Mapping mangrove outplant sites and mangrove outplant performance in relation to local environmental factors on Bonaire, Caribbean Netherlands

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Preface

This report, entitled 'Mapping mangrove outplant sites and mangrove outplant performance in relation to local environmental factors on Bonaire, Caribbean Netherlands' provides detailed insights into the location of mangrove outplanting sites on Bonaire. Moreover, the study evaluates the performance of outplanted mangroves in correlation with the environmental conditions at these sites. Conducted during my internship at Wageningen Marine Research and Wageningen University & Research, this research forms part of my double master program in Aquaculture and Marine Resource Management and Plant Sciences at Wageningen University & Research. This research was carried out on behalf of and financed by the Ministry of Agriculture, Nature and Food Quality in the Netherlands within the framework of the policy supporting research theme of the Caribbean Netherlands with project number BO-43-117-007 and contributes to the understanding of current mangrove restoration activities on Bonaire and how its success relates to environmental context and restoration methods used, with the ultimate aim to improve the success of mangrove restoration efforts on Bonaire.

Acknowledgements

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Abstract

Mangrove forests are essential habitats for species that are of commercial significance and provide various ecosystem services, including coastal protection. Yet, the health and size of mangrove forests are facing a global decline, raising concerns. To protect these ecosystems from further decline, understanding how to restore degraded forests is essential. Knowledge of planting methods and suitable locations can be used to improve the success of restoration activities. Mangrove Maniacs, an NGO, has been active in outplanting mangrove trees in Bonaire since 2020. However, precise documentation on outplanting details like areas, dates, numbers, and species of mangroves that are outplanted is sometimes missing. While the growth and survival of a sub-sample is monitored, there is currently no island-wide standardized long-term monitoring program. Therefore, the aim of this internship was two-fold, first, to identify the locations, species, outplant types, and densities of mangroves on Bonaire; second, to develop a long-term mangrove outplant monitoring program. Fourteen mangrove outplanting sites were identified on Bonaire, with 11 along the southwest coast (SW), 2 in Lac Bay, and 1 in Lagun. A total of 5,141 *Rhizophora mangle* trees and 8 *Laguncularia racemosa* trees were estimated to be outplanted in SW, with a survival rate of 29.6% and 100%, respectively. In Lac Bay, approximately 200 *R. mangle* trees were outplanted, with a survival rate of 27.5%. No data was available on initial outplanting densities at Lagun, but 48 living and 525 dead *Avicennia germinans* trees were counted, suggesting a survival rate of 8.4%. Additionally, a long-term monitoring program was developed to examine mangrove outplant performance and survival over time in a standardized way, while also providing insight into the role of local environmental variables on mangrove outplant performance. For this purpose, 1 to 5 permanent monitoring plots were assigned within each of the identified outplanting sites. In each of these plots, the environmental condition (i.e. water depth, salinity, dissolved oxygen concentration, pH, sediment layer thickness and organic content) were assessed and biotic measurements (i.e. tree species, tree height, stem thickness, number of living outplants, number of living leaves) were carried out. Only data from SW and *R. mangle* was used to analyse the influence of environmental variables on performance. Environmental conditions varied significantly among the SW sites, showing differences in dissolved oxygen, temperature, pH, sediment layer thickness, and organic content. Conductivity negatively correlated with *R. mangle* stem height, whereas water depth showed a positive correlation. Moreover, a positive relationship was observed between the distance to the nearest tree and the number of living leaves. Distance to the nearest tree and dissolved oxygen concentration both showed a positive relationship with the proportion of living *R. mangle* trees, while conductivity and sediment organic matter content showed a negative relationship with the proportion of living *R. mangle* trees. Based on these results, we recommend strategic planting of *R. mangle* along the SW coast at sites with optimal environmental conditions (i.e. low conductivity and sediment organic content, high dissolved oxygen level, minimum water level of ~10 cm). It is also advisable to avoid planting *A. germinans* in dry hypersaline sites in Lagun and to reduce salinity levels in the backwaters of Lac Bay to increase outplant survival. Finally, to allow monitoring of outplant survival and performance, no new mangroves should be planted within the assigned long-term monitoring plots.

Keywords

"Bonaire," "Mangrove restoration," "Environmental conditions," "Long-term monitoring program"

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1. Introduction

Mangroves, often referred to as the 'rainforests of the sea' (Ward & Steinke, 1982), occupy a unique ecological niche within coastal areas of (sub)tropical zones. Mangrove trees thrive in places with diverse environmental conditions like temperature fluctuations, sediment deposition, tidal rhythms, and salinity gradients. These remarkable trees have special adaptations to remove salt, allowing them to tolerate conditions that would kill most other plants. It is this ability to flourish in such challenging environmental conditions that highlights the ecological significance of mangrove ecosystems. The forests offer a multitude of benefits to millions of people, serving as a vital source of food, raw materials, and recreational spaces (Tomlinson, 1986). Mangroves also hold economic importance through tourism, attracting nature enthusiasts, birdwatchers, and eco-tourists. These forests provide fascinating landscapes and opportunities for outdoor activities, which contribute to local economies (Polidoro et al., 2010). Mangrove forests extend their influence on the coastal zones in a variety of crucial services. The forests act as a shield, both from land and ocean influences. They improve water quality, mitigate the impact of storms, reduce erosion, contribute to carbon sequestration, and provide stability on coastlines and islands (de Lacerda, 2002). Besides their benefits to humans, mangrove forests house a rich biodiverse ecosystem, providing habitats for a large number of plant and animal species that are adapted to live in this complex environment (Nagelkerken et al., 2008). This also makes mangrove forests essential habitats for species that are of commercial significance, sustaining offshore fish populations and supporting fisheries. Yet, the health and size of mangrove forests are facing a global decline (Abdul Aziz et al., 2015), signalling a reason for concern. They are decreasing due to coastal development, wood logging, extreme weather events and poor management. To protect these mangrove ecosystems from further decline, it is important to have a good understanding of the factors that determine their functioning and ecological condition and how to restore degraded forests. Such knowledge, which can be gained by the implementation of ecological monitoring programmes, can also be used to improve the success of mangrove restoration activities which are happening globally.

One place where these essential mangrove forests thrive is on the Caribbean Island of Bonaire. Here, they are dominated by the red mangrove (*Rhizophora mangle*) and black mangrove (*Avicennia germinans*), and to a lesser extent by white mangroves (*Laguncularia racemosa*). The mangrove forests on Bonaire are located in three distinct regions (Fig. 1). The most prominent mangrove forest can be found on Bonaire's southeastern coast named 'Lac Bay.' Lac Bay is the largest inland bay in the Dutch Caribbean and serves as a vital lagoon and home to mangrove forests and seagrass beds. The bay is an important feeding ground for many bird species and stands as a significant destination for tourism and recreation. Over the past few decades, the biggest threat facing this bay has been the rapid accumulation of sediment in the backwaters (Debrot et al., 2019; Senger et al., 2021). This sediment influx is not only due to land-based erosion but also stems from the inherent biological productivity of the bay itself. Within these shallow, warm, and highly saline waters located at the rear, large spread die-off is observed as they fail to survive the challenging environmental conditions (Ramsar, 2017). The second largest mangrove forest on Bonaire can be found in 'Lagun' on the east side of the island, which is a bay with direct access to the sea. Wave energy inside is strongly reduced due to the narrow water inlet. At the shoreside of Lagun grows a rim of mangroves, which is bordered by a floodplain that is occasionally inundated during the rainy season (Engel et al., 2010). Like Lac Bay, Lagun is believed to be impacted by infilling due to land-based sediment run-off (pers. obs. Sabine Engel). Unfortunately, the mangroves located towards the rear of the bay have already experienced die-offs, underscoring the fragility of this ecosystem. Since 2016, pelagic *Sargassum* algal blooms have threatened the mangroves of Bonaire, as the algae drift into the lagoons and clog up mangrove channels leading to suffocation and subsequent mortality of mangroves (López-Contreras et al., 2021). Finally, some small patches of mangroves are distributed in the southwest part of Bonaire, in a large area characterized by salt pans. This area is sparsely vegetated and hosts one of the most important nesting colonies of the Caribbean flamingo (*Phoenicopterus ruber*). Moreover, it includes 'Pekelmeer,' a shallow lagoon that provides a habitat for many waterbirds and marine life, and which is classified as a Ramsar site (Ramsar, 2019). Pekelmeer is protected by a buffer zone existing of dykes, sandy beaches and fringing reefs which form a natural protection against waves. However these protective elements are susceptible to extreme weather events (Bries et al., 2004; Meyer et al., 2003) and face heightened vulnerability with increased water depth in shallow zones (Debrot & Bugter, 2010). Research by the VU looked at climate scenarios where climate-induced sea level rise will flood parts of the island, especially in the low-lying southwest part of Bonaire (DCNA, 2023; Vrije Universiteit Amsterdam, 2022). Mangrove forests along the coast could help protect these vulnerable low-lying areas including Pekelmeer from the impacts of sea level rise. Therefore, mangrove seedlings have been outplanted along the seaward coast in the southwest of Bonaire, where there currently is only limited mangrove cover. These outplantings have been organized by the Mangrove Maniacs, a local volunteer foundation led by Sabine Engel together with Jessica Johnson.

Fig. 1. *Location of the three main mangrove-covered areas on Bonaire, namely Lac Bay, Lagun, and the southwest part of Bonaire including Pekelmeer*

The Mangrove Maniacs originated in 2015 when they started opening up former channels in Lac Bay to bring back water circulation throughout the mangrove forest. Outplanting along the southwestern coastline of Bonaire started in 2020. For this purpose, propagules are collected in Lac Bay and put in biodegradable bags filled with sediment from the mangrove forest, which are subsequently placed in crates on the bank of a mangrove channel, so that they are in water. They are let to grow in these nurseries for about six months, and occasionally up to two years, after which they are outplanted on the often-calcareous surface and occasionally mud at the southwestern coastline. At outplant, the nursed propagules, which are now considered seedlings, are placed individually or in a small group and often protected by rocks (pers. com., Mangrove Maniacs). Yet, the exact outplanting areas, outplanting dates, number and species of mangroves that are outplanted have not always been precisely documented. In addition, while the growth and survival of a selection of outplanted mangrove propagules and seedlings is monitored by the Mangrove Maniacs, there is currently no island-wide standardized long-term monitoring program, which would allow for an assessment of the success of these mangrove restoration efforts in relation to local environmental conditions.

The aim of this internship was therefore two-fold. First, we aim to identify the location, mangrove species, outplant type (i.e. propagules or seedlings) and outplant density of past and present outplanting events on Bonaire. Next, we aim to develop and initiate a long-term mangrove outplant monitoring to get a better understanding of the performance and survival of outplanted mangroves in relation to local environmental conditions at each outplanting site. In short, this monitoring survey involved the measurement of various environmental factors (e.g. water depth, salinity, dissolved oxygen, pH, sediment layer thickness, sediment organic matter content) as well as biotic measurements related to outplanted mangrove performance (e.g. tree height, stem thickness, number and percentage of living outplants, number and percentage of living leaves).

Literature states that low nitrogen (N) and phosphor (P) levels in the soil limit mangrove tree growth (Feller, 1995; Feller et al., 2003; McKee et al., 2002). In the research by Lovelock et al. (2004), fertilizing *R. mangle* trees with P increased shoot growth with 10-fold, indicating that stunted growth is partially due to nutrient deficiency. Multiple studies have demonstrated that *R. mangle* growth is reduced under low-nutrient conditions (Agraz-Hernández et al., 2018; Cardona-Olarte et al., 2006; Pascoalini et al., 2022). In addition, high wave dynamics strongly reduce settlement for mangroves (Balke et al., 2013; Toorman et al., 2018). During field observations, it appeared that mangroves outplanted in muddy sediments performed better and had a higher survival rate than when placed on rock. In addition, field observations suggested that seedlings that were outplanted in groups performed better than those outplanted alone, which could be attributed to increased protection against wave activity when planted together. As the southwest coast consists of nutrient-poor calcareous rock with high wave energy, a pilot field experiment was conducted to test whether outplant density and the addition of nutrients positively affect red mangrove outplant performance and survival in this area.

Knowledge from the mangrove outplant mapping part of this study is used to evaluate the scale and success of outplanting efforts. The development and implementation of a long-term monitoring program of mangrove outplants is used to examine mangrove outplant performance and survival over time in a standardized and cost-effective way, while it will also provide insight into the role of local environmental variables on mangrove outplant performance and survival. The data obtained in this study can be used to identify suitable locations for mangrove outplant events. Data from the pilot experiment can be used to optimize the mangrove outplanting method used in the southwest of Bonaire, giving outplants a higher chance of survival and growth.

2. Materials & Methods

2.1 Study site

Bonaire (12°10'46,6"N, 68°15'29,2"W) is a special municipality of the Netherlands, nestled within the Leeward Antilles alongside Aruba, Curaçao, and Venezuela. Located outside the Caribbean hurricane belt, Bonaire is relatively well protected from severe storms. It has a semi-arid climate with fluctuating temperatures of around 30°C. It houses around 24.000 permanent residents (CBS, 2023a), welcoming approximately 173,000 tourists by plane and 304,000 cruise visitors in 2022 (CBS, 2023b). On Bonaire, there are three distinct types of mangroves. The red mangrove (*Rhizophora mangle*) can reach heights up to 20 meters. It thrives close to water and has an impressive root system that can span up to 4 meters in width. These roots, also known as prop roots, emerge from the trunk of the plant and serve to stabilize the plant and facilitate gas exchange when submerged (Duke et al., 1984; Hill, 2001). The *R. mangle* trees' reproductive strategy involves buoyant propagules that can navigate water for an extended period before taking root (Duke et al., 1984). The second species, the black mangrove (*Avicennia germinans*), occupies a different niche. It resides more inland, away from the water's edge, and is smaller than the red mangrove, generally reaching only 2-3 meters in height. *A. germinans* trees also contain specialized root structures, so-called pneumatophores, which are lateral roots that grow upward out from the water surface, so that oxygen can directly be taken up from the air, which is transported to the submerged primary root system. Due to this feature, *A. germinans* trees can thrive in oxygen-poor sediment and water. *A. germinans* trees are also adapted to grow in relatively high salinity, as they can absorb seawater through their roots and expel excess salt through leaf glands, often forming crystals on the leaf surface. Its seeds, resembling small nuts, exhibit less water adaptability than *R. mangle* (Duke et al., 1984). Although less abundant than the red and black mangrove, there is also a third species that occurs on Bonaire, which is the white mangrove (*Laguncularia racemosa*). This species is restricted to more inland areas, away from elevated water levels. It is capable of growing up to 18 meters in height but can also be found as a low shrub. Its leaves bear distinctive white undersides and are often found in the company of Buttonwood (*Conocarpus Erectus*). Thriving in saline-rich, poorly aerated soils, the white mangrove also possesses pneumatophores, although shorter than those of the black mangrove (Santos Borges et al., 2019). Together, these three mangrove species form the mangrove forests of Bonaire (Fig. 2).

Fig. 2. *Mangrove species on Bonaire. From left to right,* R. mangle *(red mangrove),* A. germinans *(black mangrove) and* L. racemosa *(white mangrove). Picture of* A. germinans *by M. van der Geest.*

2.2 Mapping and characterization of previous mangrove outplanting sites and activities

The mapping of the mangrove outplanting sites and activities was carried out on Bonaire from the 13th of March to the 29th of April 2023. In this study, detailed information was gathered about when, where, why, by whom, which species, and which type (seedling/propagule) of mangroves were planted. This data was gathered through a combination of field visits, literature review, available data, and examination of Mangrove Maniacs' Facebook posts about their outplanting events. The accuracy of all collected outplanting data was verified in consultation with Sabine Engel and Jessica Johnson from Mangrove Maniacs and compared to Raijmakers (2022). During field visits, the exact area where mangroves were planted was mapped, by making a track around the area where mangrove trees were planted, using a handheld GPS (GARMIN GPSmap 78s) (Supplementary Table S1). Next, each outplanted mangrove tree within the outplant area was identified to species level and its health status was determined (i.e. alive or dead). Moreover, it was recorded if the outplanted mangrove tree was planted as a seedling or as a propagule. When this was not clear the Mangrove Maniacs were consulted. GPS tracks were uploaded and mapped in QGIS (QGIS Desktop 3.22.11). QGIS software was also used to determine the surface area (m^2) of each outplanting site. Next, site-specific tree density at the time of outplanting was determined by dividing the initial number of trees that were outplanted as documented by the Mangrove Maniacs by the estimated surface area of the specific outplanting site (equation 1), while field data collected in this study were used to determine current site-specific tree density (equation 2). In addition, species-specific outplant survival was determined for each site (equation 3).

$$Initial\ outplant\ density\ (nr.m^{-2})\ = \frac{Number\ of\ outplanted\ trees}{Outplant\ surface\ area\ (m^2)} \tag{1}$$

$$Current\ outplant\ density\ (nr.m^{-2})\ = \frac{Number\ of\ living\ trees}{Outplant\ surface\ area\ (m^2)} \tag{2}$$

$$Species\ specific\ outplant\ survival\ per\ site\ (\%) = \frac{Current\ nr.of\ living\ trees\ per\ species\ per\ site}{Outplanted\ trees\ per\ species\ per\ site} * 100 \tag{3}$$

2.3 Long-term monitoring survey of mangrove outplanting sites

To gain a deeper understanding of the environmental factors influencing the performance and survival of planted mangroves, a mangrove outplant monitoring survey was developed. Depending on the size of an outplanting site, two to five permanent study plots measuring 5 by 5 meters (i.e. 25 m²) were assigned within each outplanting site. Plots were assigned in a stratified random way, so that the plots represented the growing conditions at the specific site, while each plot included at least one outplanted mangrove tree. Plots were made by pushing a rebar into the sediment in the northwest corner. Next, using a measuring tape and a compass, a rebar was placed exactly 5 meters east, and from there 5 m south, and from there 5 m west, so that the rebars formed a 25 m^2 square. When all measurements were finished, all rebars except for the one in the northwest was removed. Within each plot, mangrove seedlings were identified to species level and their condition (alive or dead) was recorded. Next, a measuring tape was used to determine stem height (cm), from the soil to the apical meristem (Fig. 3A). Moreover, stem thickness (mm) was measured at the sprouting site just above the propagule using a calliper (Fig. 3B), and the number of alive and dead leaves was recorded. Distance to the nearest tree (cm) up to a maximum of 150 cm was also measured using a measuring tape.

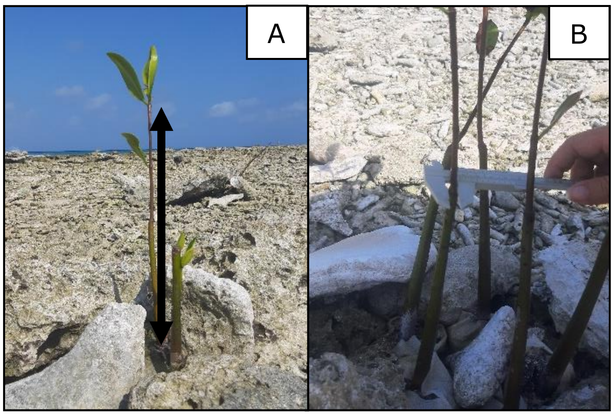

Fig. 3. *(A) mangrove plant height (cm) was measured from the soil to the meristem. (B) mangrove stem thickness (mm) was measured at the sprouting stem above the propagule.*

If water was present on the plot surface, a handheld multimeter (Hanna multi-parameter HI7698194/4) was used to measure specific abiotic parameters: pH, dissolved oxygen concentration (% and mg/L), conductivity (mS/cm), and temperature (°C). Furthermore, water depth (cm) was measured at the plot centre and each corner by positioning a measuring tape at the substrate's surface and measuring the distance from the substrate to the water surface. Sediment layer thickness (cm) was measured using an 80 cm rebar, which was hammered into the soil in the centre of each plot until reaching the limestone layer or until the rebar was inserted up to a maximum of 60 cm. After insertion, the point where the rebar sticked out of the substrate was marked. The rebar was removed from the substrate and the distance from the tip of the rebar to the marked spot was measured using a measurement tape. A sediment sample was taken in the centre of each plot by pushing a 2.6 cm diameter corer into the sediment to a depth of 6 cm. Each sediment sample was stored in a plastic bag together with a unique ID label. Note that the sediment sample was always taken at a minimum distance of 5 cm away from the site where sediment depth was determined (Appendix 1 & 2). To observe water depth differences through time, on the 19th of May water depth measurements were repeated. These measurements within each long-term monitoring plot were carried out between 13 March and 29 April in 2023. To observe water depth differences through time, on the 10th of May water depth measurements were repeated for sites SW_06 to SW_11 and on the 11th of May for LB, LN and SW_01 to SW_05 sites (Table S1).

2.3.1 Sample processing

Upon return from fieldwork, collected sediment samples were immediately (within 6 hours after collection) dried at 60°C in a ventilated oven for 24 hours. After drying, the labelled samples were carefully placed in sealed containers, protected from sunlight. After the fieldwork, the sediment samples were transported to the Wageningen Marine Research (WMR) location in Den Helder, the Netherlands, for further analysis. Here, the sediment samples were dried again at 60°C in a ventilated oven for 24 hours, after which they were homogenized, and a representative subsample of approximately 3 g was placed into a crucible, and the weight of the crucible and subsample was recorded to the nearest 0.001 g. The subsample was then subjected to ashing at 550°C for 4 hours in a furnace. Once the subsample had cooled, its weight was measured again, and the crucible was cleaned of residual ash before obtaining the empty crucible weight. Next, sediment organic matter content (SOM) was calculated (equation 4).

$$SOM(\%) = \left(1 - \frac{Mass_{crucible+ashed\ subsample}}{Mass_{crucible+dried\ subsample}}\right) \times 100 \qquad (4)$$

2.4 Pilot experiment

To assess the impact of nutrient addition and planting density on the growth and survival of outplanted propagules and seedlings from *R. mangle* trees, a pilot field experiment was conducted at the SW coastline of Bonaire located south of the huts at White Slave (Fig. 4A, B) The selected experimental site can be characterized as a rubble beach that contains relatively low nutrient levels and that is exposed to relatively high wave energy (pers. obs.). For the experiment, we used propagules from *R. mangle* trees that were collected at Lac Cai in Lac Bay and seedlings obtained from the Mangrove Maniacs nursery in Lac Bay. The experimental seedlings were grown from propagules collected at Lac Bay, where they were cultivated in nursery bags containing sediment. In the experimental study area, 10 blocks of 3 by 3 m (9 m^2) each, which are at least 10 m apart, were randomly selected (Fig. 4B). The location of each block was recorded using GARMIN GPSmap 78s (Table S8 and Table S9).

At the onset of the experiment on 16 April 2023, a sediment sample was taken in the centre of each block using a small corer (diameter 2.6 cm) that was pushed into the sediment to a depth of 6 cm. The sediment sample was stored in a plastic bag containing a unique ID label, after which it was stored in a coolbox. Subsequently, seawater depth (cm) was determined in the middle of each block using a measurement tape. If a layer of seawater was present within the block, dissolved oxygen content, temperature, pH and conductivity of the seawater was measured using a handheld multimeter (Hanna multi-parameter HI7698194/4).

The experiment comprised three treatments, namely (1) mangrove outplanting type (seedling or propagule), (2) outplanting density (1 or 5 outplants), and (3) nutrient enrichment (yes or no). This resulted in four experimental treatments per outplanting type: control (*c*; 1 outplant without nutrient addition), nutrient addition (*n*; 1 outplant with nutrient addition), high outplant density (*d*; 5 outplants without nutrient addition), and a combination of high outplant density and nutrient addition (d+n, 5 outplants and nutrient addition). Each outplanting treatment was replicated five times per outplanting type, resulting in a total of 5 blocks with each 4 experimental treatments per outplanting type. Per outplant type, treatments per block were randomly assigned, which occasionally led to the same treatment being allocated twice within a block, so not follow a completely randomised block design. Nutrients were added by filling 50 grams of Osmocote® (14N-14P-14K) into biodegradable bags and placing them within 5 cm of the roots of the outplants. Treatments which did not have added nutrients received an empty biodegradable bag. Experimental seedlings were outplanted on 21 April 2023, by digging a small hole, in which the bag from which the seedling was growing was inserted, after which the bag was stabilized by placement of some pieces of coral rock. Experimental propagules were planted on 22 April 2023, by hammering a piece of rebar 5-10 cm into the soil, where in the hole the propagule was pushed. The locations of all experimental sites were recorded using GARMIN GPSmap 78s. At the onset of the experiment (21 and 22 April 2023 for seedlings and propagules, respectively), and after ~ 1 month on 19 May 2023, height (cm), shoot thickness (mm) and the number of live and dead leaves per plant were determined. Based on these two measurements, the growth and survival of each outplanted seedling and propagule were determined for each treatment.

Fig. 4. *(A) Location of the experimental site. (B) Location of each experimental treatment; circle reflects seedling outplants; triangle reflects propagule outplants; white reflects control treatment (c); red reflects high density treatment (d); yellow reflects nutrient addition treatment (n); orange reflects a combination of high density and nutrient addition treatment (d+n).*

2.5 Data analysis

Data was analysed in RStudio version 4.3.1 and maps were made in QGIS version 3.28. Data from the long-term monitoring plots and the field experiment were first tested for normality using the Shapiro-Wilk test. When data was not normally distributed data transformations (e.g., square root, log, reciprocal) were done until normality was achieved. For proportion data, a logit transformation was done following the procedure for proportion data suggested by Warton & Hui (2011).

Biotic and abiotic measurements of long-term monitoring plots

Per monitoring plot per site, the mean values were calculated for all measured biotic variables (i.e. plant height, stem thickness, number of leaves alive). Next, for each of these variables we used the mean per plot, to test to test for the effect of "site" using an ANOVA. If a significant difference was found between sites, a post-hoc Tukey test was applied to see which sites varied from each other. The same procedure was followed to test whether abiotic conditions in each monitoring plot (i.e. dissolved oxygen content, conductivity, pH, temperature, sediment layer depth, SOM), varied between sites. In those plots where water was absent, dissolved oxygen, conductivity, pH and temperature measurements could not be taken. To find statistical relationships between biotic- and abiotic measurements a linear mixed effect model was used with the site as a random effect (biotic variable ~ abiotic variable + (1|Site_ID)). Even after trying various transformations, the data on the mean number of leaves alive per plot were not normally distributed, so no further statistical analysis were executed on these data. Statistical tests were only done for data collected at the mangrove outplanting sites in the SW part of Bonaire. Moreover, in some of the long-term monitoring plots (i.e. SW_01 and SW_05) mangroves were present that were secured by Biodegradable Ecosystem Engineering Elements (BESE) when outplanted as part of an experiment carried out by Lanjouw (2022). As they found that these BESE elements did not significantly influence outplant performance, these outplants were included in the data analysis.

Experimental data
As measurements on the experimental data were done one month after outplanting, no treatment effects were expected and therefore analysis of the data was not conducted. The same measurements were conducted in November of 2023, but that data was not available in time to include in this study.

3. Results

3.1 Outplant area descriptions

Based on field visits, literature review and discussions with members of Mangrove Maniacs, a total of 14 mangrove outplanting sites were identified on Bonaire. Area descriptions were made for each of these mangrove outplanting sites (Appendix 3), which were situated along the southwest coast of Bonaire (11 sites; further referred to as SW), Lac Bay (2 sites), and Lagun (1 site) (Fig. 5).

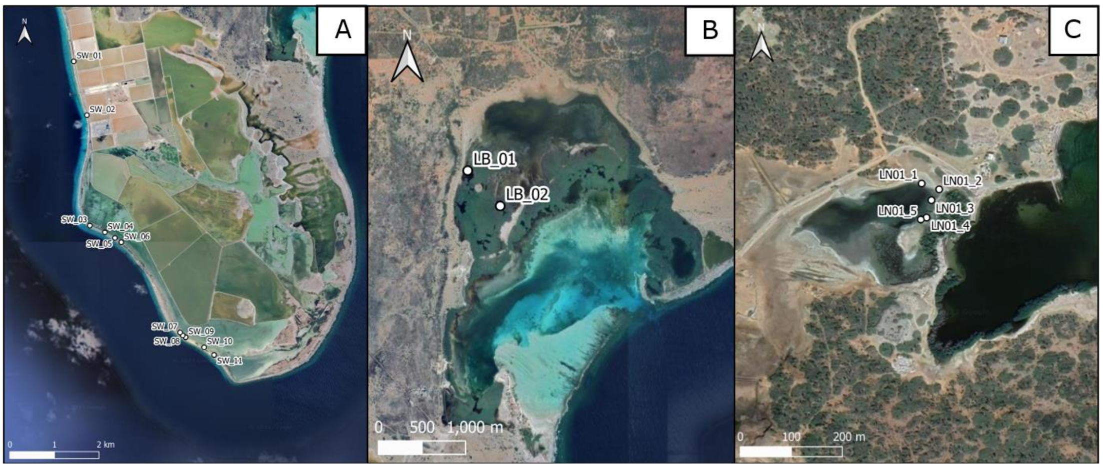

***Fig.* 5**. *Mangrove outplant locations in (A) the southwest coast (B) Lac Bay, (C) Lagun. Dots per location indicate the long-term monitoring plots assigned in this study.*

Between July 2020 and March 2023, an estimated 5141 *R. mangle* trees were planted in the SW region. Of which 1523 survived upon counting in March and April 2023. While 539 were found dead and 3079 outplants were estimated to be missing, resulting in an initial estimated outplant survival rate of 29.6%. In Lac Bay, ~200 *R. mangle* trees were outplanted in LB_01 on 11 April 2022, of which 55 were alive, 57 were dead and the remaining ~88 outplants were missing during counts in April 2023, resulting in an estimated initial outplant survival of 27.5% for LB_01. As no outplanting number could be identified for LB_02, this could not be calculated. No *R. mangle* trees were planted at Lagun. When we look at site-specific survival rates of *R. mangle* outplants in SW and in Lac Bay, they ranged from 0.8% at site SW_02 up to 77.4% at SW_08 (Fig. 6, Table 1). In Lagun, one outplanting event took place in January of 2023, but a number of outplanted trees were not available. During this study 48 living and 525 dead *A. germinans* outplants were counted on 19 April 2023 (Appendix 3), suggesting a maximum survival rate of 8.4% for *A. germinans* outplants, when not considering any outplants that went missing after being planted. *L. racemosa* trees were only found at site SW_11 in SW. In total 8 trees were outplanted that were still alive upon counting on 29 April 2023, resulting in an overall initial outplant survival of 100% (Appendix 3).

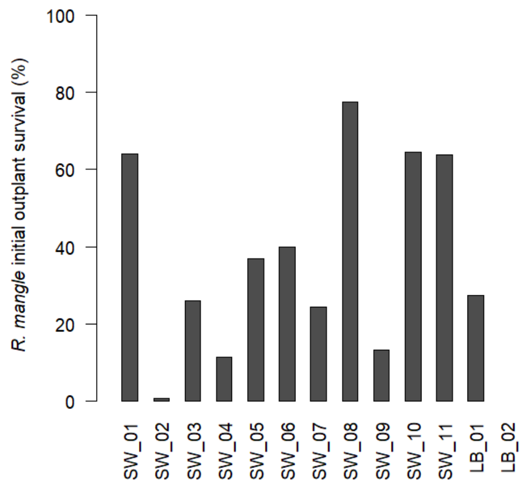

Fig. 6. R. mangle *outplant survival (%) measured from the initial date of outplanting up to March/April 2023 for each identified outplanting site. Note that there were no* R. mangle *trees outplanted in Lagun.*

Table 1. Per species, surface area, number of outplants, date and number of living and dead outplants counted per species in March/April 2023, density of outplants and percentage of outplants alive in March/April 2023, and survival rate (%) of initial outplants up to March/April 2023 for each of the identified outplanting sites.

	Surface area m^{-2}	Nr. out-planted trees	Date counted in 2023	Counted outplants Alive	Dead	Density alive m^{-2}	Outplants alive (%)	Initial outplant survival (%)
R. mangle								
SW_01	42.5	36	20-3	23	24	0.54	48.9	63.9
SW_02	150.5	500	22-3	4	9	0.03	30.8	0.8
SW_03	1265	400	24-3	104	85	0.08	55.0	26.0
SW_04	856	1000	27-3	115	27	0.13	81.0	11.5
SW_05	1554	1360	3-4	501	96	0.32	83.9	36.8
SW_06	137	20	30-3	8	1	0.06	88.9	40.0
SW_07	860	725	14-4	177	17	0.21	60.2	24.4
SW_08	959	385	26-4	298	36	0.31	89.2	77.4
SW_09	587.5	325	13-3	43	4	0.07	91.5	13.2
SW_10	646	200	27-4	129	203	0.20	38.9	64.5
SW_11	698	190	29-4	121	37	0.17	76.6	63.7
LB_01	93	200	13-4	55	57	0.59	49.1	27.5
LB_02	10	*n.d.*	18-4	32	0	3.20	100	*n.d.*
A. germinans								
LN_01	1003	*n.d.*	19-4	48	525	0.05	8.4	*n.d.*
L. racemosa								
SW_11	698	8	29-4	8	0	0.18	100	100

3.2 Abiotic conditions per monitoring plot per outplanting site

Dissolved oxygen concentration ranged between 0.0 and 8.2 mg L^{-1} and was significantly different between the outplanting sites in SW ($p < 0.001$) being significantly higher at SW_04 compared to SW_07, SW_08, SW_10, and SW_11 (Fig. 7A). Conductivity ranged between 40.7 and 81.3 mS/cm, with an exception for monitoring plot SW_10_1, where a value of 195.5 mS/cm was recorded (Fig. 7B). No significant differences in conductivity were found between sites ($p = 0.1$). Levels of pH ranged from 7.8 to 10.6 across all sites and were significantly different between the SW sites ($p < 0.001$) being significantly higher at SW_10 compared to SW_03, SW_04, and SW_09 (Fig. 7C). Seawater temperatures ranged from 26.9°C to 34.5°C across all outplant monitoring plots. Temperature significantly differed between the outplanting sites in SW ($p < 0.001$) with significantly higher seawater temperature at SW_03 compared to all other sites in SW, except SW_02 (Fig. 7D). Sediment layer thickness ranged between 3.5 and 46 cm for the outplanting sites in SW and was 60 cm (or more) at all monitoring plots at outplanting sites at Lac Bay and Lagun. Sediment thickness layer was significantly different between the outplanting sites in SW ($p < 0.001$), being significantly thicker at SW_05 compared to the other sites, apart from SW_04 (Fig. 7E). Sediment organic matter content ranged from 0.7 to 65.3 % and was significantly different between the outplanting sites in SW ($p = 0.002$), being significantly lower at SW_04 compared to SW_11. The highest sediment organic matter content was observed in Lac Bay at monitoring plot LB_02_1 (Fig. 7F; Table S2).

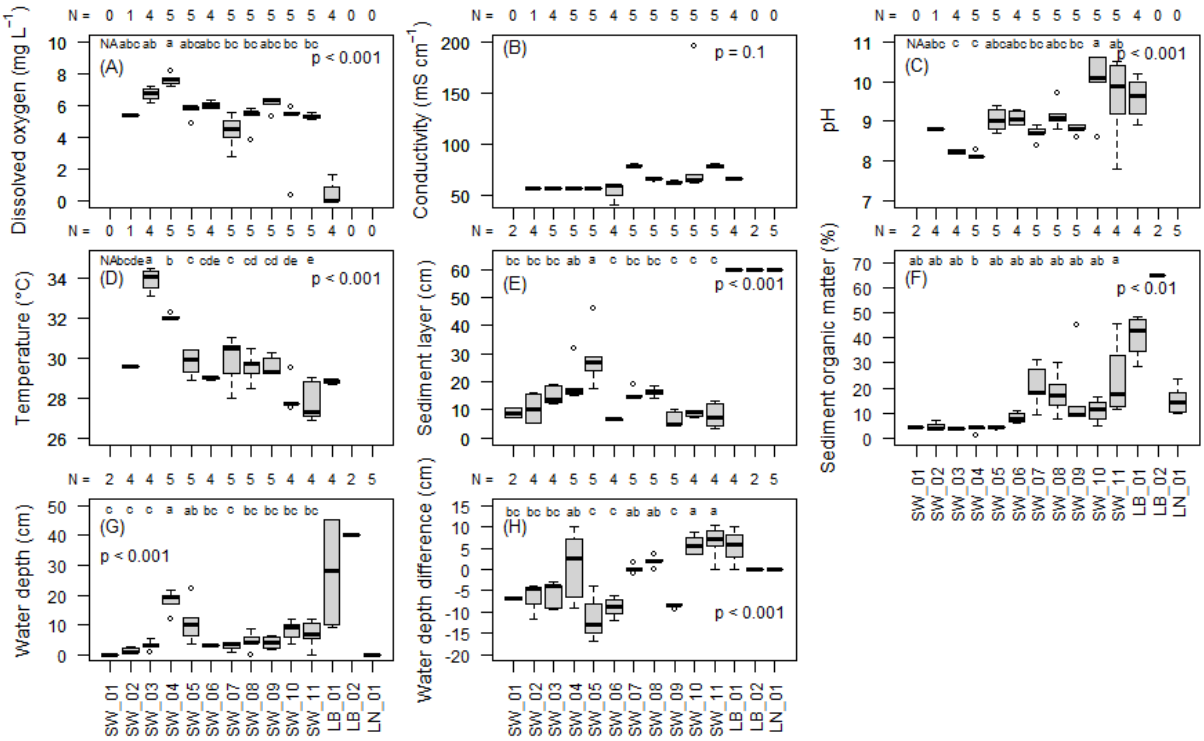

Fig. 7. *Boxplots of (A) dissolved oxygen (mg L^{-1}) (B) conductivity (mS cm^{-1}), (C), pH, (D) seawater temperature (°C), (E) sediment thickness layer (cm), (F) sediment organic matter content (%), (G) water depth (cm), (H) water depth difference (cm) positive values represent increasing water depth negative values represent decreasing water depth per monitoring plot for all mangrove outplanting sites. Midline in box; median; box: 25th and 75th percentiles; whiskers: 1.5 × interquartile range; circles: outliers. Significant differences between sites in SW are indicated by different letters ($p < 0.05$). NA = not available.*

3.3 Outplant performance per monitoring plot per site

For *R. mangle*, the mean stem height per monitoring plot varied between 20.9 and 57.5 cm, with an overall mean of 33.2 cm. Significant differences in *R. mangle* stem height were observed between outplanting sites at SW ($F_{1,10} = 10.9$, $p < 0.001$). Outplants in SW_06 were significantly taller than all other SW sites except for SW_02, SW_04, SW_05, and SW_11 (see Fig. 8A). *R. mangle* stem thickness significantly differed between the outplanting sites in SW ($F_{1,10} = 12.7$, $p < 0.001$; Fig. 8B) where it ranged from 2.7 mm to 14.3 mm, with an overall mean of 5.3 mm. Stem thickness for outplants in SW_06 was significantly thicker compared to the other outplanting sites at SW. For the proportion of trees that were alive significant differences were also observed between sites at SW ($F_{1,10} = 5.4$, $p < 0.001$; Fig. 8C). The proportion of trees alive per monitoring plot varied between 0 and 1, with an overall mean of 0.81. The proportion of trees that were alive at site SW_02 was significantly lower compared to SW_03, SW_04, SW_05, SW_07 and SW_08. The mean of the number of leaves alive per outplant per monitoring plot ranged from 3.17 to 42.7, with an overall mean of 7.3 living leaves per *R. mangle* outplant (Fig. 8D). Significant differences in number of leaves alive were observed between outplanting sites in SW ($F_{1,10} = 3.7$, $p < 0.01$) where *R. mangle* outplants in SW_06 had significantly more leaves compared to SW_01, SW_02, SW_08, and SW_10. Significant differences in distance to the nearest tree were observed between outplanting sites in SW ($F_{1,10} = 4.5$, $p < 0.001$; Fig. 8D) where outplants in SW_06 were spaced further apart compared to all SW sites except for site SW_03 (Table S3 and S4).

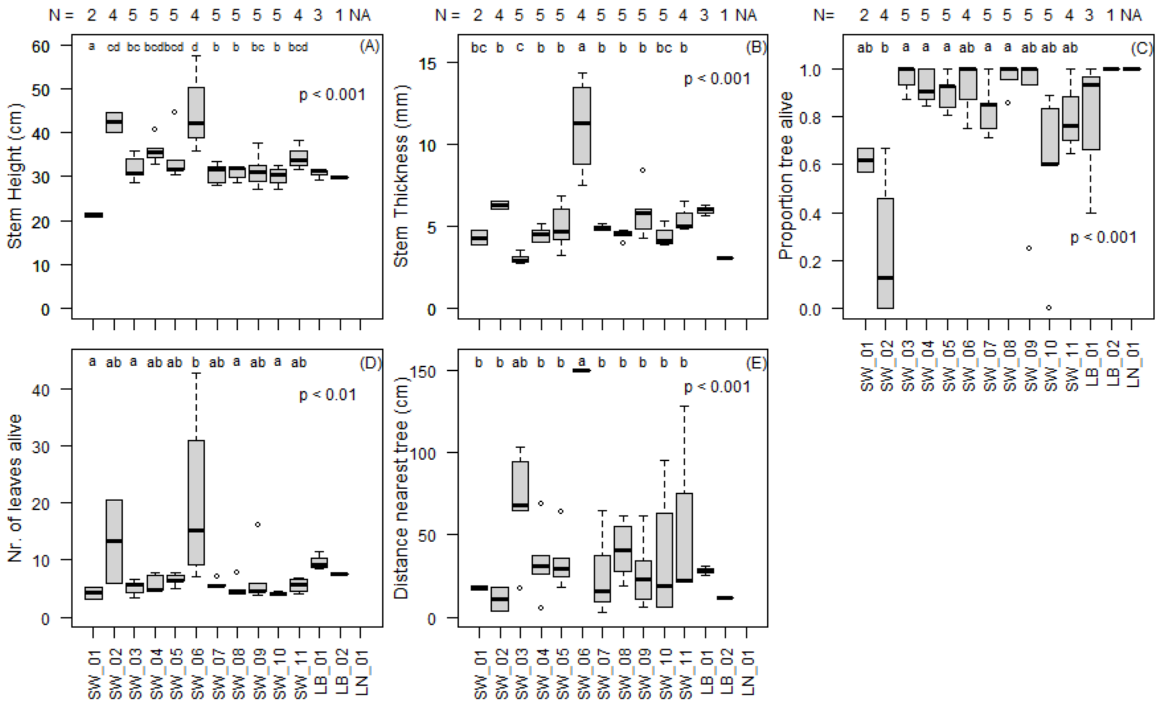

Fig. 8. *Boxplots of biotic measurements of R. mangle trees at monitoring sites with the N displayed at the top. (A) Tree height in relation to site. (B) Tree thickness in relation to site. (C) Mangrove survival in relation to SW sites, N represents the number of plots. (D) Number of living leaves. Mean of all plants within one plot was calculated and then used in statistics and make the boxplots. Midline in box; median; box: 25th and 75th percentiles; whiskers: 1.5 × interquartile range; circles: outliers. Significant differences between sites in SW are indicated by different letters (p < 0.05). NA = not available.*

Outplants of *A. germinans* were only observed in the 5 long-term monitoring plots that we established at the identified outplanting site in Lagun. In these plots, 17 living and 110 dead outplants of *A. germinans* were observed. The mean stem height of the living *A. germinans* outplants varied between 23 and 7 cm with an overall mean of 12.1 cm, while stem thickness varied between 1 and 3 mm with a mean of 1.4 mm. The number of living leaves varied between 0 and 6, with a mean of 2.9 (Table S5). *L. racemosa* outplants were only observed in 2 monitoring plots at site SW_11. Four outplants were observed in both SW_11_1 and SW_11_2. The mean stem height of the living *L. racemosa* outplants varied between 27 and 11.5 cm with an overall mean of 18.3 cm, while stem thickness varied between 1 and 4 mm with a mean of 3 mm. The number of living leaves varied between 4 and 16, with a mean of 12.9 (Table S6). Given the limited number of *A. germinans* and *L. racemosa* outplants in our long-term monitoring plots, results on the measured biotic variables were not graphically presented for these 2 species, and no statistical test were done to see if biotic variables differed between outplanting sites for these 2 species.

3.4 Correlations between environmental conditions and *R. mangle* outplant performance

The relationship between various environmental factors (i.e. dissolved oxygen, conductivity, pH, temperature, sediment organic matter content, sediment layer thickness, water depth, seasonal water depth difference, distance to the nearest outplant) and measures related to *R. mangle* outplant performance (i.e. stem height, stem thickness, number of leaves alive, proportion of outplants alive) was tested based on data collected in the permanent monitoring plots that were assigned to the outplanting sites in SW (Table S6).

Stem height

Both conductivity and water depth significantly influenced *R. mangle* stem height (Table S7). Conductivity showed a negative relationship with mean stem height per monitoring plot ($F_{1,22.3} = 13.6$, $p < 0.001$; Fig. 9A). In contrast, water depth ($F_{1,41.4} = 12.4$, $p < 0.001$; Fig. 9B) showed positive relationships with mean stem height per monitoring plot. Dissolved oxygen content ($p = 0.95$), pH ($p = 0.94$), temperature ($p = 0.86$), sediment organic matter ($p = 0.37$), sediment layer ($p = 0.91$), water depth difference ($p = 0.35$), and distance to the nearest tree ($p = 0.11$) were not significant (Table S7).

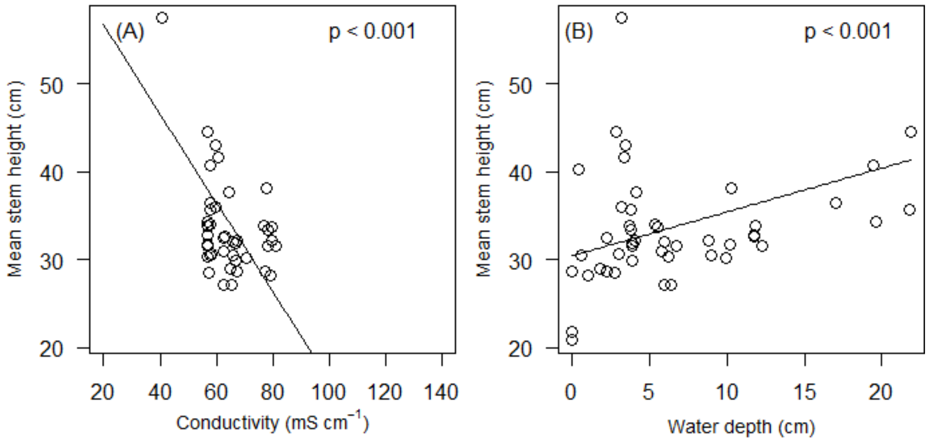

Fig. 9. *Relationship between (A) R. mangle stem height (cm) and conductivity (mS/cm (n = 43), (B) R. mangle stem height (cm) and water depth (cm) (n = 49) and (C) R. mangle stem height (cm) and distance to the nearest tree (n = 49). All relationship is based on mean values per monitoring plot for outplanting sites at SW.*

Stem thickness

Dissolved oxygen content (p = 0.61), conductivity (p = 0.40), pH (p = 0.70), temperature (p = 0.51), sediment organic matter (p = 0.58), sediment layer (p = 0.16), water depth (p = 0.28), water depth difference (p = 0.45), and distance to nearest tree (p = 0.77) did not significantly influence *R. mangle* stem thickness (Table S7).

Number of leaves alive

Distance to the nearest tree significantly ($F_{1,32}$ = 4.38, $p < 0.05$; Fig. 10) influenced the number of leaves alive at an *R. mangle* outplant. However, dissolved oxygen content (p = 0.40), conductivity (p = 0.31), pH (p = 0.83), temperature (p = 0.79), sediment organic matter (p = 0.38), sediment layer (p = 0.95), water depth (p = 0.42) and water depth difference (p = 0.24) did not significantly influence *R. mangle* number of leaves alive (Table S7).

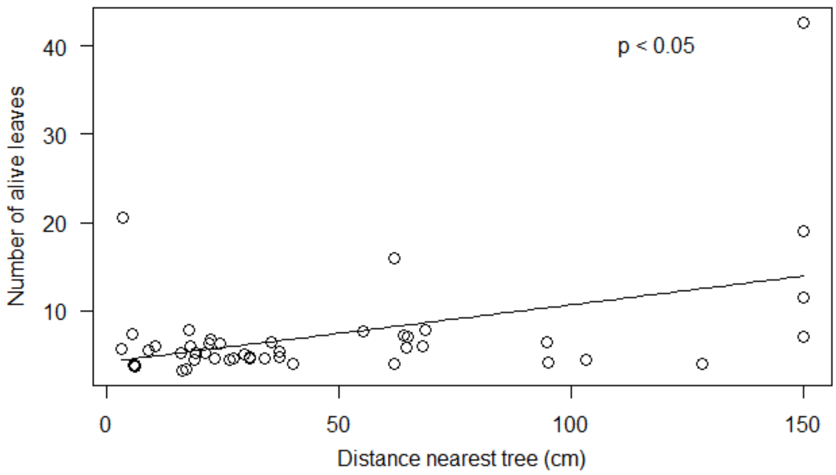

Fig. 10. *Relationship between mean number of leaves alive for R. mangle outplants within a monitoring plot and mean distance to the nearest tree (n = 46). Plotted values reflect mean values per monitoring plot for outplanting sites at the SW.*

Proportion of living trees

Dissolved oxygen concentration showed a positive relationship with the proportion of *R. mangle* outplants that were alive within a monitoring plot ($F_{1,39.5}$ = 20.47, p < 0.001; Fig. 11A), while conductivity showed a negative relationship with the proportion of *R. mangle* outplants that were alive ($F_{1,36.6}$ = 18.71, p < 0.001; Fig. 11B), which was also the case for sediment organic matter content ($F_{1,40.9}$ = 8.85, p < 0.01; Fig. 11C). Moreover, mean distance to the nearest tree had a positive influence on the proportion of *R. mangle* outplants that were alive ($F_{1,34.0}$ = 7.86, p < 0.01; Fig. 12D). Environmental variables pH (p = 0.88), temperature (p = 0.42), sediment layer (p = 0.81), water depth (p = 0.16) and water depth difference (p = 0.49) did not significantly influence the proportion of living *R. mangle* outplants (Table S7).

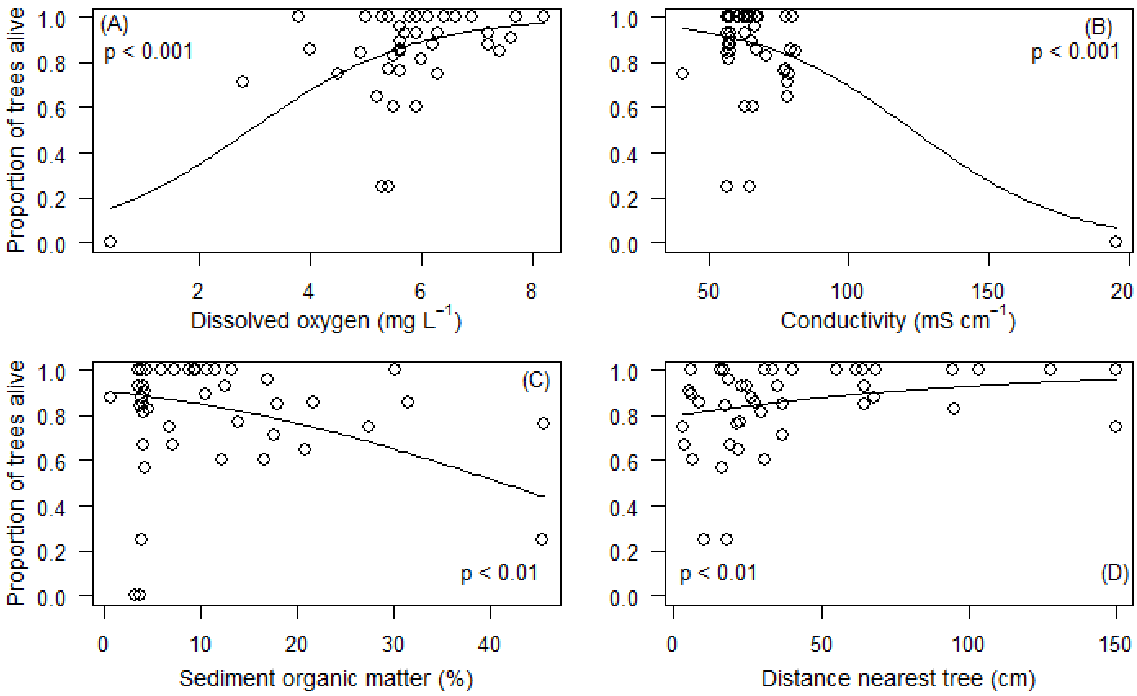

Fig. 11. *Relationships between the proportion of* R. mangle *outplants alive and (A) dissolved oxygen concentration (mg L^{-1}) (n=43), (B) conductivity (mS cm^{-1}) (n = 43), (C) sediment organic matter content (%) (n=47) , and (D) distance to the nearest tree (cm) (n = 46). Plotted values reflect mean values per monitoring plot for outplanting sites at SW.*

3.5 Pilot experiment

In total, 60 *R. mangle* seedlings and 60 *R. mangle* propagules were planted. On outplanting, the mean height of the seedlings was 32.4 cm (±6.48), with a thickness of 2.8 mm (±0.57), and all leaves were alive. The propagules had a mean height of 18.1 cm (±2.17). When the experimental seedling was revisited 28 days after they were planted, one seedling was found to be missing. The remaining seedlings had a mean height of 33.6 cm (±18.4) and a thickness of 2.71 mm (±0.72), while 97.7% (±0.08) of their leaves remained alive. When experimental propagules were revisited 27 days after they were planted, 30 propagules were missing. The remaining propagules had a mean height of 18.4 cm (±2.54).

4. Discussion

4.1 Mangrove outplant survival

Across all 11 SW sites, only 29.6% of the estimated 5141 outplanted *R. mangle* trees since 2020 were still alive in spring 2023 and ranged between 0.8% at SW_02 and 64.5% at SW_10. In the Lac Bay site, LB_01 initial outplant survival was 27.5%. No *R. mangle* trees were outplanted in Lagun, but 48 living and 525 dead *A. germinans* outplants were counted resulting in a maximum survival rate of 8.4%. The overall *R. mangle* outplant survival rate on Bonaire is within the range of those reported for other outplanting sites in the Caribbean. An analysis of 163 outplanting actions in Colombia, where 77.1% used only *R. mangle* mangroves, showed that only 24% were deemed successful, with 53% achieving a medium success level (Rodríguez-Rodríguez et al., 2021). These results underscore the need for further research to enhance the overall success of mangrove outplanting initiatives. No analysis on the success of outplanted *A. germinans* efforts was found, highlighting the importance of these monitoring programmes. In addition to physical and environmental factors, social and economic aspects play a critical role in mangrove restoration. Many projects have failed due to insufficient engagement from local residents in the long-term management of restored areas. Successful restoration sites often demonstrate strong community participation throughout the planning, implementation, and monitoring stages. Fortunately, on Bonaire, the Mangrove Maniacs show high community involvement, with a diverse group of volunteers, including short-term tourists and local residents, participating in outplanting actions and restoration of the channels in Lac Bay. Their proactive approach, including regular information evenings and collaboration with local nature organizations like STINAPA, indicates a positive trajectory for their long-term success regarding social and economic aspects.

4.3 Environmental conditions and outplant performance

SW

Our results showed that environmental conditions (dissolved oxygen, pH, temperature, sediment layer thickness, sediment organic content, water depth, distance between outplants) and *R. mangle* outplant performance (stem height, stem thickness, proportion of outplants alive, number of leaves alive) varied significantly between the 11 sites along SW sites. *R. mangle* outplants at SW_06, were notably larger, thicker, and had more leaves alive than those at other SW-sites. The better performance of *R. mangle* outplants at SW_06 in terms of stem height, stem thickness and the number of leaves alive, may be explained by this site being located on the relatively sheltered shores of Pekelmeer, while all other sites in SW were located on the exposed seaside. In addition, the distance to the nearest outplant, which was observed to have a positive influence on the number of leaves alive and the proportion of outplants alive, was highest at SW_06 compared to the other outplanting sites in SW. As the trees were directly rooted in the shallow water on the edge of Pekelmeer, dissolved oxygen content and conductivity may have been less prone to fluctuations compared to outplants on the ocean side, where water levels at most sites fluctuate between 0-30 cm depending on the tide, rainfall, and evaporation. Research by Lin & Sternberg (1993) showed that *R. mangle* grown under fluctuating salinity levels had lower photosynthesis- and growth rates compared to trees grown under constant salinity levels. Additionally, it is hypothesized that the lower wave activity of the lake compared to the ocean has a positive impact on the performance of the outplants in SW_06. Multiple studies showed that high-wave activity has a negative impact on mangrove performance (Lovelock et al., 2015; Mai Van et al., 2021; van Bijsterveldt et al., 2020). The initial outplant survival in SW_02 was notably lower compared to other sites in SW. The low initial outplant survival is likely attributed to the high wave energy experienced at this site. The intense wave action could have dislodged and washed away many of the outplanted trees, leading to the observed low survival rate. These challenging environmental conditions could also play a role in the overall reduced proportion of trees that were alive in SW_02. This high-wave action was also observed at SW_03. A day after outplanting by the mangrove maniacs in a public event with the goal of raising awareness, SW_03 revealed many newly planted trees washed ashore on the high tide line during a wave reversal event, indicating that the current method of securing trees with rocks is insufficient against wave action. BESE elements as used in Lanjouw (2022) may help with this issue. At one of the long-term monitoring plots in site SW_10 (i.e. SW_10_1) all 15 *R. mangle* outplants that were counted, were observed to be dead, while the proportion of living *R. mangle* outplants in the other 4 monitoring plots at SW_10 ranged between 0.6-0.89 (Table S3). Having a closer look at the environmental conditions, the plot showed extremely high conductivity and low dissolved oxygen levels at SW_10_1 compared to the other long-term monitoring plots at this site (Appendix 3, Table S2). We suggest that a small, elevated ridge that separated monitoring plot SW_10_1 from the other 4 monitoring plots at SW_01 that were located closer to the sea (Appendix 3), may have resulted in less water inflow and thus low water levels, high conductivity and low dissolved oxygen levels within this plot, which may have caused all outplants to die within this plot. At outplanting site SW_11, a section closer to the road experienced a considerable number of deaths in *R. mangle* outplants. It is hypothesized that ammonia levels, possibly from pelagic *Sargassum* influxes in Pekelmeer, contributed to this local die-off. Pelagic *Sargassum* entered Pekelmeer in 2018, accumulating just north of the site. Degraded *Sargassum* may have reached the site through percolation (Bravo, 2022). Bravo (2022) suggested planting *A. germinans* in higher elevated sulfidic pools, considering *R. mangle's* preference for less sulphide-rich areas.

Lac Bay

Small-scale outplanting efforts in Lac Bay primarily served as a test to assess the success of newly outplanted *R. mangle* trees in locations appointed by A.D. Debrot (pers. comm., Mangrove Maniacs). Over time, increased sediment build-up clogged lagoons and creeks in Lac Bay, reducing the hydrological connectivity between the front and back of the forest, and creating hypersaline conditions. This change in conditions resulted in *A. germinans* replacing *R. mangle* in Lac Bay backlands (Debrot et al., 2010). With the Mangrove Maniacs opening up old channels to increase water circulation in the forest and subsequently reduce salinity levels, there is a likelihood that *R. mangle* can settle again in this area. Signs of increased water circulation are found in the backlands, as reflected in the fluctuating water level of LB_01 corresponding to the tides (Fig. 7, Fig. 12). The water depth in LB_01 appeared to fluctuate, but the site comprised one shallow plateau of approximately 10 cm water depth directly adjacent to a deeper channel of about

45 cm depth (Fig. 7). In addition, the temperature in LB_01 was below the average compared to SW, suggesting a higher degree of shading which was also personally observed. Gillis et al. (2019) showed that elevated temperatures reduce root complexity and consequently growth.

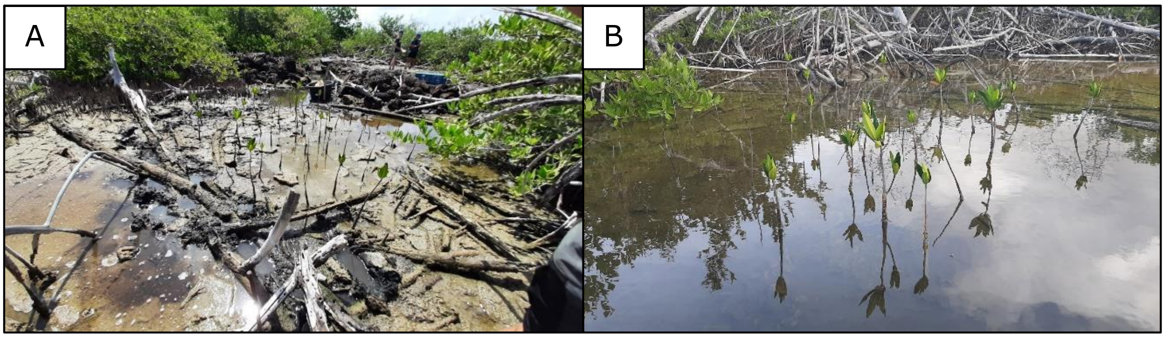

Fig. 12. *Fluctuating water level at LB_01 with R.* mangle *outplants. (A) Picture taken around noon on the 6th of April 2023. (B) picture taken on the 13th of April 2023 in the early morning.*

Lagun

Abiotic factors related to water could not be carried out in Lagun due to no water being present in the outplanted area. In March 2023, at the end of the rainy season, a small pond was observed west of the outplanted area which after a few weeks completely dried up, leaving a dry and barren plain. Ellerbroek (2023) carried out a more elaborate assessment of the area and observed the same phenomenon. A factor explaining the low survival of *A. germinans* outplants here could be the dry conditions. Although *A. germinans* is more tolerant to dry conditions than *R. mangle*, they show a limited tolerance for soil moisture limitations (Alleman & Hester, 2011). Observations by Elster (2000) found that mortality of *A. germinans* propagules reached 100% in two months for very dry soils. When water levels lay close to the soil surface, many propagules were able to establish, but they desiccated shortly after these soils dried out. In addition, due to the lack of moisture and the open character of the area, air temperatures were considerably higher than SW and Lac Bay (pers. obs.). *A. germinans* shows reduced root growth and lower assimilation rates under high temperatures (Cobacho et al., 2024; Krauss et al., 2008) suggesting that temperature could play a role in the reduced growth of the mangroves in Lagun.

4.4 Correlations between environmental conditions and *R. mangle* outplant performance

This study revealed a negative relationship between conductivity and some of our proxies for *R. mangle* outplant performance (i.e. proportion of outplants alive, stem height), which is also supported by other studies (Devaney et al., 2021; Hao et al., 2009). Biber (2006) demonstrated that elevated salinity levels lead to decreased stomatal conductance and photosynthesis in *R. mangle*. It is also mentioned that the salt tolerance in trees can change over their lifespan, indicating that seedlings may be more vulnerable to salinity stress compared to mature trees. Previous studies showed that A. *germinans* had significantly higher photosynthetic rates, and lower transpiration rates, compared to *R. mangle* (Devaney et al., 2021; Sobrado, 2000). They found that the growth of *R. mangle* seedlings was severely reduced in salinities of 60 ppt, while *A. germinans* was able to grow in salinity conditions of 90 ppt. Additionally, fluctuating salinity levels had negative effects on photosynthesis and plant growth compared to constant salinities with the same mean (Biber, 2006), underscoring the importance of maintaining water exchange with the ocean to minimize fluctuations. In contrast, we found a positive correlation between water depth and *R. mangle* tree height. Ellison & Farnsworth (1997) found that increasing water depth leads to an increase in growth for young *R. mangle* saplings. In addition, monitored outplants in Mexico showed a positive association between the growth rate of *R. mangle* saplings and the water level in the lagoon (Taylor et al., 2013). This suggests a preference for wetter areas for *R. mangle*, while drier parts are more suitable for *A. germinans*. Thirdly, a positive relationship between distance to the nearest R. mangle outplant and the proportion of outplants that were alive was found. This contrasts with the research by Kumara et al. (2010), where survival decreased with decreasing densities for *Rhizophora mucronate* a closely related species to *R. mangle*. Also, a positive relationship between distance to the nearest *R. mangle* outplant and *R. mangle* number of leaves alive was identified, suggesting that leaf number in *R. mangle* outplants decreased with increasing density of *R. mangle*. Although no supporting evidence was found in the literature, it is hypothesized that the increased density of *R. mangle* may result in increased competition for nutrients and light, followed by reduced growth. If true, this would suggest that at the SW-sites, *R. mangle* seedlings should be outplanted as far apart as possible from each other to reduce potential competition for resources. However, it is also hypothesized that in areas with high wave activity such as at the SW coastline, increased density might positively impact *R. mangle* outplant performance, as density may increase protection against wave exposure. We also found that the proportion of *R. mangle* outplants that were alive was positively correlated with dissolved oxygen levels. While this has not been specifically proven for *R. mangle*, research by McKee & Mendelssohn (1987) suggested that reduced oxygen for *A. germinans* minimized aerobic root respiration, reducing the net metabolic energy available for growth. Similar mechanisms could potentially apply to *R. mangle* as well. Moreover, the proportion of *R. mangle* outplants that were alive was negatively affected by sediment organic matter content. This may be attributed to the fact that in soils with high organic matter content a high rate of denitrification takes place. This process reduces nitrate and nitrite and produces ammonia (Alongi, 1994; Corredor & Morell, 1994). In addition, high organic matter content facilitates the conversion of sulphate to sulphides, which is toxic to plants and a potent phytotoxin, which strongly affects plant fitness and thus may reduce survival (Lamers et al., 2013). Oxygenation around the roots can reverse this process, reducing the toxicity of the soil as well. But this process releases H^+ protons, which results in a more acidic soil (Nickerson & Thibodeau, 1985; Reef et al., 2010).

4.5 Pilot field experiment

To investigate the potential nutrient deficiency in mangrove trees in SW, a pilot has successfully been planted. In November 2023 measurements on stem height, thickness, number of leaves and status were recorded, but analysis of these data laid beyond the scope of this report.

4.6 Recommendations

Planting mangroves in coastal areas requires careful consideration of several factors such as location, species, and planting methods to reach a high survival rate. Therefore, careful monitoring of the mentioned parameters is essential to evaluate the performance and survival of these efforts. Planting new trees in areas with previously outplanted trees introduces a layer of complexity that makes it challenging to accurately monitor the success of the outplanting efforts. This complexity makes contributing variation in growth to abiotic factors without being able to correct for the age of the tree complicated. To gain the most accurate data, it is discouraged to plant new mangrove trees between previously outplanted trees, especially within the permanent mangrove outplant monitoring plots. Conductivity and dissolved oxygen could not be measured in plots without water, it is advised to take pore fluid samples to gain a better understanding of local conditions as done by Devaney et al. (2021). In addition, as the recorded number of outplanted trees is an approximation, the calculated survival rate is also a rough estimate. During future outplant events, it is recommended to carefully note down how many trees are planted at which date to be able to monitor survival over time. Furthermore, *Dasycladus vermicularis* algae was found growing on outplant trunks in SW_07, SW_08, SW_10 and SW_11 (Fig. 13). Known for its ability to oxygenate the sediment, this alga has the potential to enhance tree growth by improving root oxygenation (Chapman, 2013; Ross et al., 2005). Therefore, it would be interesting to also monitor the absence or presence of *Dasycladus vermicularis* growing on the stems of outplant mangroves in the long-term monitoring plots, so that its potential positive effect on outplant performance can be investigated. If a positive correlation is eventually observed, experiments can be undertaken to transplant *Dasycladus vermicularis* to other outplanted mangrove trees. This could potentially serve as a strategy to enhance growth in areas where oxygen-poor conditions occur. The experimental pilot shows whether increased planting density has a positive influence on *R. mangle* growth and survival, results from the monitoring programme show that this influence could be negative. Therefore, it is advised to keep planting density low. The recommended monitoring frequency is two years.

Fig. 13. *Long-term monitoring plot in SW_07 with* Dasycladus vermicularis *algae growing on the stems of many of the outplants.*

Area-specific recommendations

SW

Planting mangroves in coastal areas requires careful consideration of several factors such as location, species, and planting methods to reach a high survival rate. Therefore, it is advised to keep planting *R. mangle* along the SW coast of Bonaire close to the water's edge and provide support in the first few months against wave action, especially at SW_02 and SW_03. To get an indication on site-specific wave action methods by Lanjouw (2022) can be used. When considering a potential new site, it is recommended to assess water parameters. Ideal conditions found in this study include dissolved oxygen levels exceeding 5 mg/L, conductivity below 90 mS/cm, sediment organic levels below 10%, and a water depth of more than 10 cm, as these factors indicate optimal growing conditions in SW. Additionally, it is advisable to maintain a minimum distance of 50 cm between trees.

Lac Bay

The biggest threat to the mangroves in Lac Bay arises from the infilling of channels with sediment, leading to subsequent hypersaline conditions. Opening up these channels serves to alleviate these stressors. The successful outcomes observed in the two trial sites underscore that enhanced water flow makes the area suitable for *R. mangle* once more. Consequently, it is strongly advised to implement measures aimed at reducing sediment infilling, to prevent the creeks from closing again.

Lagun

In Lagun the conditions in most plots are too dry, hot and saline for *A. germinans* outplants and it is not advised to keep outplanting there without appropriate actions taken to mitigate these conditions. Survival of *A. germinans* outplants at the backlands of Lagun, could be increased by increasing the water level. Higher water levels can be achieved by excavating the area to lower its elevation, allowing ocean water to freely flow into the backlands. However, before undertaking such measures, it is crucial to construct barriers to prevent the entry of pelagic *Sargassum* and plastics originating from the ocean, which are currently polluting the area (Fig. 14). Additionally, sedimentation from the catchment area must be minimized to prevent further infilling. It is also recommended to protect the area from vehicles, such as quads, who utilize the barren terrain for off-road driving, to protect any newly planted mangroves from being run over by these vehicles.

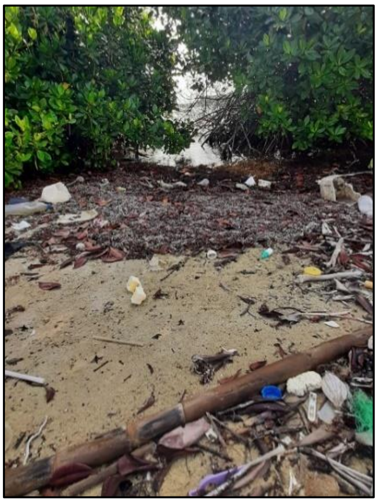

Fig. 14. *Plastic pollution and decomposing Sargassum washed up on the shore of Lagun.*

4.7 Conclusion

This report underscores the challenges and successes of mangrove outplantings on Bonaire. Survival rates of outplanted mangroves were overall low, but varied between species and across sites, with environmental conditions playing a pivotal role. In SW success varied but big steps have been made. Lac Bay's successful restoration efforts highlight the importance of water circulation. Lagun's dry conditions showed challenges, indicating the need for water level adjustments. Recommendations stress the necessity for site selection, careful record-keeping, and tailored interventions. The report offers valuable insights for optimizing mangrove outplanting, recognizing the interplay of environmental factors, planting strategies, and community engagement.

5. References

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Supplementary tables

Supplementary Table S1. *Coordinates of appointed long-term monitoring plots in each identified outplanting site with names and ID codes, and date monitoring abiotic and biotic conditions. Second water depth measurements for SW_11 to SW_06 took place on the 10th of May and for LB, LN and SW_01 to SW_05 took place on the 11th of May.*

Area	Local name	Site ID	Plot	Plot ID	Latitude	Longitude	Date
Lac Bay	Kaminda sorobon	LB_01	1	LB_01_1	12.1159	-68.2408	13-04
	Kaminda sorobon	LB_01	2	LB_01_2	12.1159	-68.2407	
	Kaminda sorobon	LB_01	3	LB_01_3	12.1158	-68.2407	
	Kaminda sorobon	LB_01	4	LB_01_4	12.1159	-68.2407	
	-	LB_02	1	LB_02_1	12.1123	-68.2373	18-04
Lagun	Lagun	LN_01	1	LN_01_1	12.1818	-68.2186	19-04
	Lagun	LN_01	2	LN_01_2	12.1817	-68.2183	
	Lagun	LN_01	3	LN_01_3	12.1815	-68.2185	
	Lagun	LN_01	4	LN_01_4	12.1812	-68.2185	
	Lagun	LN_01	5	LN_01_5	12.1812	-68.2186	
Southwest (SW)	Safe Haven	SW_01	1	SW_01_1	12.0896	-68.2831	20-03
	Safe Haven	SW_01	2	SW_01_2	12.0896	-68.2831	
	Salt Pier	SW_02	1	SW_02_1	12.0786	-68.2805	22-03
	Salt Pier	SW_02	2	SW_02_2	12.0787	-68.2805	
	Salt Pier	SW_02	3	SW_02_3	12.0788	-68.2805	
	Salt Pier	SW_02	4	SW_02_4	12.0788	-68.2805	
	White Slave N	SW_03	1	SW_03_1	12.0566	-68.2802	24-03
	White Slave N	SW_03	2	SW_03_2	12.0564	-68.2799	
	White Slave N	SW_03	3	SW_03_3	12.0563	-68.2797	
	White Slave N	SW_03	4	SW_03_4	12.0561	-68.2795	
	White Slave N	SW_03	5	SW_03_5	12.0560	-68.2792	
	White Slave	SW_04	1	SW_04_1	12.0553	-68.2772	27-03
	White Slave	SW_04	2	SW_04_2	12.0552	-68.2771	
	White Slave	SW_04	3	SW_04_3	12.0551	-68.2770	
	White Slave	SW_04	4	SW_04_4	12.0550	-68.2769	
	White Slave	SW_04	5	SW_04_5	12.0549	-68.2767	
	Margate Bay	SW_05	1	SW_05_1	12.0542	-68.2753	03-04
	Margate Bay	SW_05	2	SW_05_2	12.0540	-68.2750	
	Margate Bay	SW_05	3	SW_05_3	12.0538	-68.2748	
	Margate Bay	SW_05	4	SW_05_4	12.0535	-68.2744	
	Margate Bay	SW_05	5	SW_05_5	12.0535	-68.2741	
	Margate Bay Pekelmeer	SW_06	1	SW_06_1	12.0532	-68.2731	30-03
	Margate Bay Pekelmeer	SW_06	2	SW_06_2	12.0533	-68.2732	
	Margate Bay Pekelmeer	SW_06	3	SW_06_3	12.0535	-68.2735	
	Margate Bay Pekelmeer	SW_06	4	SW_06_4	12.0538	-68.2737	
	Sweet Dreams N	SW_07	1	SW_07_1	12.0349	-68.2614	14-04
	Sweet Dreams N	SW_07	2	SW_07_2	12.0348	-68.2614	
	Sweet Dreams N	SW_07	3	SW_07_3	12.0347	-68.2613	
	Sweet Dreams N	SW_07	4	SW_07_4	12.0347	-68.2612	
	Sweet Dreams N	SW_07	5	SW_07_5	12.0346	-68.2612	
	Sweet Dreams	SW_08	1	SW_08_1	12.0342	-68.2610	26-04
	Sweet Dreams	SW_08	2	SW_08_2	12.0342	-68.2608	
	Sweet Dreams	SW_08	3	SW_08_3	12.0341	-68.2609	

	Sweet Dreams	SW_08	4	SW_08_4	12.0340	-68.2608	
Southwest (SW)	Sweet Dreams	SW_08	5	SW_08_5	12.0339	-68.2606	
	Sweet Dreams S	SW_09	1	SW_09_1	12.0338	-68.2601	13-03
	Sweet Dreams S	SW_09	2	SW_09_2	12.0338	-68.2602	
	Sweet Dreams S	SW_09	3	SW_09_3	12.0337	-68.2602	
	Sweet Dreams S	SW_09	4	SW_09_4	12.0336	-68.2602	
	Sweet Dreams S	SW_09	5	SW_09_5	12.0336	-68.2601	
	Flamingo Pond	SW_10	1	SW_10_1	12.0319	-68.2564	27-04
	Flamingo Pond	SW_10	2	SW_10_2	12.0317	-68.2562	
	Flamingo Pond	SW_10	3	SW_10_3	12.0316	-68.2562	
	Flamingo Pond	SW_10	4	SW_10_4	12.0316	-68.2562	
	Flamingo Pond	SW_10	5	SW_10_5	12.0317	-68.2561	
	Red Slave	SW_11	1	SW_11_1	12.0303	-68.2542	29-04
	Red Slave	SW_11	2	SW_11_2	12.0302	-68.2541	
	Red Slave	SW_11	3	SW_11_3	12.0300	-68.2541	
	Red Slave	SW_11	4	SW_11_4	12.0301	-68.2544	
	Red Slave	SW_11	5	SW_11_5	12.0302	-68.2544	

Supplementary Table S2. *Raw data for environmental conditions measured per appointed long-term monitoring plot in each identified outplanting site.*

	Dissolved oxygen conc.	Conductivity	pH	Temperature	Sediment layer	Water depth	SOM
	mg/L	mS/cm		°C	cm	cm	%
SW_01_1	*n.d.*	*n.d.*	*n.d.*	*n.d.*	7	0	4.1
SW_01_2	*n.d.*	*n.d.*	*n.d.*	*n.d.*	10.5	0	4.2
SW_02_1	5.4	56.7	8.8	29.6	5	2.8	3.9
SW_02_2	*n.d.*	*n.d.*	*n.d.*	*n.d.*	16	0.8	3.3
SW_02_3	*n.d.*	*n.d.*	*n.d.*	*n.d.*	5.5	1.2	3.8
SW_02_4	*n.d.*	*n.d.*	*n.d.*	*n.d.*	15	0.4	7.1
SW_03_1	*n.d.*	*n.d.*	*n.d.*	*n.d.*	12	3.8	3.6
SW_03_2	*6.2*	57.1	8.2	33.1	12.5	2.7	3.9
SW_03_3	7.2	58	8.2	33.9	19	3	3.6
SW_03_4	6.9	57.7	8.3	34.2	18.5	5.3	*n.d.*
SW_03_5	6.6	57.6	8.3	34.5	13.5	0.6	3.9
SW_04_1	8.2	56.9	8.3	32.3	15.5	11.7	4.4
SW_04_2	7.2	57.9	8.1	32	16.5	21.8	0.7
SW_04_3	7.4	57.9	8.1	31.9	32	19.4	4.0
SW_04_4	7.6	57.9	8.1	32	17.5	17	4.2
SW_04_5	7.7	57	8.1	32.1	15	19.6	3.8
SW_05_1	5.9	56.8	9.3	29.3	29	21.9	4.1
SW_05_2	4.9	56.6	8.7	30.4	27	3.7	3.8
SW_05_3	5.7	56.7	9.3	29.9	24	10.2	4.1
SW_05_4	6.0	56.9	8.8	30.4	46	6.2	4.0
SW_05_5	5.9	56.7	9	28.9	17.5	12.3	4.0
SW_06_1	6.1	60.5	8.9	29	7	3.3	10.7
SW_06_2	6.3	40.7	8.9	29	6	3.2	6.8
SW_06_3	5.9	59.8	9.2	28.9	6.5	3.4	5.9
SW_06_4	5.8	59.8	9.2	29	6.5	3.2	8.9
SW_07_1	4.5	79	8.7	28	15	1	27.5
SW_07_2	5.0	77.4	8.8	30.5	14.5	2.2	9.3
SW_07_3	4.0	79.5	8.7	30.6	14.5	4	31.6
SW_07_4	2.8	78.1	8.4	29.2	14	3.8	17.7
SW_07_5	5.6	80.8	8.8	31	19	3.9	18.0
SW_08_1	5.8	67.4	9.1	29.8	16	0	30.2
SW_08_2	5.4	67.3	9.2	29.7	17	8.8	7.3
SW_08_3	3.8	65.6	8.8	28.5	15.5	5.9	13.3
SW_08_4	5.6	66.9	9	29.2	14	3.9	21.7
SW_08_5	5.6	66.7	9.7	30.5	18.5	3.9	16.9
SW_09_1	5.3	64.8	8.6	30.3	10	1.8	45.4
SW_09_2	6.1	64.2	8.8	30	9	4.1	8.9
SW_09_3	6.4	62.7	8.8	29.2	4.5	2.2	9.5
SW_09_4	7.3	62.7	8.8	29.2	4.5	5.8	12.6
SW_09_5	6.4	62.3	8.9	29.3	4.5	6.4	8.7
SW_10_1	0.4	195.5	8.6	29.5	9	3.4	*n.d.*
SW_10_2	5.5	70.5	10.6	27.5	9.5	9.9	4.6
SW_10_3	5.6	65.3	10.1	27.7	9.5	5.9	10.4
SW_10_4	5.5	63.2	10	27.7	7	11.7	16.7
SW_10_5	5.9	65.7	10.6	27.7	7.5	9	12.2

SW_11_1	5.3	79.7	7.8	27.3	12	5.5	11.5
SW_11_2	5.1	81.3	9.2	28.8	7	0	*n.d.*
SW_11_3	5.2	78.1	9.9	26.9	13	6.7	20.8
SW_11_4	5.4	77.6	10.5	27.1	3.5	10.3	13.9
SW_11_5	5.6	76.9	10.4	29	4	11.8	45.6
LB_01_1	1.7	66.4	9.4	28.7	60	11.2	46.2
LB_01_2	0.1	66.5	9.8	28.9	60	45.4	48.5
LB_01_3	0.0	66	8.9	28.9	60	9.1	28.5
LB_01_4	0.0	66	10.2	28.8	60	45.4	40.3
LB_02_1	*n.d.*	*n.d.*	*n.d.*	*n.d.*	60	40	65.3
LB_02_2	*n.d.*	*n.d.*	*n.d.*	*n.d.*	60	40	68.2
LN_01_1	*n.d.*	*n.d.*	*n.d.*	*n.d.*	60	0	9.9
LN_01_2	*n.d.*	*n.d.*	*n.d.*	*n.d.*	60	0	10.2
LN_01_3	*n.d.*	*n.d.*	*n.d.*	*n.d.*	60	0	23.5
LN_01_4	*n.d.*	*n.d.*	*n.d.*	*n.d.*	60	0	18.1
LN_01_5	*n.d.*	*n.d.*	*n.d.*	*n.d.*	60	0	14.0

Supplementary Table S3. *Mean values ± SD values for biotic measurements on* R. mangle *outplants per appointed long-term monitoring plot in each identified outplanting site.*

Site	Total trees	Alive trees	Height (mean±SD;N) cm	Thickness (mean±SD;N) mm	Leaves count (mean±SD;N) Alive	Dead
SW_01_1	21	14	20.9 ± 5.4 ; N= 14	4.7 ± 1.4 ; N= 14	5.2 ± 1.8 ; N= 14	0.3 ± 0.5 ; N= 14
SW_01_2	21	12	21.8 ± 5.9 ; N= 12	3.8 ± 1.1 ; N= 12	3.2 ± 3.5 ; N= 12	0.1 ± 0.3 ; N= 12
SW_02_1	8	2	44.5 ± 0.7 ; N= 2	6 ± 2.8 ; N= 2	6 ± 4.2 ; N= 2	0 ± 0 ; N= 2
SW_02_2	1	*0*	*n.d.*	*n.d.*	*n.d.*	*n.d.*
SW_02_3	1	*0*	*n.d.*	*n.d.*	*n.d.*	*n.d.*
SW_02_4	3	2	40.2 ± 3.9 ; N= 2	6.5 ± 0.7 ; N= 2	20.5 ± 9.2 ; N= 2	0 ± 0 ; N= 2
SW_03_1	8	8	35.8 ± 11 ; N= 8	3.1 ± 0.7 ; N= 7	4.4 ± 2.1 ; N= 8	0 ± 0 ; N= 8
SW_03_2	8	7	28.5 ± 12.3 ; N= 7	2.7 ± 1 ; N= 7	6 ± 4.3 ; N= 7	0 ± 0 ; N= 7
SW_03_3	15	14	30.7 ± 9.5 ; N= 14	2.8 ± 0.6 ; N= 13	5.8 ± 2.7 ; N= 14	0 ± 0 ; N= 14
SW_03_4	6	6	34 ± 5.5 ; N= 6	2.8 ± 0.8 ; N= 6	6.5 ± 2.2 ; N= 6	0.2 ± 0.4 ; N= 6
SW_03_5	10	10	30.4 ± 11.7 ; N= 10	3.6 ± 1 ; N= 9	3.4 ± 2.7 ; N= 10	0.1 ± 0.3 ; N= 10
SW_04_1	11	7	32.7 ± 11.7 ; N= 7	4 ± 1.3 ; N= 7	7.9 ± 6.7 ; N= 7	0.1 ± 0.4 ; N= 7
SW_04_2	8	7	35.6 ± 5.7 ; N= 7	4 ± 0.8 ; N= 7	4.4 ± 0.5 ; N= 7	0.4 ± 0.5 ; N= 7
SW_04_3	13	11	40.7 ± 18.1 ; N= 11	4.7 ± 1.6 ; N= 11	4.8 ± 2.2 ; N= 11	0 ± 0 ; N= 11
SW_04_4	11	10	36.5 ± 5.4 ; N= 10	5.1 ± 1.2 ; N= 10	7.3 ± 2.4 ; N= 10	0 ± 0 ; N= 10
SW_04_5	6	6	34.2 ± 5.5 ; N= 6	4.5 ± 1.2 ; N= 6	4.8 ± 1.9 ; N= 6	0 ± 0 ; N= 6
SW_05_1	14	13	44.5 ± 4.3 ; N= 13	6.8 ± 1.3 ; N= 13	6.3 ± 2 ; N= 13	0.4 ± 0.9 ; N= 13
SW_05_2	19	16	33.9 ± 5 ; N= 16	6 ± 1.5 ; N= 16	7.8 ± 3.4 ; N= 16	0.1 ± 0.3 ; N= 16
SW_05_3	28	26	31.8 ± 7.7 ; N= 26	4.2 ± 1 ; N= 26	6.4 ± 2.1 ; N= 26	0 ± 0.2 ; N= 26
SW_05_4	21	17	30.4 ± 6.8 ; N= 17	3.2 ± 1 ; N= 16	5 ± 3.5 ; N= 17	0.2 ± 0.5 ; N= 17
SW_05_5	8	8	31.6 ± 9.4 ; N= 8	4.6 ± 1.7 ; N= 8	7.2 ± 1.8 ; N= 8	0 ± 0 ; N= 8
SW_06_1	3	3	41.7 ± 8.5 ; N= 3	14.3 ± 4 ; N= 3	42.7 ± 25 ; N= 3	0.7 ± 1.2 ; N= 3
SW_06_2	3	2	57.5 ± 0.7 ; N= 2	12.5 ± 2.1 ; N= 2	19 ± 4.2 ; N= 2	0.5 ± 0.7 ; N= 2
SW_06_3	2	2	43 ± 31.8 ; N= 2	7.5 ± 7.8 ; N= 2	11.5 ± 10.6 ; N= 2	0 ± 0 ; N= 2
SW_06_4	1	1	36 ; N= 1	10 ; N= 1	7 ; N= 1	0 ; N= 1
SW_07_1	28	21	28.1 ± 7.6 ; N= 21	4.9 ± 1.1 ; N= 21	5.7 ± 2.1 ; N= 21	0 ± 0.2 ; N= 21
SW_07_2	14	14	28.7 ± 6 ; N= 14	4.7 ± 1.1 ; N= 14	5.2 ± 2.2 ; N= 14	0.1 ± 0.3 ; N= 14
SW_07_3	21	18	32.2 ± 5.9 ; N= 18	5.1 ± 1.3 ; N= 18	5.5 ± 1.8 ; N= 18	0.1 ± 0.3 ; N= 18
SW_07_4	28	20	33.3 ± 10.3 ; N= 20	5 ± 1.1 ; N= 20	5.4 ± 4.3 ; N= 20	0 ± 0.2 ; N= 20
SW_07_5	27	23	31.5 ± 6.8 ; N= 23	4.7 ± 1.1 ; N= 23	7.1 ± 5.2 ; N= 23	0.1 ± 0.3 ; N= 23
SW_08_1	11	11	28.7 ± 3.9 ; N= 11	4.5 ± 1.2 ; N= 11	7.7 ± 4.6 ; N= 11	0.1 ± 0.3 ; N= 11
SW_08_2	16	16	32.2 ± 6.1 ; N= 16	4.7 ± 1.2 ; N= 16	4.1 ± 1.1 ; N= 16	0.1 ± 0.2 ; N= 16
SW_08_3	20	20	32 ± 6.5 ; N= 20	3.9 ± 0.9 ; N= 20	4 ± 1.4 ; N= 20	0 ± 0.2 ; N= 20
SW_08_4	21	18	31.9 ± 6.8 ; N= 18	4.7 ± 0.9 ; N= 18	4.7 ± 1.3 ; N= 18	0.2 ± 0.4 ; N= 18
SW_08_5	23	22	30 ± 4.7 ; N= 22	4.6 ± 1.1 ; N= 22	4.5 ± 1.4 ; N= 22	0.1 ± 0.3 ; N= 22
SW_09_1	4	1	29 ; N= 1	6 ; N= 1	6 ; N= 1	0 ; N= 1
SW_09_2	9	9	37.6 ± 6.7 ; N= 9	8.3 ± 4.8 ; N= 9	16 ± 20.8 ; N= 9	0 ± 0 ; N= 9
SW_09_3	11	11	32.5 ± 7 ; N= 11	4.8 ± 1.1 ; N= 11	4.6 ± 0.7 ; N= 11	0 ± 0 ; N= 11
SW_09_4	15	14	31 ± 4.5 ; N= 14	5.8 ± 1.4 ; N= 14	4.6 ± 1.4 ; N= 14	0.1 ± 0.4 ; N= 14
SW_09_5	8	8	27.1 ± 5.2 ; N= 8	4.2 ± 1.5 ; N= 8	3.9 ± 1.1 ; N= 8	0.1 ± 0.4 ; N= 8
SW_10_1	15	*0*	*n.d.*	*n.d.*	*n.d.*	*n.d.*
SW_10_2	12	10	30.2 ± 2.9 ; N= 10	4 ± 1.1 ; N= 10	4.2 ± 1 ; N= 10	0 ± 0 ; N= 10
SW_10_3	27	24	27.1 ± 4.5 ; N= 24	3.8 ± 1 ; N= 24	3.8 ± 1.1 ; N= 24	0.1 ± 0.3 ; N= 24
SW_10_4	15	9	32.6 ± 6.9 ; N= 9	5.3 ± 0.7 ; N= 9	4.6 ± 0.9 ; N= 9	0.2 ± 0.7 ; N= 9
SW_10_5	20	12	30.5 ± 7.1 ; N= 12	4.2 ± 1.3 ; N= 12	3.8 ± 0.8 ; N= 12	0.2 ± 0.4 ; N= 12
SW_11_1	6	2	33.8 ± 1.8 ; N= 2	5 ± 1.4 ; N= 2	4 ± 1.4 ; N= 2	0.5 ± 0.7 ; N= 2

SW_11_2	4	*0*	*n.d.*	*n.d.*	*n.d.*	*n.d.*
SW_11_3	17	11	31.5 ± 7.5 ; N= 11	4.8 ± 1.3 ; N= 11	6.3 ± 1.6 ; N= 11	0.4 ± 0.7 ; N= 11
SW_11_4	13	10	38.2 ± 6.4 ; N= 10	6.5 ± 2.3 ; N= 10	6.8 ± 4.5 ; N= 10	0.3 ± 0.7 ; N= 10
SW_11_5	21	16	33.8 ± 6.8 ; N= 16	5 ± 1.2 ; N= 16	5.2 ± 1.2 ; N= 16	0 ± 0 ; N= 16
LB_01_1	48	19	31.3 ± 3.8 ; N= 19	6.3 ± 1 ; N= 19	8.4 ± 2.2 ; N= 19	0.3 ± 0.6 ; N= 19
LB_01_2	15	14	29.4 ± 4.1 ; N= 14	5.6 ± 0.8 ; N= 14	9.1 ± 4.1 ; N= 14	0.5 ± 0.8 ; N= 14
LB_01_3	10	*0*	*n.d.*	*n.d.*	*n.d.*	*n.d.*
LB_01_4	4	2	31.2 ± 10.3 ; N= 2	6 ± 2.8 ; N= 2	11.5 ± 3.5 ; N= 2	0 ± 0 ; N= 2
LB_02_1	32	29	29.9 ± 6.7 ; N= 29	3 ± 1.5 ; N= 29	7.6 ± 3.2 ; N= 29	0.4 ± 0.8 ; N= 29
LN_01	0	*0*	*n.d.*	n.d.	n.d.	n.d.

Supplementary Table S4. *Output of all statistical tests that were carried out to explore differences in* R. mangle *outplant performance per site. Significant p-values are shown in* ***bold****.*

Biotic variable	Random effect	Transformation	Shapiro-Wilk normality	DF	*F*-value	*p*-value
Stem height	Site	Reciprocal	0.31	10	10.93	**<0.001**
Stem thickness	Site	Logit	0.12	10	12.72	**<0.001**
Number of leaves alive	Site	Reciprocal	0.91	10	3.667	**0.002**
Proportion of outplants alive	Site	Logit	0.01	10	5.387	**<0.001**
Distance nearest tree	Site	Square root	0.33	10	4.52	**<0.001**

Supplementary Table S5. *Mean values ± SD values for biotic measurements on* A. germinans *outplants per appointed long-term monitoring plot in each identified outplanting site.*

Site	Total trees	Alive trees	Height (mean±SD;N) cm	Thickness (mean±SD;N) mm	Leaves count (mean±SD;N) Alive	Dead
LN_01_1	17	0	*n.d.*	*n.d.*	*n.d.*	*n.d.*
LN_01_2	30	0	*n.d.*	*n.d.*	*n.d.*	*n.d.*
LN_01_3	14	9	10.3 ± 2.9 ; N= 9	1.2 ± 0.4 ; N= 9	4 ± 1.7 ; N= 9	0.4 ± 0.5 ; N= 9
LN_01_4	25	5	15.6 ± 6.6 ; N= 5	1.8 ± 0.8 ; N= 5	2.2 ± 1.1 ; N= 5	0 ± 0 ; N= 5
LN_01_5	28	3	12 ± 3.5 ; N= 3	1.3 ± 0.6 ; N= 3	0.7 ± 1.2 ; N= 3	0.7 ± 0.6 ; N= 3

Supplementary Table S6. *Mean values ± SD values for biotic measurements on* L. racemosa *outplants per appointed long-term monitoring plot in each identified outplanting site.*

Site	Total trees	Alive trees	Height (mean±SD;N) cm	Thickness (mean±SD;N) mm	Leaves count (mean±SD;N) Alive	Dead
SW_11_1	4	4	18.0 ± 5.6; N= 4	3.2 ± 1; N= 4	13.8 ± 2.6; N= 4	0 ± 0; N= 4
SW_11_2	4	4	18.6 ± 6.4; N= 4	2.8 ± 1.3; N= 4	12 ± 5.4; N= 4	0.8 ± 1; N= 4

Supplementary Table S7. *Output of all statistical tests that were carried out to explore potential relationships between environmental factors and* R. mangle *outplant performance.* Df_n *= numerator degrees of freedom,* DF_d*= denominator degrees of freedom. Significant p-values are shown in* ***bold****.*

Response variable	Explanatory variable	Random effect	Transformation	Shapiro-Wilk normality	DF_n, DF_d	*F*-value	*p*-value
Stem height (cm)	Dissolved oxygen (mg/L)	Site	Reciprocal	0.14	1, 35.87	0.01	0.948
	Conductivity (mS/cm)	Site	None	0.15	1, 22.30	13.55	**0.001**
	pH	Site	Reciprocal	0.14	1, 37.92	0.01	0.936
	Temperature (°C)	Site	Reciprocal	0.15	1, 19.27	0.03	0.856
	Sediment organic matter content (%)	Site	Reciprocal	0.31	1, 36.01	0.82	0.373
	Sediment layer (cm)	Site	Reciprocal	0.23	1, 41.07	0.01	0.912
	Water depth (cm)	Site	Reciprocal	0.67	1, 41.37	12.44	**0.001**
	Water depth difference (cm)	Site	Reciprocal	0.22	1, 43.18	0.878	0.354
	Distance nearest tree (cm)	Site	Reciprocal	0.20	1, 41.53	2.65	0.111
Stem thickness (mm)	Dissolved oxygen (mg/L)	Site	Logit	0.20	1, 39.77	0.27	0.607
	Conductivity (mS/cm)	Site	Logit	0.16	1, 33.42	0.73	0.398
	pH	Site	Logit	0.22	1, 39.31	0.15	0.698
	Temperature (°C)	Site	Square root	0.06	1, 30.49	0.43	0.512
	Sediment organic matter (%)	Site	Logit	0.12	1, 37.86	0.31	0.581
	Sediment layer (cm)	Site	Logit	0.17	1, 42.95	2.03	0.161
	Water depth (cm)	Site	Logit	0.27	1, 43.27	1.18	0.283
	Water depth difference (cm)	Site	Logit	0.13	1, 43.89	0.57	0.454
	Distance nearest tree (cm)	Site	Logit	0.16	1, 42.64	0.09	0.767
Number of alive leaves	Dissolved oxygen (mg/L)	Site	Reciprocal	0.78	1, 29.95	0.72	0.402
	Conductivity (mS/cm)	Site	Reciprocal	0.74	1, 14.99	1.12	0.306
	pH	Site	Reciprocal	0.88	1, 32.75	0.04	0.834
	Temperature (°C)	Site	Reciprocal	0.89	1, 16.08	0.08	0.787
	Sediment organic matter content (%)	Site	Reciprocal	0.38	1, 42.35	0.79	0.379
	Sediment layer (cm)	Site	Reciprocal	0.80	1, 38.62	0.01	0.950
	Water depth (cm)	Site	Reciprocal	0.86	1, 35.21	0.67	0.419
	Water depth difference (cm)	Site	Reciprocal	0.81	1, 23.77	1.49	0.235
	Distance nearest tree (cm)	Site	Reciprocal	0.96	1, 32.25	4.38	**0.044**
Proportion of outplants alive	Dissolved oxygen (mg/L)	Site	Logit	0.110	1, 39.46	20.47	**0.000**
	Conductivity (mS/cm)	Site	Logit	0.001	1, 36.63	18.71	**0.000**
	pH	Site	Logit	0.000	1, 31.52	0.02	0.88
	Temperature (°C)	Site	Logit	0.000	1, 8.56	0.72	0.42
	Sediment organic matter content (%)	Site	Logit	0.162	1, 40.92	8.85	**0.005**
	Sediment layer (cm)	Site	Logit	0.002	1, 45.69	0.06	0.81
	Water depth (cm)	Site	Logit	0.014	1, 42.00	2.05	0.16
	Water depth difference (cm)	Site	Logit	0.001	1, 39.63	0.50	0.49
	Distance nearest tree (cm)	Site	Logit	0.030	1, 34.03	7.86	**0.008**

Supplementary Table S8. *Coordinates of each block used in the experimental study.*

Area	Tree type	Plot ID	Latitude	Longitude
SW	Seedling	S1	12.0561	-68.2792
SW	Seedling	S2	12.0560	-68.2788
SW	Seedling	S3	12.0559	-68.2787
SW	Seedling	S4	12.0558	-68.2785
SW	Seedling	S5	12.0557	-68.2784
SW	Propagule	P1	12.0556	-68.2782
SW	Propagule	P2	12.0556	-68.2781
SW	Propagule	P3	12.0555	-68.2780
SW	Propagule	P4	12.0553	-68.2775
SW	Propagule	P5	12.0553	-68.2773

Supplementary Table S9. *Coordinates and treatment of each individual experimental unit.*

Area	Plot ID	Tree type	Nutrients	Density	Latitude	Longitude
SW	S1	Seedling	N	D	12.05609	-68.27916
SW	S1	Seedling	C	C	12.05610	-68.27916
SW	S1	Seedling	N	C	12.05607	-68.27917
SW	S1	Seedling	C	D	12.05609	-68.27920
SW	S2	Seedling	N	C	12.05598	-68.27882
SW	S2	Seedling	C	C	12.05596	-68.27878
SW	S2	Seedling	C	C	12.05594	-68.27880
SW	S2	Seedling	N	D	12.05595	-68.27883
SW	P1	Propagule	C	C	12.05589	-68.27872
SW	P1	Propagule	N	D	12.05587	-68.27868
SW	P1	Propagule	C	D	12.05584	-68.27870
SW	P1	Propagule	C	D	12.05586	-68.27872
SW	P2	Propagule	N	C	12.05578	-68.27852
SW	P2	Propagule	N	D	12.05577	-68.27852
SW	P2	Propagule	C	C	12.05575	-68.27853
SW	P2	Propagule	C	C	12.05577	-68.27854
SW	S3	Seedling	N	D	12.05572	-68.27838
SW	S3	Seedling	C	C	12.05572	-68.27836
SW	S3	Seedling	N	D	12.05570	-68.27838
SW	S3	Seedling	C	C	12.05570	-68.27838
SW	S4	Seedling	N	C	12.05565	-68.27820
SW	S4	Seedling	N	D	12.05563	-68.27818
SW	S4	Seedling	C	D	12.05562	-68.27820
SW	S4	Seedling	C	D	12.05564	-68.27821
SW	P3	Propagule	N	C	12.05558	-68.27813
SW	P3	Propagule	N	D	12.05558	-68.27809
SW	P3	Propagule	N	D	12.05556	-68.27812
SW	P3	Propagule	N	C	12.05557	-68.27815
SW	S5	Seedling	C	D	12.05556	-68.27801
SW	S5	Seedling	N	C	12.05555	-68.27798
SW	S5	Seedling	C	D	12.05553	-68.27801
SW	S5	Seedling	N	C	12.05555	-68.27803
SW	P4	Propagule	C	C	12.05530	-68.27754
SW	P4	Propagule	C	D	12.05533	-68.27752
SW	P4	Propagule	C	C	12.05530	-68.27753
SW	P4	Propagule	C	D	12.05531	-68.27753
SW	P5	Propagule	N	C	12.05528	-68.27732
SW	P5	Propagule	N	D	12.05526	-68.27729
SW	P5	Propagule	N	C	12.05523	-68.27730
SW	P5	Propagule	C	D	12.05523	-68.27734

Appendix 1: Long-term monitoring material list

General

- Field work booklet
- Phone (and watch)
- Food and drink
- Protective clothing
- Suncream
- Insect spray
- Sunglasses
- Booties
- Gloves
- Swimwear
- Towel
- mesh bag
- Waterproof backpack
- Sail for the boot of the car
- Plastic bin for dirty stuff
- Camera charged and empty SD card

Area measurements

- Rebar 25+ (of which at least 5 with label)
- Tie wraps
- Transect
- GPS (charged batteries + extra)
- GPS waterproof cover
- Slates + 2 pencils
- Pencil sharpener + eraser
- quadrant
- 2x sediment syringe
- Sediment bags
- ID labels sediment (check number at least 10)
- ID photo labeller
- Hammer
- Depth stick
- Bag
- Multimeter oxygen and salinity + check battery charged + jar
- Scissors/knife

Mangrove measurements

- Tape measure + spare
- Calliper + spare

Appendix 2: Long-term monitoring protocol

Before fieldwork

1. Collect all materials stated in Appendix 1 in a bag.
2. Check that the batteries of the multimeter, GPS and camera are full and check that the extra batteries are also full.
3. Check whether there are at least 10 water-resistant sample ID labels in a bag.

During fieldwork

4. View the plot and note the location, date and time in the fieldwork booklet and make an overview picture of the site.
5. Asses how many monitoring plots can be distributed across the site with a maximum of 5 monitoring plots. Each plot must contain a minimum of 1 tree and accurately represent the environmental conditions of its location.
6. Put a rebar in the ground and walk 5 meters to the east, place a 2^{nd} rebar there. Then south for the 3^{rd} rebar and west for the 4^{th} rebar. Now there is an area of 5 by 5 meters.
7. Record the GPS point of most northwestern rebar and check if it has a card attached.
8. Area measurements
    a. Record location, site, plot and start time.
    b. Take a photo with a visual ID number.
9. Biotic measurements
    a. Select a tree within the plot
        i. *Optional: in case there are a lot of trees, a 50cm2 quadrant can be used on the four corners and the centre*
    b. Measure stem height
    c. Measure stem thickness
    d. Count the number of leaves dead and alive
    e. Note whether the tree is dead or alive
    f. Note if there are signs of herbivory
    g. When trees are close together, note which subplot they are in and measure the distance between them
    h. Measure the distance to the nearest other subplot
    i. Complete the other monitoring plots in the same way
10. Abiotic measurements
    a. Measure and record conductivity
        i. *If not deep enough, fill the jar with water*
    b. Measure and record dissolved oxygen concentration
    c. Measure water depth with the stick or tape measure
    d. Measure with rebar sediment depth (up to max 40-60 cm)
    e. Take a sediment sample in the centre of the plot (4cm deep)
    f. Record sediment ID
    g. Complete the other four plots in the same way
11. Remove all of the northeast, southeast, and southwest rebar from the water
12. Record the end time and take a picture of all slates

After fieldwork

13. Rinse the multimeter probes with water
14. Rinse off other materials such as transect, hammer, camera, calliper, tape measure, photo labeller, scissors/knife.
15. Upload the photos of the fieldwork and the slate
16. Enter data in the Excel sheet.
17. Clean the slate and prepare it for next use
18. Place the sediment samples in the oven
19. Recharge the batteries of the multimeter, GPS and camera
20. Log all completed tasks on the schedule

Appendix 3: Outplanting Area descriptions

SW_01

Fig. 14 (A) Polygon of mangrove outplant area in the southwest (SW). Dots reflect the location of long-term mangrove outplant monitoring plots of 5 m² each. (B) Overview photo of the SW_01 mangrove outplanting site.

1. Local name of site	Safe haven
2. Short area description	This is an experimental site where *R. mangle* seedlings were outplanted on Biodegradable Ecosystem Engineering Elements (BESE) and without BESE (Lanjouw, 2022b). These elements are made out of potato starch and stabilize sediment, attenuate waves and mimic dense root mats and may facilitate mangrove performance.
3. Why this location?	This location was selected for the BESE experiment because it is an exposed site with high wave activity and as there were no mangroves present.
4. Date restoration work	1st outplant: 18 February 2022
5. Species outplanted	Red mangrove (*Rhizophora mangle*)
6. Approximate number outplanted	1st outplant: 36 seedlings (from Lanjouw, 2022)
7. Surface area	42.5 m^2
8. Number of seedlings 20 March 2023	Red mangrove seedlings alive: 23 Red mangrove seedlings dead: 24
9. Density of seedlings alive	18 February 2022: 0.85 seedlings m^{-2} 20 March 2023: 0.54 seedlings m^{-2}
10. Initial outplants still alive	63.9%
11. Remarks	On 20 March 2023, the sum of the number of dead and living outplants was higher than the number of seedlings initially planted on 18 February 2022.

SW_02

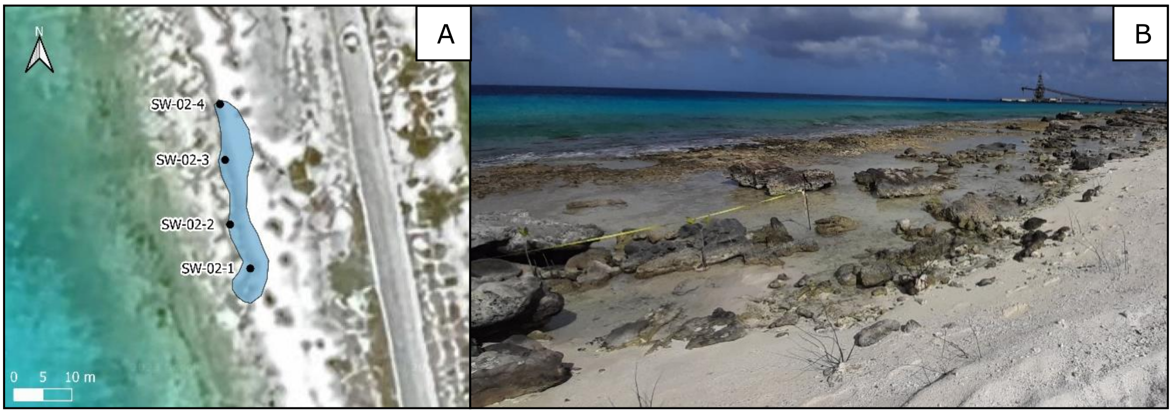

Fig. 15 (A) Polygon of mangrove outplant area in the southwest (SW). Dots reflect the location of long-term mangrove outplant monitoring plots of 5 m^2 each. (B) Overview photo of the SW_02 mangrove outplanting site.

1. Local name of site	Salt Pier
2. Short area description	South of the Salt Pier. Highly dynamic area, this can be seen on the many soft corals that are washed up on shore. The area has some deeper and some shallower areas. High water levels as it is in direct contact with the ocean.
3. Why this location?	Location was chosen to test if seedlings can survive in such a high-energy location.
4. Date restoration work	1st outplant: 9 February 2021 2nd outplant: 15 July 2022
5. Species outplanted	Red mangrove (*Rhizophora mangle*)
6. Approximate number outplanted	1st outplant: 100 2nd outplant: 400
7. Surface area	150.5 m^2
8. Number of seedlings 22 March 2023	Red mangrove seedlings alive: 4 Red mangrove seedlings dead: 9
9. Density of seedlings alive	9 February 2021: 0.66 seedlings m^{-2} 15 July 2022: 3.32 seedlings m^{-2} 22 March 2023: 0.03 seedlings m^{-2}
10. Initial outplants still alive	0.8%

SW_03

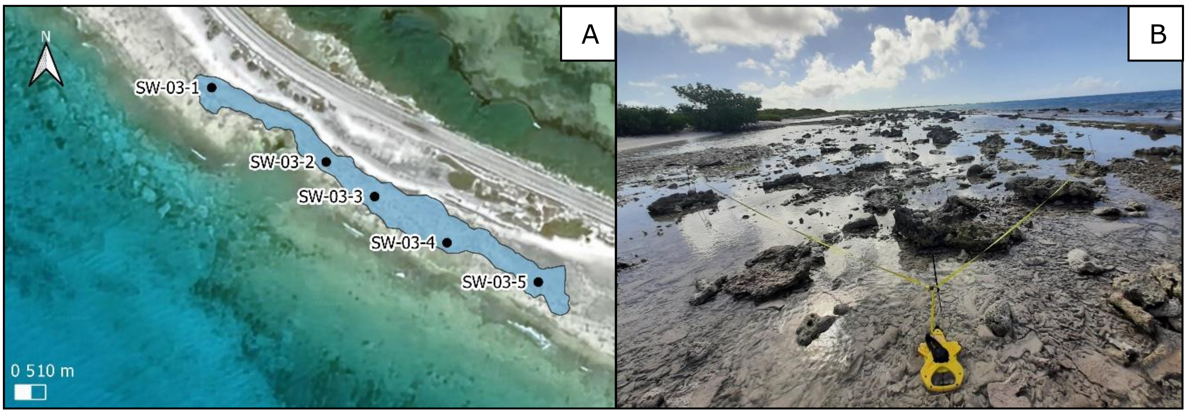

Fig. 16 (A) Polygon of mangrove outplant area in the southwest (SW). Dots reflect the location of long-term mangrove outplant monitoring plots of 5 m^2 each. (B) Overview photo of the SW_03 mangrove outplanting site.

1. Local name of site	White Slave North
2. Short area description	Barren area with lots of coral rubble. High energy location with a connection to the ocean. The area has some deeper and some shallower areas. A few days after outplanting many seedlings were found washed up on shore or were washed away. Were planted in collaboration with a Danish school.
3. Why this location?	Some naturally occurring mangroves but overall low vegetation cover therefore this area needs more coastal protection.
4. Date restoration work	23 March 2023
5. Species outplanted	Red mangrove (*Rhizophora mangle*)
6. Approximate number outplanted	400
7. Surface area	1265 m^2
8. Number of seedlings 24 March 2023	Red mangrove seedlings alive: 104 Red mangrove seedlings dead: 85
9. Density of seedlings alive	23 March 2023: 0.32 seedlings m^{-2} 24 March 2023: 0.08 seedlings m^{-2}
10. Initial outplants still alive	26.0%

SW_04

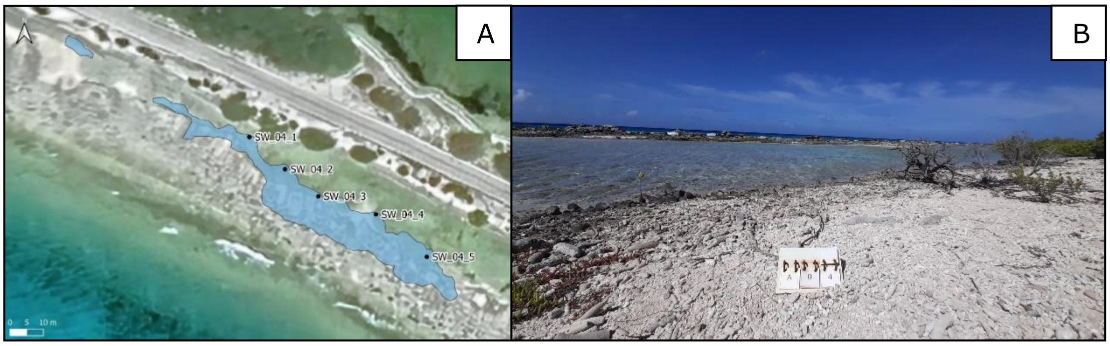

Fig. 17 (A) Polygon of mangrove outplant area in the southwest (SW). Dots reflect the location of long-term mangrove outplant monitoring plots of 5 m² each. (B) Overview photo of the SW_04 mangrove outplanting site.

1. Local name of site	White slave
2. Short area description	Just south of White Slave North. From the road to the ocean is a shallow lagune, at low tide this is not in contact with the sea. At high tide, water exchange happens. Seedlings are planted in the area between the lagune and the ocean. Naturally occurring mangroves at the roadside.
3. Why this location?	Some naturally occurring mangroves but overall low vegetation cover therefore this area needs more coastal protection.
4. Date restoration work	1st outplant: 29 July 2020 2nd outplant: 19 June 2022 3rd outplant: 26 July 2022
5. Species outplanted	Red mangrove (*Rhizophora mangle*)
6. Approximate number outplanted	1st outplant: 50 2nd outplant: 400 3rd outplant: 550
7. Surface area	856 m^2
8. Number of seedlings 27 March 2023	Red mangrove seedlings alive: 115 Red mangrove seedlings dead: 27
9. Density of seedlings alive	29 July 2020: 0.06 seedlings m^{-2} 19 June 2022: 0.53 seedlings m^{-2} 26 July 2022: 1.17 seedlings m^{-2} 27 March 2023: 0.13 seedlings m^{-2}
10. Initial outplants still alive	11.5%

SW_05

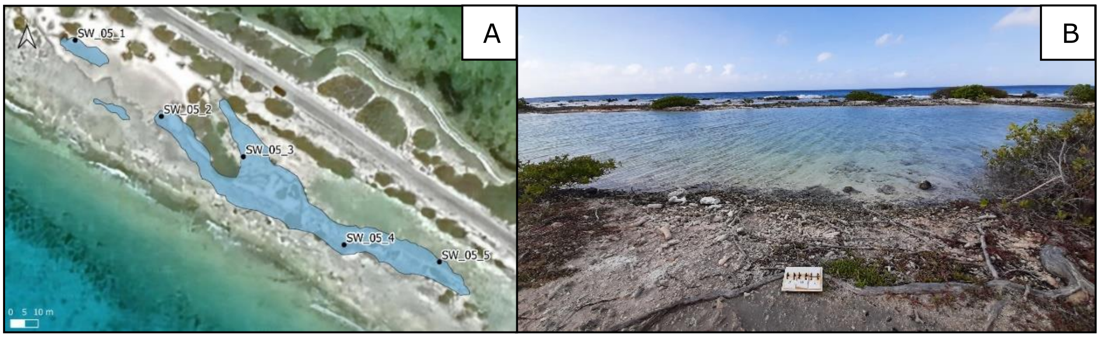

Fig. 18 (A) Polygon of mangrove outplant area in the southwest (SW). Dots reflect the location of long-term mangrove outplant monitoring plots of 5 m² each. (B) Overview photo of the SW_05 mangrove outplanting site.

1. Local name of site	Margate bay
2. Short area description	Large and diverse location. Top left two separate areas are part of the BESE experiments. Some parts have a direct exchange with the ocean. From the road to the ocean is a shallow lagune, at low tide some parts dry up. At high tide, water exchange happens. Seedlings were planted in the area between the lagune and the ocean and closer to the road in a deeper part of the lagune. Outplants focussed on the area between the lagune and the ocean.
3. Why this location?	Some naturally occurring mangroves but overall low vegetation cover therefore this area needs more coastal protection.
4. Date restoration work	1^{st} outplant: 9 February 2021 2^{nd} outplant: 23 September 2022
5. Species outplanted	Red mangrove (*Rhizophora mangle*)
6. Approximate number outplanted	1^{st} outplant: 60 2^{nd} outplant: 1300
7. Surface area	1554 m^2
8. Number of seedlings 3 April 2023	Red mangrove seedlings alive: 501 Red mangrove seedlings dead: 96
9. Density of seedlings alive	9 February 2021: 0.04 seedlings m^{-2} 23 September 2022: 0.88 seedlings m^{-2} 3 April 2023: 0.32 seedlings m^{-2}
10. Initial outplants still alive	36.8%

SW_06

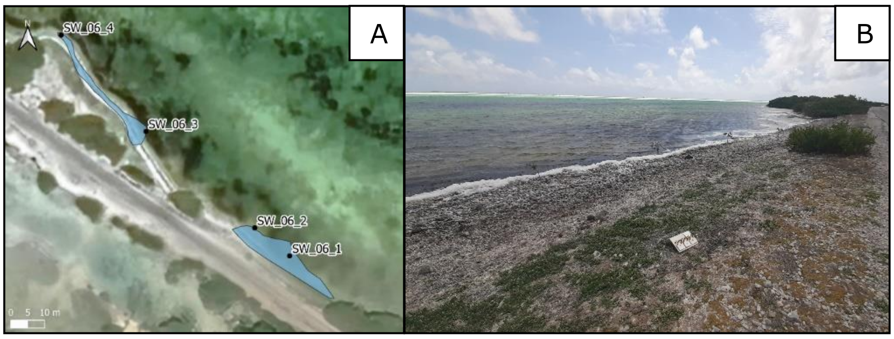

Fig. 19 (A) Polygon of mangrove outplant area in the southwest (SW). Dots reflect the location of long-term mangrove outplant monitoring plots of 5 m^{2} *each. (B) Overview photo of the SW_06 mangrove outplanting site.*

1. Local name of site	Margate bay Pekelmeer
2. Short area description	A small section on the side of the 'Pekelmeer.' Trees are larger compared to other sites. Large mangroves are present close by. Planted along a strip next to the road. The lake has calm waters.
3. Why this location?	The only site not located at the ocean site. Experiment if seedlings could grow here.
4. Date restoration work	9 February 2021
5. Species outplanted	Red mangrove (*Rhizophora mangle*)
6. Approximate number outplanted	20
7. Surface area	137 m^{2}
8. Number of seedlings 30 March 2023	Red mangrove seedlings alive: 8 Red mangrove seedlings dead: 1
9. Density of seedlings alive	9 February 2021: 0.15 seedlings m^{-2} 30 March 2023: 0.06 seedlings m^{-2}
10. Initial outplants still alive	40.0%

SW_07

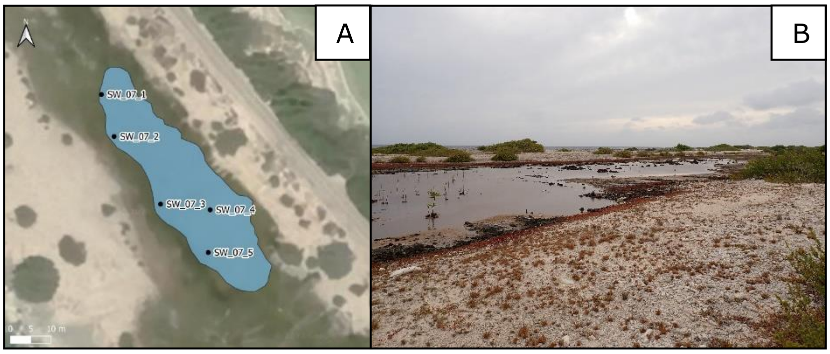

Fig. 20 (A) Polygon of mangrove outplant area in the southwest (SW). Dots reflect the location of long-term mangrove outplant monitoring plots of 5 m² each. (B) Overview photo of the SW_07 mangrove outplanting site.

1. Local name of site	Sweet dreams North
2. Short area description	Closely located by SW_08 and SW_09. Out of all three the wettest. It has no open connection to the ocean as a coral rubble dyke protects it. Wet area consists of muddy soil with a large number of snails. Smells like ammonium. Throughout March to May, the water level noticeably reduced.
3. Why this location?	Some naturally occurring mangroves but overall low vegetation cover therefore this area needs more coastal protection.
4. Date restoration work	1st outplant: 3 October 2021 2nd outplant: 19 November 2021 3rd outplant: 13 February 2022
5. Species outplanted	Red mangrove (*Rhizophora mangle*)
6. Approximate number outplanted	1st outplant: ±142 (425 distributed over SW_07, SW_08 and SW_09) 2nd outplant: 450 3rd outplant: ±133 (400 distributed over SW_07, SW_08 and SW_09)
7. Surface area	860 m^2
8. Number of seedlings 14 April 2023	Red mangrove seedlings alive: 177 Red mangrove seedlings dead: 117
9. Density of seedlings alive	3 October 2021: 0.17 seedlings m^{-2} 19 November 2021: 0.69 seedlings m^{-2} 13 February 2022: 0.84 seedlings m^{-2} 14 April 2023: 0.21 seedlings m^{-2}
10. Initial outplants still alive	24.4%

SW_08

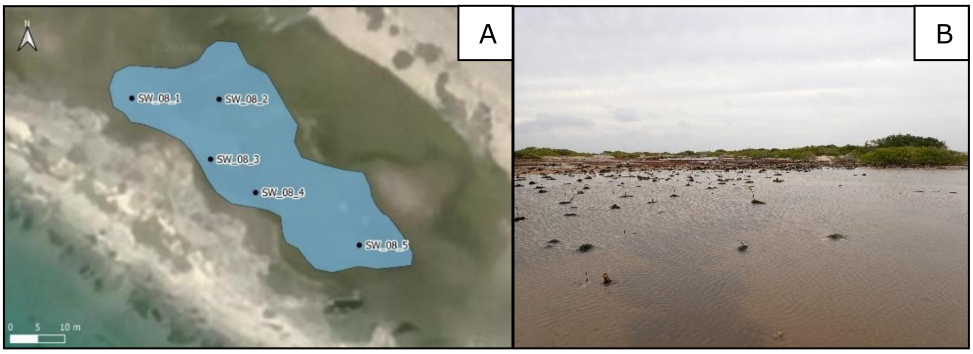

Fig. 21 (A) Polygon of mangrove outplant area in the southwest (SW). Dots reflect the location of long-term mangrove outplant monitoring plots of 5 m² each. (B) Overview photo of the SW_08 mangrove outplanting site.

1. Local name of site	Sweet dreams/ vista blue
2. Short area description	Closely located by SW_07 and SW_09. It has no open connection to the ocean as a coral rubble dyke protects it. Wet area consists of muddy soil with a large number of snails. Smells like ammonium. Throughout March to May, the water level noticeably reduced.
3. Why this location?	Some naturally occurring mangroves but overall low vegetation cover therefore this area needs more coastal protection.
4. Date restoration work	1st outplant: 9 February 2021 2nd outplant: 25 July 2021 3rd outplant: 3 October 2021 4th outplant: 13 February 2022
5. Species outplanted	Red mangrove (*Rhizophora mangle*)
6. Approximate number outplanted	1st outplant: 60 2nd outplant: ±50 propagules (100 distributed over SW_08 and SW_09) 3rd outplant: ±142 (425 distributed over SW_07, SW_08 and SW_09) 4th outplant: ±133 (400 distributed over SW_07, SW_08 and SW_09)
7. Surface area	959 m^2
8. Number of seedlings 26 April 2023	Red mangrove seedlings alive: 298 Red mangrove seedlings dead: 36
9. Density of seedlings alive	9 February 2021: 0.06seedlings m^{-2} 25 July 2021: 0.11 seedlings m^{-2} 3 October 2021: 0.26 seedlings m^{-2} 13 February 2022: 0.40 seedlings m^{-2} 26 April 2023: 0.31 seedlings m^{-2}
10. Initial outplants still alive	77.4%

SW_09

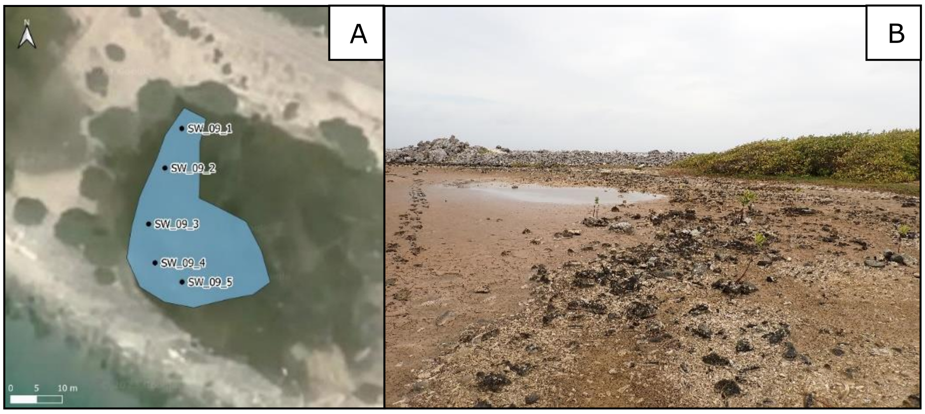

Fig. 22 (A) Polygon of mangrove outplant area in the southwest (SW). Dots reflect the location of long-term mangrove outplant monitoring plots of 5 m² each. (B) Overview photo of the SW_09 mangrove outplanting site.

1. Local name of site	Sweet dreams South
2. Short area description	Closely located by SW_07 and SW_08. Out of all three the driest. No connection with the ocean as a coral rubble dyke protects it. It has no open connection to the ocean. The wet area consists of muddy soil. Smells like ammonium. From March to May, the water level noticeably reduced.
3. Why this location?	Some naturally occurring mangroves but overall low vegetation cover therefore this area needs more coastal protection.
4. Date restoration work	1st outplant: 25 July 2021 2nd outplant: 03 October 2021 3rd outplant: 13 February 2022
5. Species outplanted	Red mangrove (*Rhizophora mangle*)
6. Approximate number outplanted	1st outplant: ±50 propagules (100 distributed over SW_08 and SW_09) 2nd outplant: ±142 (425 divided over SW_07, SW_08 and SW_09) 3rd outplant: ±133 (400 divided over SW_07, SW_08 and SW_09)
7. Surface area	587.5 m^2
8. Number of seedlings 13 March 2023	Red mangrove seedlings alive:43 Red mangrove seedlings dead: 4
9. Density of seedlings alive	25 July 2021: 0.09 seedlings m^{-2} 03 October 2021: 0.33 seedlings m^{-2} 13 February 2022: 0.55 seedlings m^{-2} 13 March 2023: 0.07 seedlings m^{-2}
10. Initial outplants still alive	13.2%

SW_10

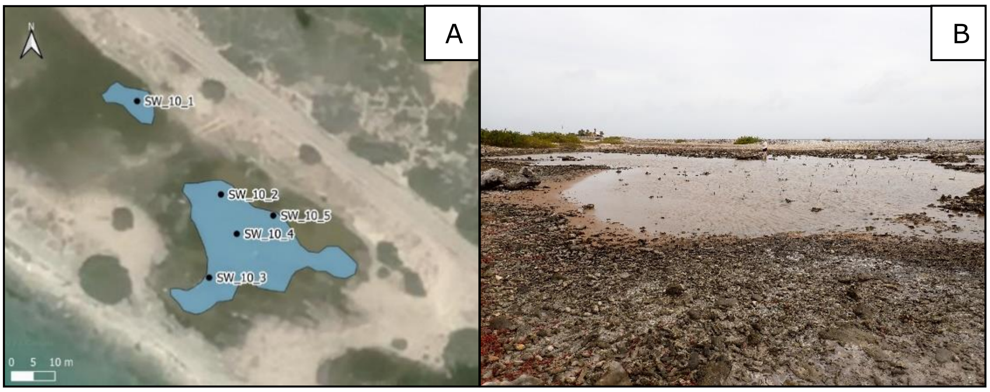

Fig. 23 (A) Polygon of mangrove outplant area in the southwest (SW). Dots reflect the location of long-term mangrove outplant monitoring plots of 5 m² each. (B) Overview photo of the SW_10 mangrove outplanting site.

1. Local name of site	Flamingo pond
2. Short area description	Close to SW_11. No connection with the ocean as a coral rubble dyke protects it. Minimal exchange with the ocean. Consists of a small pond and a larger pond. Lots of dead trees and crabs smells like ammonium.
3. Why this location?	Some naturally occurring mangroves but overall low vegetation cover therefore this area needs more coastal protection.
4. Date restoration work	26 July 2021
5. Species outplanted	Red mangrove (*Rhizophora mangle*)
6. Approximate number outplanted	200
7. Surface area	646 m^2
8. Number of seedlings 27 April 2023	Red mangrove seedlings alive: 129 Red mangrove seedlings dead: 203
9. Density of seedlings alive	26 July 2021: 0.31 seedlings m^{-2} 27 April 2023: 0.07 seedlings m^{-2}
10. Initial outplants still alive	64.5%

SW_11

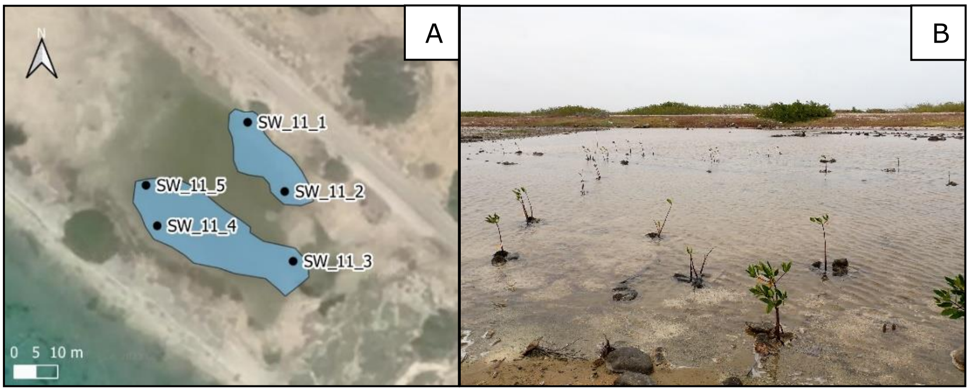

Fig. 24 (A) Polygon of mangrove outplant area in the southwest (SW). Dots reflect the location of long-term mangrove outplant monitoring plots of 5 m^2 each. (B) Overview photo of the SW_11 mangrove outplanting site.

1. Local name of site	Red slave
2. Short area description	Next to the red slave houses. Minimal exchange with the ocean. The area near the coast is doing better than the area closer to the road. The cause of the die-off of mangroves closer to the road is higher ammonia levels due to *Sargassum* influxes. In 2018 *Sargassum* entered the 'Pekelmeer' at Misha's Bridge and accumulated just north of the site. Products of degradation could have moved to the site through percolation (Bravo, 2022). White mangroves are planted on a drier patch.
3. Why this location?	Some naturally occurring mangroves but overall low vegetation cover therefore this area needs more coastal protection.
4. Date restoration work	*R. mangle* 1st outplant: 9 February 21 2nd outplant: 25 July 21 *L. racemosa* unknown
5. Species outplanted	Red mangrove (*Rhizophora mangle*) White mangrove (*Laguncularia racemosa*)
6. Approximate number outplanted	*R.* mangle 1st outplant: 90 2nd outplant: 100 *L. racemosa* unknown
7. Surface area	698 m^2
8. Number of seedlings 28 April 2023	Red mangrove seedlings alive: 121 Red mangrove seedlings dead:37 White mangrove seedlings alive: 8 White mangrove seedlings dead: 0
9. Density of seedlings alive	9 February 21: 0.13 seedlings m^{-2} 25 July 21: 0.27 seedlings m^{-2} 28 April 2023: 0.18 seedlings m^{-2}
10. Initial outplants still alive	*R. mangle* 63.7%

LB_01

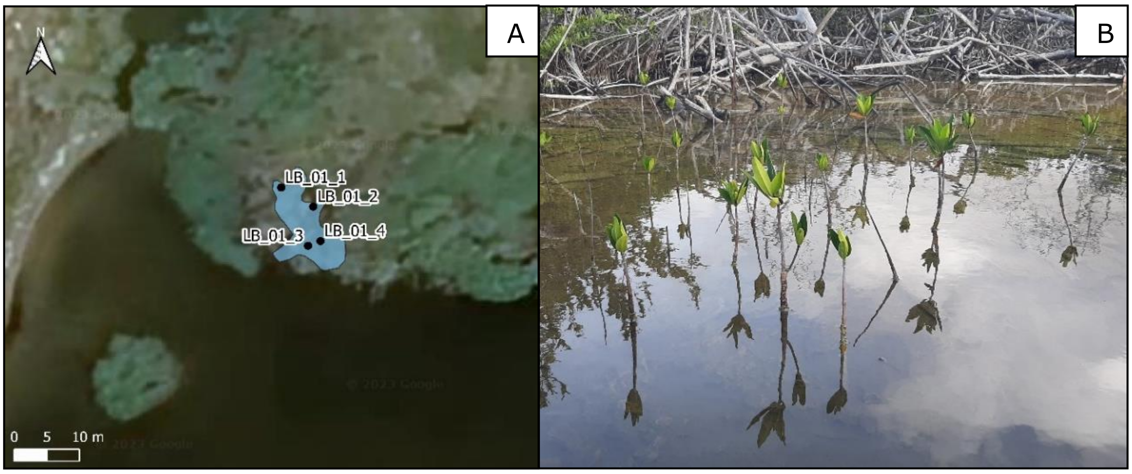

Fig. 25 (A) Polygon of mangrove outplant area in Lac Bay (LB). Dots reflect the location of long-term mangrove outplant monitoring plots of 5 m² each. (B) Overview photo of the LB_01 mangrove outplanting site.

1. Local name of site	Kaminda sorobon
2. Short area description	Small plot located close to Kaminda Sorobon road. Close to the waterside relatively healthy mangroves, where 5-10 meters inwards strongly degraded and retreated forest. Due to erosion, land sediments silt up the backwaters and prevent fresh water from reaching the mangroves which causes die-off leaving mudflats with dead trees. Third pilot site of Debrot et al. (Debrot, Meesters, & Slijkerman, 2010)(Debrot et al., 2010). The first two located across the mangrove information centre were unsuccessful as there was just a small section of mud before impenetrable limestone was hit by the tree roots. The pilot sites aimed to increase water flow in degraded areas to see if new mangrove outplants could survive and grow.
3. Why this location?	The pilot site is easily accessible by foot.
4. Date restoration work	11 April 2022
5. Species outplanted	Red mangrove (*Rhizophora mangle*)
6. Approximate number outplanted	200
7. Surface area	93 m^2
8. Number of seedlings 13 April 2023	Red mangrove seedlings alive: 55 Red mangrove seedlings dead: 57
9. Density of seedlings alive	11 April 2022: 2.15 seedlings m^{-2} 13 April 2023: 0.59 seedlings m^{-2}
10. Initial outplants still alive	27.5%

LB_02

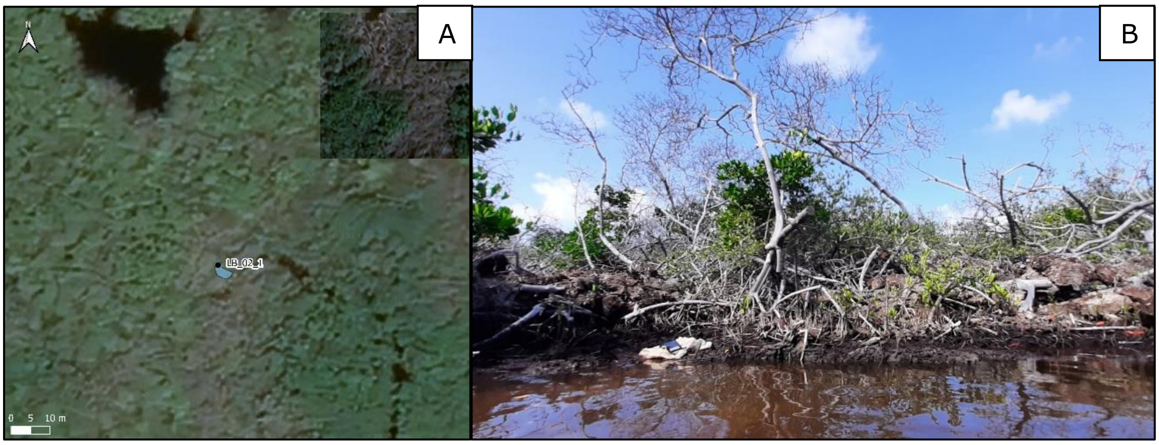

Fig. 26 (A) Polygon of mangrove outplant area in Lac Bay (LB). Dots reflect the location of long-term mangrove outplant monitoring plots of 5 m^2 each. (B) Overview photo of the LB_02 mangrove outplanting site.

1. Local name of site	-
2. Short area description	Located in the centre of the mangrove forest. The MangroveManiacs have been working here to restore old channels to improve water flow to the backlands. The area used to have *R. mangle* trees, but due to reduced water flow, they died and were replaced with *A. germinans* trees.
3. Why this location?	Located on the bank of the channels the Mangrove Maniacs opened up again, regularly visited. A small flat area where *A. germinans* trees were cut back, and *R. mangle* trees were planted to assess if they could survive again.
4. Date restoration work	Unknown
5. Species outplanted	Red mangrove (*Rhizophora mangle*)
6. Approximate number outplanted	Unknown
7. Surface area	10 m^2
8. Number of seedlings 18 April 2023	Red mangrove seedlings alive: 32 Red mangrove seedlings dead: 0
9. Density of seedlings alive	18 April 2023: 3.5 seedlings m^{-2}
10. Initial outplants still alive	Unknown

LN_01

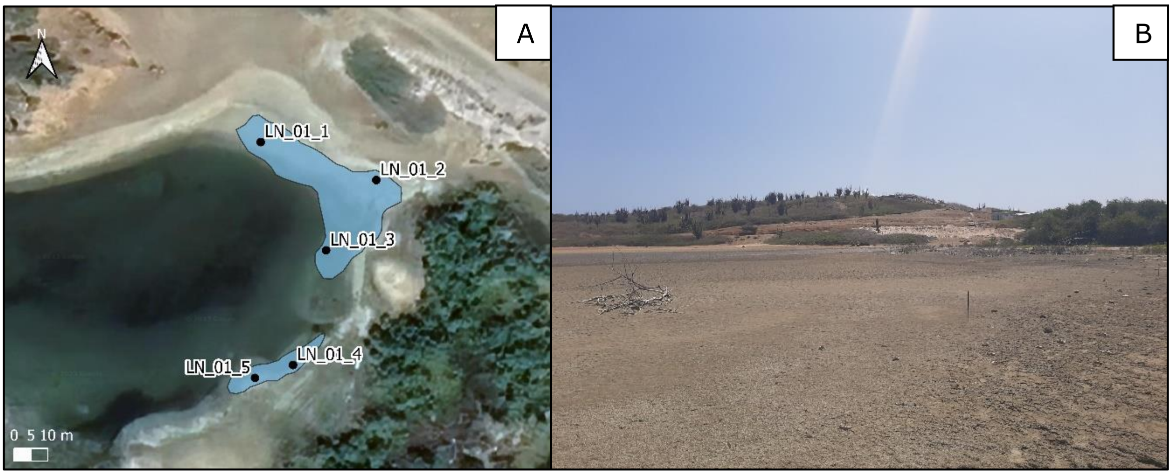

Fig. 27 (A) Polygon of mangrove outplant area in Lagun (LN). Dots reflect the location of long-term mangrove outplant monitoring plots of 5 m^2 each. (B) Overview photo of the LN_01 mangrove outplanting site.

1. Local name of site	Lagun
2. Short area description	During the rainy season, it is a shallow lake with a large catchment area. During the dry season, the lake completely dries up. The area is becoming more elevated, and thus drier, due to sedimentation. Recommended to excavate the area to have more exchange with the ocean and increase water level. But first barriers need to be in placed to prevent *Sargassum* and (plastic) pollution from entering the area.
3. Why this location?	Until a few years ago this area was vegetated by healthy black mangroves. Efforts to restore, but without more water small chance of success.
4. Date restoration work	January 2023
5. Species outplanted	Black mangrove (*Avicennia germinans*)
6. Approximate number outplanted	Unknown
7. Surface area	1003 m^2
8. Number of seedlings 19 April 2023	Black mangrove seedlings alive: 48 Black mangrove seedlings dead: 525
9. Density of seedlings alive	19 April 2023: 0.05 seedlings m^{-2}
10. Initial outplants still alive	Unknown