field (Casal et al., 2024).

5.5.3 Productivity

Mean Net Primary Production (NPP) values in 2021/2022 were estimated to be 8.82 ± 1.46 (g Cm^{-2} d^{-1}), and showed a zonal distribution with highest values in the mid-West and East on the seaward side, and lowest values in the northern landward part of the mangrove forest of Lac Bay (Casal et al., 2024). Casal et al. (2024) also provided mean values for predicted Effective Leaf Area Index (LAI_e) in Lac Bay, which ranged from 3.37 to 3.85, with significantly higher values in the wet season (3.82 ± 0.57) compared to the dry season (3.40 ± 0.56). This suggest that a decrease in annual precipitation as predicted by Taylor *et al.* (2020), most likely will have a negative impact on mangrove productivity in Lac Bay.

5.5.4 Other characteristics

When investigating changes in carbon storage dynamics in gradually degrading mangrove forest of Lac Bay, Senger et al. (2021) calculated a loss of 1.51 $MgCO_2$ ha^{-1} yr^{-1} for degraded mangrove sites compared to intact mangrove sites. This illustrates that, as the mangrove forest area as a whole becomes silted up, it will lose all characteristic features of a mangrove forest, including its ecosystem services, and ecological values.

5.6 Assessment of future perspective

The most substantial threat to the mangroves forest is siltation due to natural and human-induced erosion of terrestrial sediments, that in turn can cause hypersaline conditions in the backwaters of Lac Bay. The restoration of historic tidal creeks is a promising intervention to increase the tidal connection between the lagoon and the backwater of Lac Bay, and reduce the threat of hypersaline conditions, yet it does not reduce the erosion of terrestrial sediments (Gijsman et al., under review). Additional threats to the quality of the mangroves are not only the recent coastal *Sargassum* influxes (van der Geest et al., 2024; Mücher & van der Geest, 2024), but also recreation (Debrot et al., 2012), pollution, eutrophication and litter (Slijkerman et al., 2011; Debrot et al., 2013). The effects of climate change on the mangrove forests are unclear. A decrease in annual precipitation, as predicted by Taylor *et al.* (2020), will most likely negatively impact mangrove productivity, while an increase in extreme events will most likely increase erosion of terrestrial sediments. Even though the decline of the mangrove forest continues steadily, the fact that restoration is technically possible and likely cost-effective provides perspective.

6 Comparison to the 2018 State of Nature Report

Overall, the current state of the mangrove forest of Bonaire has slightly worsened compared to the 2017 assessment by Debrot et al. (2018), especially due to siltation and recent reoccurring coastal *Sargassum* influxes. The overall assessment of the national conservation state of the mangrove forest of Bonaire in 2024 is considered to be 'unfavourable-inadequate' (Table 4).

Table 4. *Overview of the assessment of the national conservation state of mangrove forests of Bonaire for different ecological aspects.*

Aspect mangrove forest	**2024**
Distribution	Unfavourable-inadequate
Surface area	Unfavourable-inadequate
Habitat quality	Unfavourable-inadequate
Future outlook	Unfavourable-inadequate
Overall conservation assessment:	**Unfavourable-inadequate**

7 Recommendations for the National Conservation Objectives

7.1 Long-term goals

The goal for a favourable State of Conservation is the preservation of the distribution and area, and the improvement of the quality of the mangrove forest in Lac Bay and Lagun.

7.2 Short-term (5 years) goals

Improving the quality mainly involves restoring water depth and circulation in the already filled-in parts of Lac Bay and Lagun, by removing accumulated sediment, by strategic placement of booms to prevent *Sargassum* influxes into the mangrove forest, and by opening up existing and historic tidal creeks. In addition to a) carrying out pilot interventions in this regard and monitoring their effects, other priorities include: b) reducing overgrazing by free-roaming livestock; c) controlling human disturbance; d) reforestation of overgrazed hinterland with native trees, e) building and maintenance of water retention structures in the hinterland, and f) implementing legislation to prevent excessive urban development and industrial activity in the watersheds of Lac Bay and Lagun, to reduce the downstream inflow of toxins, sediments, nutrients, and pathogens through surface and groundwater.

8 Key threats and management implications

Table 5. *Overview of the main threats to the mangrove forests of Bonaire and implications for management.*

Key threat	Consequence	Management intervention
Infilling	Reduced water circulation resulting in hypoxia, hypersalinity, and elevated temperatures during dry season	• Reduce overgrazing and actively manage livestock in hinterland. • Replant hinterland • Build and maintain water retention structures in hinterland • Reclaim eroded topsoil from silted mangrove areas to restore lost water areas. • Cut open and maintain channels
Sargassum influxes	Reduced water quality due to degrading *Sargassum* biomass causing hypoxia and sulfide levels that are toxic to all marine life	• Strategic placement of oil booms to prevent *Sargassum* from invading the mangrove forest. • Timely clearing of *Sargassum* that accumulates behind oil booms during *Sargassum* influx event
Pollution	Soil and water pollution is washed away with surface and bottom water and accumulates in the mangrove areas	• Urban planning to prevent excessive development and industrial activity in upstream drainage areas • Remediation of landfill area upstream of Lagun
Disturbance	Disturbance of resting and foraging birds by uncontrolled recreational activity	• Zoning and improved visitor management • Surveillance and law enforcement

9 Data quality and completeness

There is sufficient knowledge on the distribution, coverage, species composition, ecological condition and stressors of the mangrove forests in the Caribbean Netherlands. This allows for testing and evaluating the effectiveness of mangrove conservation and restoration measures. Continued monitoring of these mangrove parameters at a 3 year interval, will provide sufficient insight into the trend, while it will also allow for the testing and evaluation of future mangrove conservation and restoration interventions.

10 Quality Assurance

Wageningen Marine Research utilises an ISO 9001:2015 certified quality management system. The organisation has been certified since 27 February 2001. The certification was issued by DNV.

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Justification

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The scientific quality of this report has been peer reviewed by a colleague scientist and a member of the Management Team of Wageningen Marine Research

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