The effects of salinity, temperature and soil composition on mangrove abundance at Lagun, Bonaire

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Internship at Mangrove Maniacs

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MANGROVE MANIACS
LAC RESTORATION PROJECT

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Acknowledgements

Firstly, I want to thank Sabine Engel for supervising me during my research. It was really inspiring to see someone with such a great passion for nature at work. She gave me enough space and freedom to set up my research individually and I feel like I have improved a lot because of it. She was also very generous in giving me rides, supplies and information when I needed it and got me involved in a number of activities outside my research (replanting, site maintenance, seagrass monitoring and World Wetland Day, algae collection). I appreciate that she stimulated me to do more than just focus on my own study, because it allowed me to see a more full picture of all the efforts that go into nature conservation on Bonaire.

I also want to thank Dedrie, who helped me with conducting my vegetation analyses at Lagun. She was not only a great help with the practical aspect, but also provided some key observations during analyses which I could later fall back on when studying the results. She was very kind and enthusiastic, and offered me a free ride on her catamaran ‘The Woodwind’ for seagrass monitoring. For soil sampling, I have to thank Lotte, a WUR student who took the time to help out with mud-digging all across Lagun. Jessica Johnson was a great help for Lac bay monitoring, walking with me to plot sites, answering many of my questions about mangroves and kindly taking the time to explain how to use measuring equipment.

The volunteers from Mangrove Maniacs were a real inspiration to me. They all were very welcoming and showed interest in not only my work but also in me personally. I felt really lucky to meet such amazing people with very interesting and different career paths that showed so much voluntary involvement in nature conservation and restoration. It really opened my eyes to a number of possibilities for my own career. During this internship, I have only developed more interest and passion for marine biology, and I am definitely continuing down this road.

Abstract

Mangroves are important intertidal forests that exist in tropical and subtropical areas around the world. They are important coastal protectors, providing coastal stabilization and wave mitigation. Besides their protective ability, they fulfill a number of ecosystem services like nursery grounds for juvenile fish, carbon sequestration and pollutant filtering. However, mangroves have been under heavy threat in many countries due to anthropogenic pressure, causing major degradation rates. In Lac bay, Bonaire, a big lagoon consisting of mangroves and seagrass for example, high sedimentation due to erosion has caused channels to close, creating hypersaline conditions in ponds together with high temperatures. The forest around Lac bay therefore experienced high mortality rates and a strong decline in the systems' health. Another bay, Lagun, showed similar degradation in the back pond, but due to lack of documentation the actual cause is still uncertain. It is important to find out whether siltation, hypersalinity and high temperatures are also an issue at Lagun in order to create a successful restoration plan.

Vegetation, soil composition, conductivity and temperature were analyzed for several plots at different location types around Lagun, including the degraded part in the pond. Results showed that the silt layer in the pond was significantly higher than the other location types, which indicates root burial caused by high sedimentation rates. Conductivity (as a measure for salinity) and temperature were, contrary to the hypothesis, not higher in the pond compared to other locations, and showed no significant relationship to mangrove abundance. This could be explained by fresh water input due to heavy rainfall during the rainy season that had just ended. For now, restoration measures should focus on mitigating external pressures through habitat regeneration. Sediment trapping in and around watersheds and runoff areas connected to Lagun could decrease the sedimentation rate and prevent burial and floor elevation. Channel connection to Lagun could increase water circulation and might help to prevent a larger part of the pond from drying out during the dry season. Active planting can be combined with habitat restoration measures to increase survivability of mangrove seedlings. Besides restoration efforts, more research needs to be done on the existing pressures at Lagun, including Sargassum and trash inflow from the ocean, erosion rates, pond water and soil quality and the effect of the nearby landfill on mangroves. Documentation and monitoring of Lagun should be continued in order to obtain more information about the processes at hand. With sea levels rising due to climate change, it is crucial for Bonaire to have stable coastlines that can mitigate effects of storm surges, in which mangrove forests play an important role.

Introduction

Mangroves exist in subtropical and tropical intertidal systems and in many countries function as coastal protectors by stabilizing the soil and creating a barrier against waves and tsunamis (Alongi, 2002). Besides their protective ability, they provide a number of other ecosystem services like carbon storage, provision of nursery grounds for juvenile fish and pollutant filtering (Mitra, 2020). Their importance is increasingly receiving more recognition globally. Mangrove forests have however been under threat since before the 21st century due to anthropogenic pressure and climate change. A strong decline in mangrove cover and health is recorded in many countries, which threatens their ecosystem functioning (Richards & Friess, 2016). Protecting and restoring these habitats is important for many organisms such as ourselves and disappearance of mangrove forests could result in major climate hazards and a strong decrease in ecosystem functioning.

Siltation is often a cause of human interference disrupting natural sedimentation, and can affect mangroves negatively (Noor, 2015). When the sedimentation rate exceeds the erosion rate, it can disrupt seedling growth and cause the burial of pneumatophores in *Avicennia germinans* and eventually death (Ellison, 1999). In the *Rhizophora mangle,* respiration happens through lenticels, and the number of these cells decline with the height above the soil. For this reason, increased soil height can lead to a decline in respiration and can also cause higher mortality for this species. Increased siltation can also cause ponds adjacent to mangroves to become more shallow, which, in combination with high temperatures could lead to hypersaline environments and soil drought (Orihuela et al., 1991). During rainy seasons, high sediment deposition in combination with rain storms can cause high turbidity in ponds, creating anoxic environments.

Increased salinity has been reported to be a major issue as a cause of siltation in mangrove growth in many studies. The effect of increased salinity is known to cause internal drought, toxicity and nutrient imbalance. To compensate for high salt concentrations, mangroves try to maintain a favorable balance through conservative water use (Suárez & Medina, 2005). This leads to restricted growth and an increase in mortality. Pond evaporation causes salinization and creates especially harmful environments for surrounding vegetation, including mangroves (Cardoso-Mohedano, 2018). Another issue with high salinization is the reduction of propagule establishment, which occurs mostly in *Avicennia germinans* (black mangroves).

Temperature can greatly impact mangrove survival and growth as well. Mangroves are generally well-adapted to higher temperatures. Extremities in temperature however, can cause a number of problems, including deterioration and death of plant tissue, as well as enzyme denaturation (Krauss et al., 2008). Although mangroves show high tolerance to both increased salinity concentrations and temperatures, combined negative effects could increase mortality for these forests (Su et al., 2020).

This study will focus on mangrove forests on Bonaire, located in the Dutch Caribbean. Most of the mangrove forest is situated at Lac Bay, which together with seagrass meadows covers roughly 700 ha (Debrot et al., 2012). Lagun, a smaller bay also has a small areal of mangroves. In the past years, there has been a shift in mangrove cover area around Lac. Mangroves closer to the land-side were quickly dying due to the closing of water channels because of high sediment runoff. Together with high temperatures and increasing salinity in ponds in the mangrove forest, this resulted in high mortality (Van Zee, 2022). At Lagun, major decreases in mangroves have also been recorded, and the decrease is clearly evident between 2011 and 2014 (Appendix 1). From 2014 and on, the mangrove cover in the pond completely disappeared (Appendix 1c). Most of the degradation is located in the pond behind Lagun where *A.germinans* populate the area, but there is also some die-off at the canopy on the south side of Lagun, consisting mostly of *Rhizophora mangle*. Lagun experiences a majority of problems which could cause a decline in mangrove health. One of those issues is excessive runoff of sediment and nutrients from land (Van der Geest et al. 2020; Ouwersloot, 2020). The nutrients that are deposited through erosion cause a major influx, which could have a negative impact on the system.

Ouwersloot (2022) conducted a research on several bays on Bonaire, including Lagun, assessing issues through chemicals present in seagrass communities in these areas. However, the decline in mangrove forest at Lagun has not been closely examined yet. The presence of the pond together with the pattern of forest decline leads to belief that there are several issues concerning the abiotic variables in the pond. Because salinity, temperature and siltation have been reported issues for the decline at Lac Bay, it would be interesting to find out whether these problems are still a concern at Lagun, in order to create an accurate restoration plan (Debrot et al., 2010). The following research questions are proposed:

Is there a difference in tree abundance in different locations around Lagun?

Is there a difference in the effect of salinity, temperature and soil composition in different locations around Lagun?

How do salinity, temperature and soil composition influence the species composition and plot sites around Lagun?

What measures could be taken for mangrove restoration at Lagun?

I expect there to be a notable difference in tree abundance, with the pond having the lowest abundance compared to plots in areas on the south side of Lagun as well as plots on the barrier between Lagun and the pond. Conductivity (as a measure for salinity) is expected to be higher in the pond, as well as temperature due to high solar radiation and evaporation, which has a negative effect on mangrove growth and might be restrictors. I expect that soil composition will not have a big impact on mangrove growth, as the composition of sediment around the island does not differ that much. However, silt buildup might be an indication that establishment for seedlings is restricted for *A.geminans*, so seedling abundance might be lower in the pond due to silt. Lastly, I hypothesize that measures should be taken to re-open small channels to the pond behind Lagun to increase water circulation, which could help lowering temperatures and salinity. This combined with active planting could help restore the system.

Relevance

With sea level rise being recorded as a major issue resulting from climate change, it is important especially for small islands to have a steady coastline which can protect from storm surges and land erosion (GREENPEACE, 2022). Protecting mangrove forests on Bonaire is therefore highly important.

Additional research

During my internship with Mangrove Maniacs I performed a number of activities besides the research around Lagun. Most of these activities were based around continued monitoring projects from other students. One in particular was a monitoring project at Lac Bay, which I studied every week. However, these studies differed a bit too much to put together in one official report, which is why I added my findings and data for Lac bay in Appendix 2.

Method

Study site

Lagun is situated on the east coast of Bonaire (Fig. 1). It is a lagoon with an opening to the ocean. The landward current is strong in this area. Due to ocean currents, a lot of trash enters Lagun and stays behind after high tide or gets stuck between mangrove roots. During Sargassum season, a high amount of this algae drifts into the lagoon and clogs up the mangrove channels. Inside the lagoon, there is a small sandy shore with a mangrove canopy creating a barrier between Lagun and a pond situated behind the mangrove canopy. Lagun is surrounded by hills with dry vegetation, including shrubs and cactuses. The island can be sorted in several different erosion streams, of which two culminate in the pond of Lagun. Much sediment is therefore distributed there.

Fig. 1; Map of Bonaire. Yellow pin shows the location of the study site, Lagun.

The mangrove canopy around Lagun can be separated into two types; along the south edge of Lagun, the forest consists mostly of red mangroves (*Rhizophora mangle*), and a few white mangroves (*Laguncularia racemosa*) (Fig. 2). The canopy on the division between Lagun and the pond consists mostly of black mangroves (*Avicennia germinans*). This area is also covered by a salicornia species: *Sarcocornia perennis*.

Fig. 2; Close up shot of Lagun showing the pond, the division canopy (red polygon), and the south side canopy (blue polygon).

Due to a major decrease in mangrove forest, there is a lot of dead mangrove material in the pond, as well as in channels in the division between the pond and Lagun. Mangrove Maniacs recently opened up a few of these closed up channels by removing the dead material. They also opened up a channel which connects to the pond. The dead matter on the south side of Lagun was not removed.

Plot selection

20 plots of 5 by 5 meters were selected in areas around Lagun where mangroves were either present or degraded. The plots are stratified randomly dispersed, with several plots in fully degraded areas (Fig. 3). Five different location types were identified: “Channel Adjacent”, “Lagun Adjacent”, “Land”, “Pond”, “Pond Adjacent”, in which the plots were divided (Table 1). “Adjacent” in this case meant that plots were situated right at the edge of either the pond, a channel or Lagun. The selection of the plots was done before field observations according to satellite imagery, and were later specified when actual observations started (locations could differ slightly due to accessibility). The plots were placed around as many different areas as possible to create an accurate image of the study site. Plots were only chosen in areas where mangrove cover is present, or was present in the past. Coordinates of the plots were mapped on ‘GPS Tracks’, a mobile phone app, later coordinates were copied into Google Earth Pro. A materials list for plot analysis and soil analysis can be found in **Appendix ..**

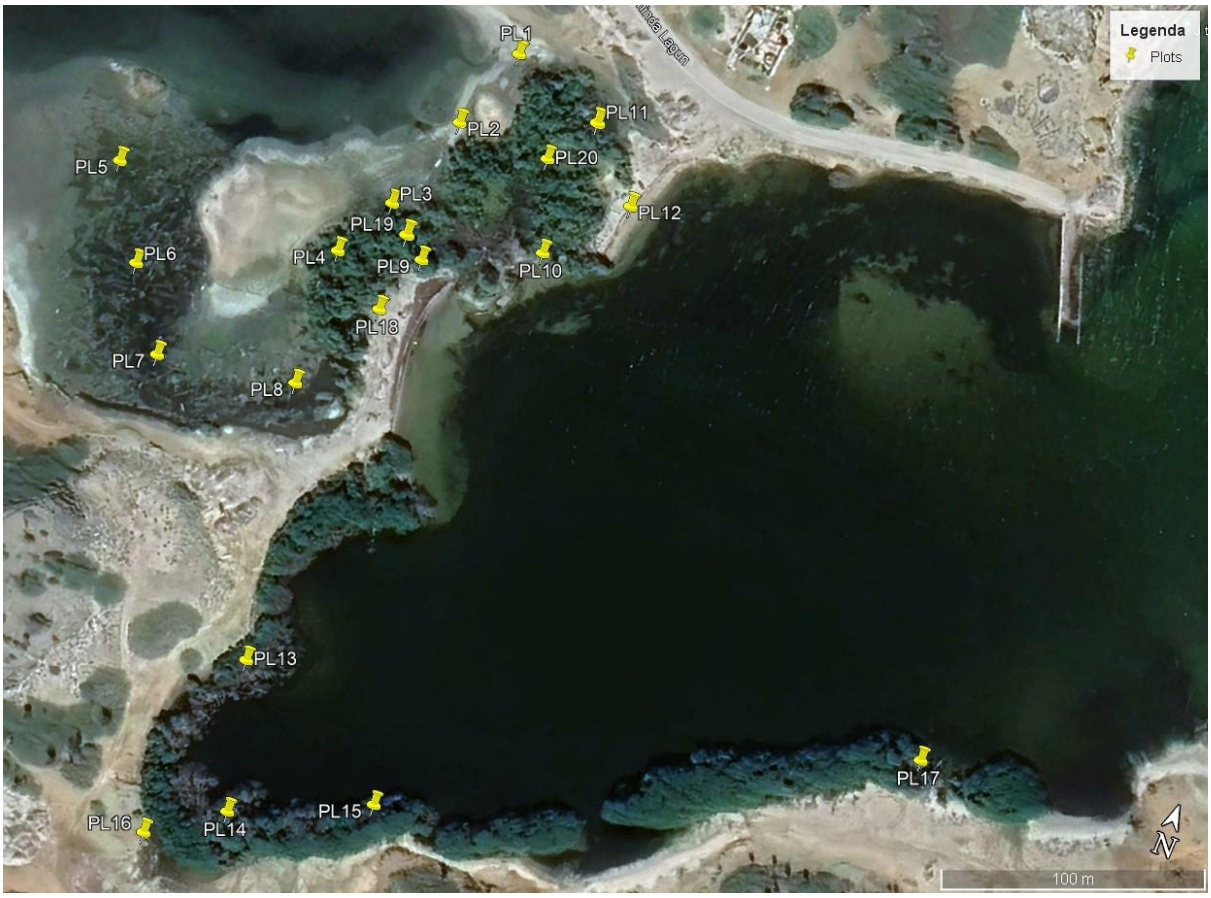


Fig. 3; Map of Lagun showing the plot locations (Google Earth Pro)

Plot	**Location**
PL01	Pond Adjacent
PL02	Pond Adjacent
PL03	Pond Adjacent
PL04	Pond Adjacent
PL05	Pond
PL06	Pond
PL07	Pond
PL08	Pond
PL09	Channel Adjacent
PL10	Channel Adjacent
PL11	Pond Adjacent
PL12	Land
PL13	Lagun Adjacent
PL14	Lagun Adjacent
PL15	Lagun Adjacent

PL16	Land
PL17	Lagun Adjacent
PL18	Land
PL19	Channel Adjacent
PL20	Land

Table 1. Location type per plot

Plot analysis

Plots were analyzed by two people (myself and Dedrie), except for three plots (PL8, 9 and 10). In order to carefully conduct the plot analysis, four poles were used as corner points, to which 5m of rope was attached to create a square (Fig. 4). For every plot, the following was noted:

- Name of plot
- Date of measure
- Who did measurements
- Number and species of adult trees (>1m; Braun-Blanquet score)
- Number and species of seedlings (<1m; Braun-Blanquet score)
- Average height of seedlings (cm)
- Salicornia cover (Braun-Blanquet score)
- Dead material cover (%)
- Vegetation presence (%)
- Trash cover (%)
- Herbivory (eaten leaves; none, some, much, very much)
- Other notes

Fig. 4; Several examples of plot set ups around Lagun (Photo shot by Saar)

Height of seedlings was calculated by measuring the maximum and minimum height of the seedlings, and estimating the average height of all the seedling heights in the plot.

Percentage of trash, dead matter and vegetation presence were estimated by imagenitively separating the plot in smaller parts to reconstruct the actual covered area. Herbivory was evaluated by analyzing the leaves of the trees inside the plot. If almost every leaf was eaten, it would be scored with 'Much', if only a few trees had eaten leaves, or if it was only a couple of leaves per tree, it would be scored with 'Some', and if (almost) no leaves showed herbivory, 'None' would be written down.

First the number and species of adult trees would be counted, carefully measuring if smaller trees were higher than 1 meter, and following trunks to see whether several trunks led to one tree. Afterwards, silt, salicornia, trash, dead material and vegetation presence were analyzed by walking around the plot. Lastly, the number, species and height of seedlings was measured. The cover of adult trees, Salicornia and seedlings was estimated using the Braun-Blanquet method. Afterwards, the code assigned to the plot coverage was converted to mean coverage using a conversion table (Fig. 5)

Class	**Cover (%)**	**Cover mean (%)**

r	<0.1	0.05
+a	0.1 - 0.5	0.3
+b	0.6 - 1	0.8
1a	1.1 - 3	2
1b	3.1 - 5	4
2a	6 - 15	10
2b	16 - 25	20
3	26 - 50	37.5
4	51 - 75	62.5
5	>75	87.5

Fig. 5 Braun-Blanquet scoring table

Soil samples

Soil samples were made using a shovel to dig up 20 centimeters of the top layer in three different areas in each plot. Soil per plot was mixed in a plastic bag to create a homogenous mixture.

Jar test

For every plot, the jar test was performed. One third of a glass jar was filled with soil, and two thirds with water. The jar was then shaken until the soil and water were stirred in a homogenous mix. Afterwards, the different layers of soil were measured. The height of the sand layer was written down after one minute, the height of the silt after two hours, and the clay layer after 1-2 days. The total height of the soil within the jar was also measured. Percentage of the different soil types were calculated:

% Sand = (sand height) / (total soil height)
% Silt = (silt height) - (sand height) / (total soil height)
% Clay = 1 - %Sand - %Silt

Conductivity and temperature

Soil samples were sieved by hand to create smaller pieces and take out big pieces such as leaves, rocks and smaller animals (crabs and worms). Every sample contained ⅕ soil and ⅘ demineralised water. The mixture was then put aside to let the substrate sink. After settling, a TDS & EC meter(hold) was used to measure conductivity (µs/cm) by putting the meter into the water of each sample. Temperature of the soil was also measured with this instrument, however these measurements were taken in the field by sticking the meter into the soil at the plot sites. The measurement was read and noted after a few seconds.

Statistical analysis

To answer the sub questions several statistical tests were used and corresponding assumptions were tested in the program R (using Rstudio), version 4.2.2. Used packages are: ggplot2, vegan, dplyr, hrbrthemes, tidyverse, SparseM, labdsv, mgcv, nlme, car and GridExtra. Raw data can be found here.

Is there a difference in tree abundance (adult and seedling) for the different location types?
Kruskal-Wallis tests were performed to test whether the abundance of adult trees and seedlings differed for different location types. Assumptions were tested with a residual and a normal Q-Q plot (Appendix 4A & B). A Shapiro-Wilk's test was used to test normality, a levene's test for homogeneity of the variances and a function in R to check for outliers. When the test resulted in a significant difference ($P<0.05$), a Dunn's test for pairwise comparisons was carried out.

Is there a difference in temperature, conductivity, sand layer, silt layer for the different location types?
To answer this question, Kruskal-Wallis tests were performed to test whether temperature, conductivity and silt layer showed significant difference for different location types. The assumptions were tested with a residual and a normal Q-Q plot (Appendix 4C, E, F). A Shapiro-Wilk's test was used to test normality and a levene's test for homogeneity of the variances. Boxplots were created and a function in R was used to check for outliers. For every variable showing a significant difference ($P<0.05$), a Dunn's test for pairwise comparisons was used. For sand layer, a one-way ANOVA was carried out together with a Tukey-Kramer test for pairwise comparisons. Assumptions were checked the same way as the other variables (Appendix 4D).

Do abiotic variables (conductivity, temperature, sand layer and silt layer) have an effect on vegetation abundance?
Generalized linear regression was used to test whether there is a relation between each abiotic variable and the adult tree abundance, as well as the seedling abundance. Assumptions for generalized linear regression were tested using a normal Q-Q plot (Appendix 4G-N). Homogeneity was tested with levene's test. A Detrended Correspondence Analysis (DCA) with environmental fit was also performed to analyze how the plots were influenced by the abiotic factors.

Results

Difference in species abundance (adult or seedling) for the different location types

According to the data the species abundance (divided in adult trees and seedling abundance) is different for the different location types (Fig. 6).

Adult tree abundance
The mean adult tree abundance per location in cover means (%) is shown in Table 2. Land has the highest mean tree abundance compared to the other locations (M = 10.1, SD = 6.25). Pond and Pond Adjacent had the lowest tree abundance (M = 0.15, SD = 6.26; M = 0.28, SD = 5.98). The means in adult tree abundances per location were not significantly different [Chi squared = 6.33, p = .17, df = 4].

Location	Mean (cover means, %)
Channel Adjacent	1.03
Lagun Adjacent	0.162
Land	10.1
Pond	0.15
Pond Adjacent	0.28

Table 2. Mean tree abundance per location type

Seedling abundance
The mean seedling abundance per location in cover means (%) is shown in Table 3. Data was transformed on a log scale to increase normality. Land had the highest mean for seedling abundance (M = 28, SD = 11.2) and Lagun Adjacent the lowest (M = .512, SD = 11.2). The differences in seedling abundance per location was significant for the transformed data [Chi squared = 6.33, p = .17, df = 4)].

Pairwise comparisons using Dunn's test indicated that mean seedling abundance for the transformed data of Lagun Adjacent (M = .512, SD = 11.2) were observed to be significantly different from those of Land (M = 10.1, SD = 11.23 ; p = .005). Lagun Adjacent and Pond Adjacent (M = .28, SD = 10.74) also differed significantly in seedling abundance (p = .034), and Pond (M = .15, SD = 11.23) also differed significantly from Land (p = 0.09).

Location	Mean (cover means, %)
Channel Adjacent	14.1
Lagun Adjacent	0.512
Land	28
Pond	3.7
Pond Adjacent	6.96

Table 3. Mean seedling abundance per location type

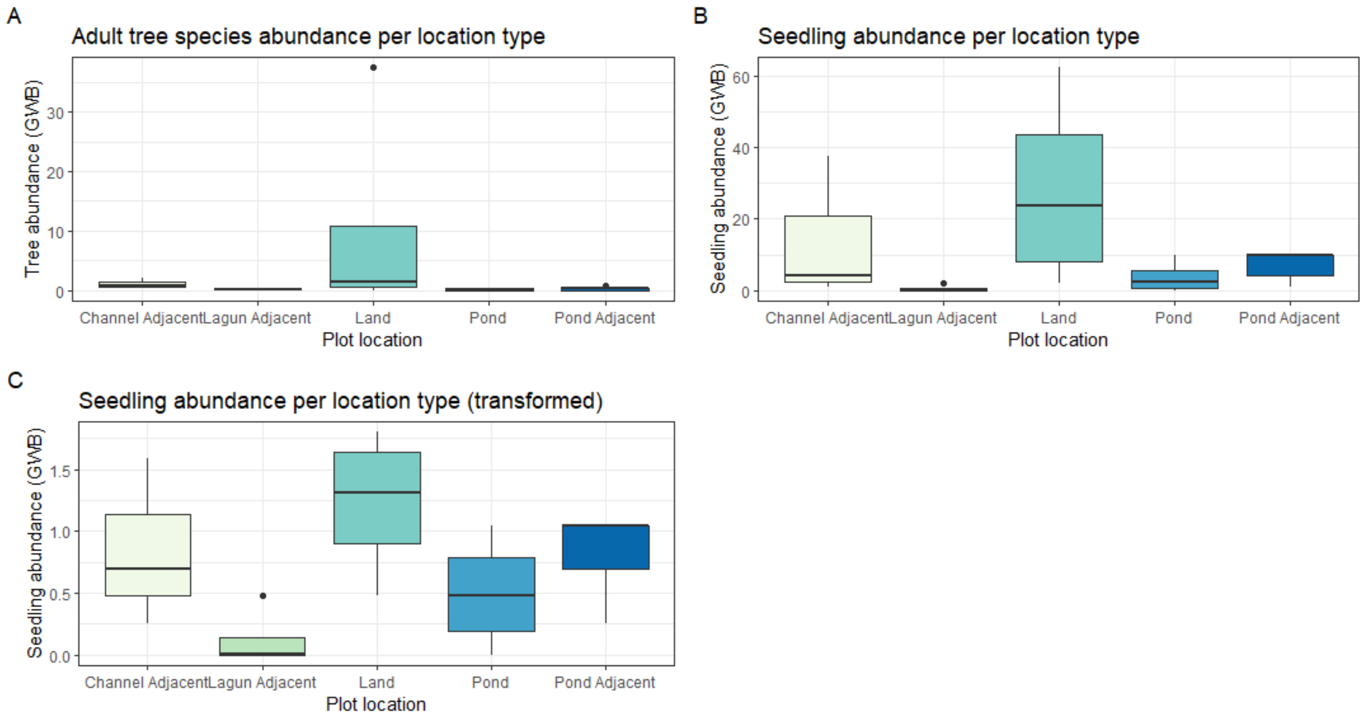


Fig. 6; Adult tree abundance, seedling abundance and seedling abundance (transformed data) shown for different location types. A shows the adult tree abundance (GWB) per location type, B the seedling abundance (GWB) per location type and C the transformed data of seedlings abundance per location type.

Difference in abiotic variables for the different location types

According to the data, conductivity, temperature, silt layer and sand layer are different for the different location types (Fig. 7).

Silt

The mean fraction of silt for every location type is shown in Table 4. Pond and Pond Adjacent showed the highest mean silt layer (M = .766, SD = .16; M = .799, SD = 0.15). Differences in silt layer were significant [Chi squared = 14.34, p = .006, df = 4].

According to pairwise comparisons using Dunn's test, the mean silt layer of Lagun Adjacent (M = .069, SD = .15) was observed to be significantly different from that of Pond (M = .766, SD = .16 ; p = .003) and of Pond Adjacent (M = .766, SD = .16; p = .001). Land (M = .326, SD = .15) was observed to significantly differ in mean silt layer from Pond (p = .045) and Pond Adjacent (p = .028).

Location	**Mean (fraction)**
Channel Adjacent	0.425
Lagun Adjacent	0.069
Land	0.326

Pond	0.766
Pond Adjacent	0.799

Table 4. Mean fraction of silt layer per location type

Sand

The mean fraction of sand per location is shown in Table 5. Lagun Adjacent had the highest mean sand layer (M = 0.930, SD = .15), and Pond Adjacent had the lowest (M = 0.258, SD = .14). Differences in the fraction of sand layer between locations was found to be significant [F(4,15) = 8.22, p = .001].

A post hoc Tukey test found that the difference between Pond (M = .356, SD = .15) and Lagun Adjacent (M = 0.930, SD = .15) was significant (p = .006). There was also a significant difference between Pond Adjacent ((M = 0.258, SD = .14) and Lagun Adjacent (p = .0009) and Land (M = .694, SD = .15; p = .03).

Location	**Mean (fraction)**
Channel Adjacent	0.574
Lagun Adjacent	0.930
Land	0.694
Pond	0.356
Pond Adjacent	0.258

Table 5. Mean fraction of sand layer per location type

Conductivity

The mean conductivity (μs/cm) for every location is shown in Table 6. Land had the highest mean conductivity (M = 7430, SD = 1231.8) and Lagun Adjacent the lowest (M = 3742, SD = 1231.8). Differences in conductivity between locations was significant [Chi squared = 11.826, p = .018, df = 4].

Pairwise Dunn comparisons showed a significant difference between Lagun Adjacent (M = 3742, SD = 1231.8) and Land (M = 7430, SD = 1231.8; p = .002). Conductivity for Lagun Adjacent was also significantly different from Pond (M = 6592, SD = 1231.8; p = .023), and Land showed a significant difference from Pond Adjacent (M = 4460, SD = 1177.8; p = .016).

Location	**Mean (μs/cm)**
Channel Adjacent	5754
Lagun Adjacent	3742
Land	7430

Pond	6592
Pond Adjacent	4460

Table 6. Mean soil conductivity per location type

Temperature

The mean temperature for every location type is shown in Table 7. Pond Adjacent had the lowest mean temperature ($M = 27.2$, $SD = 0.62$), and Lagun Adjacent the highest ($M = 30.8$, $SD = 0.65$). Differences in mean temperature for every location were found to be significant [Chi squared = 13.63, $p = .008$, $df = 4$].

According to pairwise comparisons using Dunn's test, Lagun Adjacent ($M = 30.8$, $SD = 0.65$) differed significantly in mean temperature from Pond ($M = 27.4$, $SD = .65$; $p = .005$) and Pond Adjacent ($M = 27.2$, $SD = 0.62$; $p = .001$). Pond Adjacent also showed a significant difference compared to Land ($M = 29.5$, $SD = .65$; $p = .04$).

Location	**Mean (°C)**
Channel Adjacent	29.8
Lagun Adjacent	30.8
Land	29.5
Pond	27.4
Pond Adjacent	27.2

Table 7. Mean soil temperature per location type

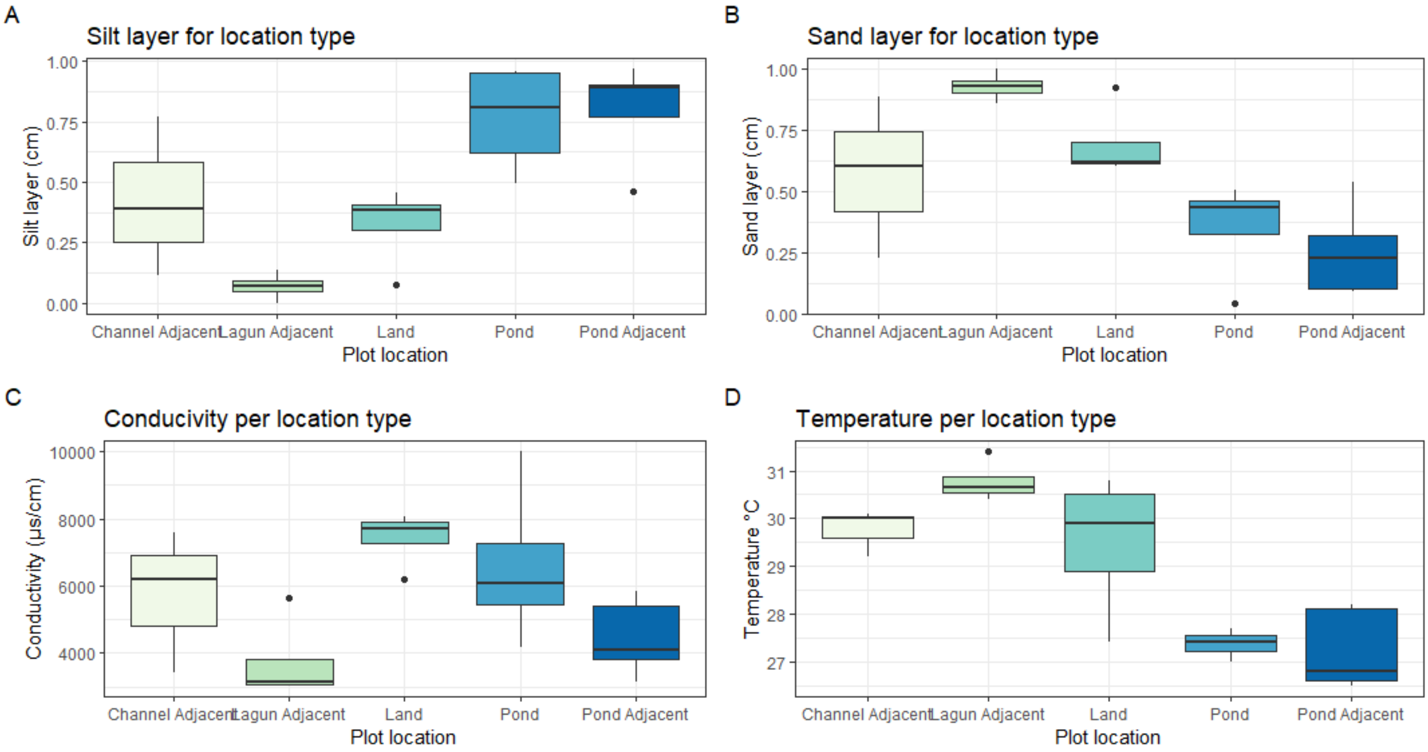


Fig. 7; Mean Silt layer, Sand layer, Conductivity and Temperature for different plot locations. A shows the silt layer (cm) per location type, B the sand layer (cm) per location type, C the conductivity (µs/cm) per location type and D the temperature (°C) per location type.

Effect of abiotic variables on tree abundance (adult or seedling)

Generalized linear regression models were used to analyze the interaction between species abundance (adult and seedling) and abiotic variables (Fig. 8 & 9)

Seedlings

The generalized linear regression for silt layer and seedling abundance was not significant, but shows a slight negative trend [GLM, $t = -.81$, $p = .42$]. For the sand layer and seedling abundance there was also no significance found, but a positive trend is noticeable [GLM, $t = .93$, $p = .36$].

For conductivity and seedling abundance , there was no significance found with the generalized linear regression [GLM, $t = 1.34$, $p = .19$]. Temperature and seedling abundance also did not show significant results [GLM, $t = -.39$, $p = .70$]. Conductivity and seedling abundance showed a positive trend, and temperature and seedling abundance showed a negative trend.

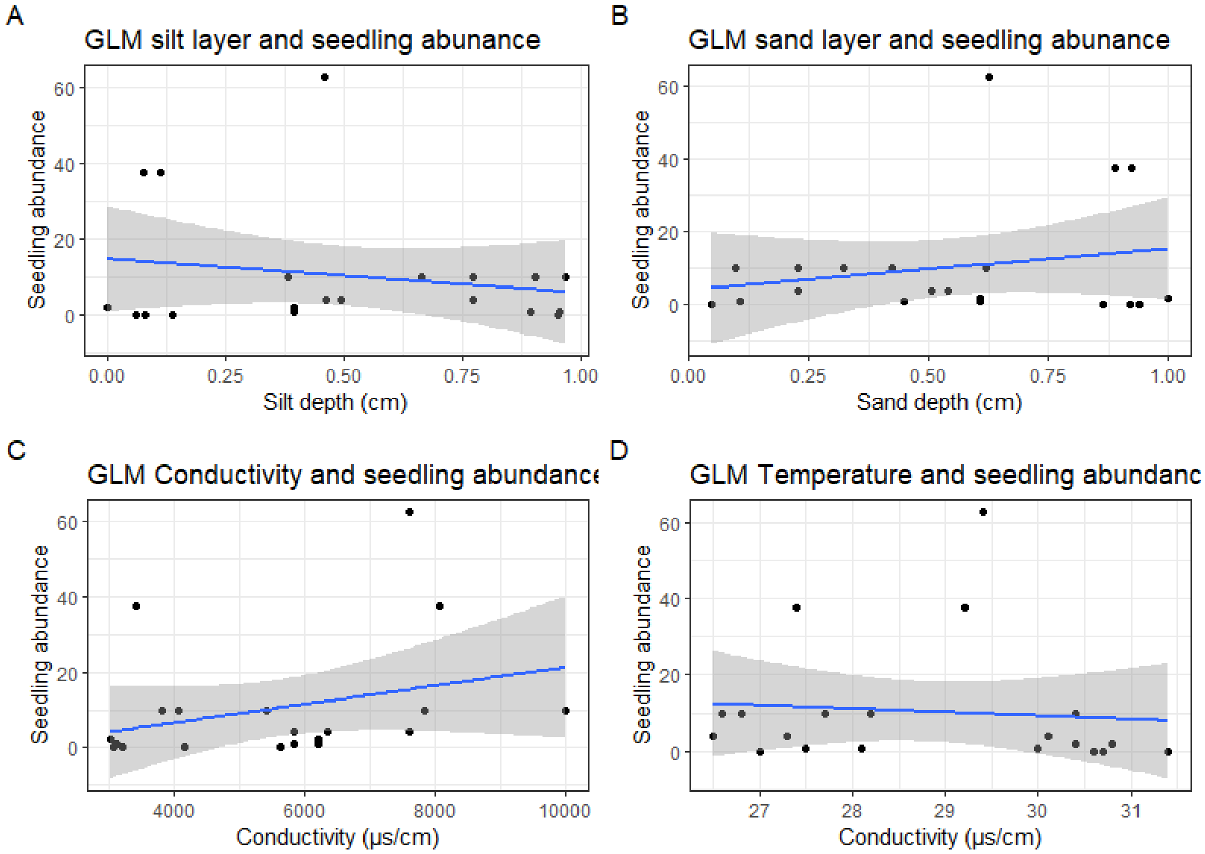


Fig. 8; GLM seedling abundance vs abiotic variables (silt layer, sand layer, conductivity and temperature). A shows the regression for silt layer (cm) and seedling abundance (GWB), B the regression for sand layer (cm) and seedling abundance (GWB), C the regression for conductivity (µs/cm) and seedling abundance (GWB) and D the regression for temperature (°C) and seedling abundance (GWB).

Adults

The generalized linear regression model showed no significant interaction between adult tree abundance and silt layer [GLM, t = -.24, p = .81], as well as adult tree abundance and sand layer [GLM, t = .38, p = .70]. A negative trend in interaction is observed for silt layer and adult abundance, and a positive trend for sand layer and adult abundance.

For conductivity and adult tree abundance, the generalized linear model showed a positive trend, however this result was not significant [GLM, t = 1.11, p = .28]. Temperature and adult tree abundance also displayed a positive interaction, but was also insignificant [GLM, t = .34, p = .733].

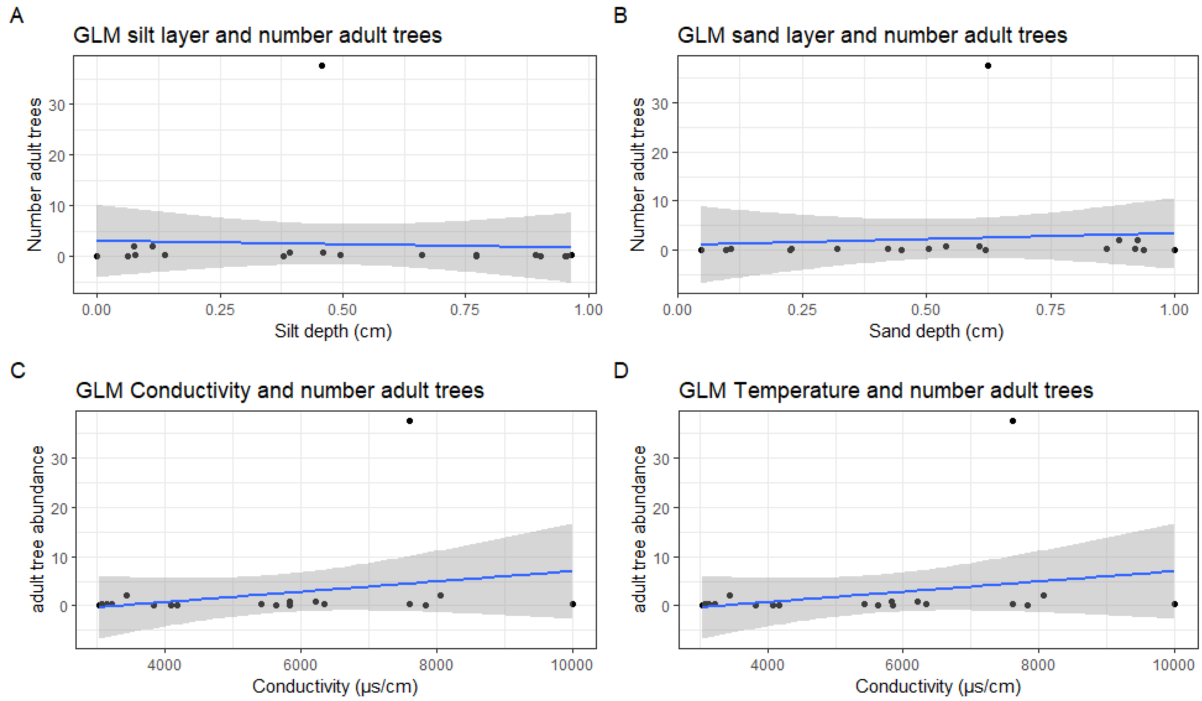


Fig. 9; GLM adult tree abundance vs abiotic variables (silt layer, sand layer, conductivity and temperature). A shows the regression for silt layer (cm) and adult tree abundance (GWB), B the regression for sand layer (cm) and adult tree abundance (GWB), C the regression for conductivity (µs/cm) and adult tree abundance (GWB) and D the regression for temperature (°C) and adult tree (GWB).

Effect of abiotic variables on species composition and plots

To study the significance of the association between abiotic variables, species composition and plot location, a Detrended Correspondence Analysis (DCA) with environmental fit was carried out (Fig. 10). Note that PL05 was not considered in this analysis due to lack of vegetation in the plot.

The output of the DCA shows four axes (DCA1, DCA2, DCA3. DCA4). The Eigenvalue of DCA1 is 1.00, and the Eigenvalue of DCA2 is .30. The first axis seems to explain the difference between Lagun Adjacent plots and all other locations. PL13 - PL17 are the only plots where *R. mangle* was found. The second seems to explain the difference between Pond Adjacent, Land, Channel Adjacent and Pond.

Environmental factors (silt layer, sand layer, temperature and conductivity) are shown in the DCA plot with blue arrows. The direction of the arrows in combination with the plots shows association between environmental factors and plots. High conductivity seems to be associated with plots at Pond locations, and low associated with most Pond Adjacent plots except for PL01 and PL02. Silt layer seems to have an association with most Pond Adjacent plots, and temperature with Lagun Adjacent plots.

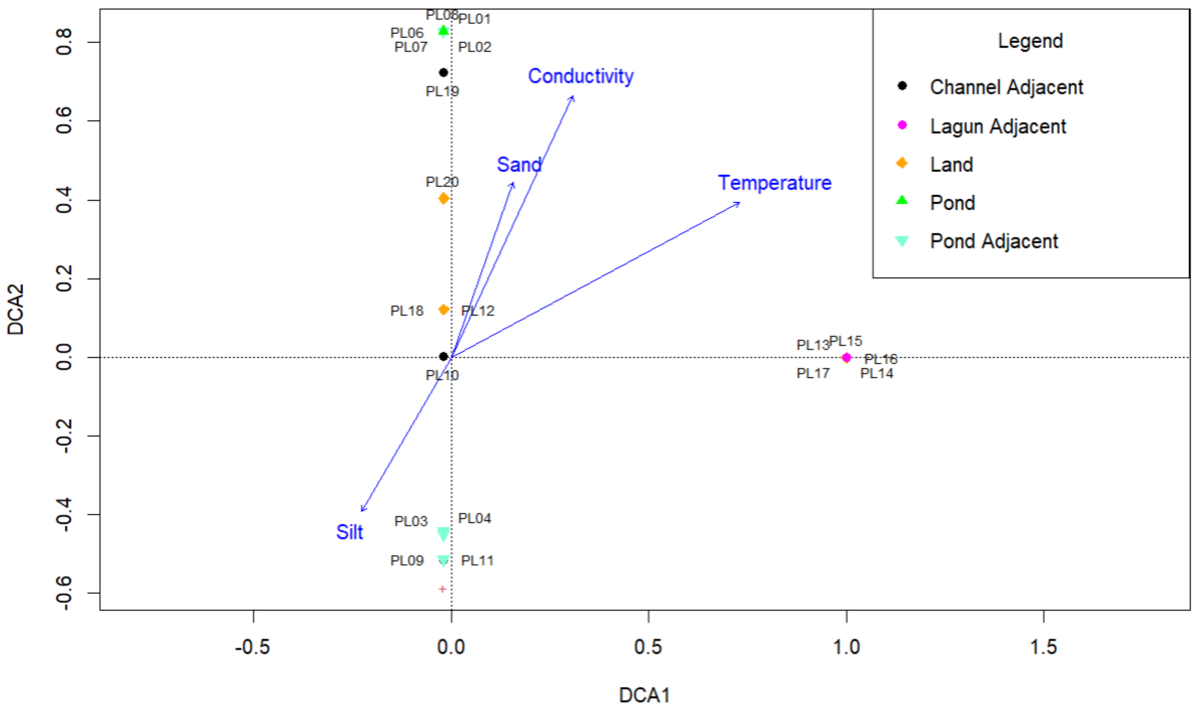


Fig. 10; Detrended Correspondence ordination with environmental fit for different types of plots. The different plot types (Channel Adjacent, Lagun Adjacent, Land, Pond and Pond Adjacent) and their relation to each other is shown. The environmental factors (sand layer, silt layer, conductivity and temperature) are displayed as arrows. The first axis shows the difference between Lagun Adjacent and all other plot locations, and the second axis shows the difference between Pond, Pond Adjacent, Land and Channel Adjacent.

Discussion

Salinity and high temperatures in mangrove ponds caused by high sedimentation have been reported as contributing factors to mangrove degradation around Lac Bay, Bonaire (Van Zee, 2022). Increased salinity and temperature can cause internal drought, tissue-death and overall increased mortality (Cardoso-Mohedano, 2018; Krauss et al. 2008). Lagun, another bay on Bonaire, also experienced high mortality rates. However, lack of documentation makes it difficult to establish the cause of this degradation event. For this research, adult tree and seedling abundance, as well as temperature, conductivity (as measure for salinity) and sediment composition were measured for different locations around Lagun, with the prospect of finding out whether salinity and temperature have a negative effect on tree abundance in this area.

Tree abundance and location

Differences were found in the cover means of adult tree abundance and seedling abundance for the different location types. However, for adult tree abundance there were no significant results, contrary to my hypothesis. The adult tree density was, in all plots that did show mangrove growth (pond not considered) not very high except for a few that only had adult trees just over one meter in height (PL20), which counted as adult trees according to protocol. In PL13-PL17, it was difficult to establish the actual number of trees, because these areas consisted mostly of *R.mangle* with extensive root formation. Tree abundance might therefore not be an optimal indicator for the health of a mangrove system. It might be better to study root formation and density. According to Alongi (2014), root formation is an advantageous investment for mangrove trees because it allows for more water uptake. Therefore, high root density can indicate a healthy system.

For seedling abundance there was a significant difference between Pond and Land sites, which could have something to do with a difference in soil composition for these locations. The high seedling abundance for Land plots can be explained by PL20 and PL16, which both almost solely consisted of seedlings (and PL20 of small adult trees as well). While species differed between these two, they showed similarity in soil composition, sun exposure and crab abundance. PL20 consists solely of *A.germinans*, which have seedlings that cannot establish themselves in flooded soil (Elster et al. 1999). The abundance of *A.germinans* on land plots (which is the species present in PL1-PL12 and PL18-PL20), can therefore be explained. Seedling abundance of *A.germinans* in Pond plots was highest closer to the reopened channel, most of them found close to new adult trees, or anchored to dead material. Peterson & Bell (2012) studied salt marsh structures' influence on *A.germinans* recruitment, and found that entrapment through other plant species was an effective way for seedlings to establish due to their smaller size. This could explain the presence of *Sarcocornia perennis* in the majority of plots also containing *A.germinans*.

During the weeks of research, it was notable that the water level of the pond increasingly dropped during low tide, causing major drying out of the soil. PL1-3 were situated at the edge of the pond water during the first measurements, but during low tide the soil started to dry out in those plots. Because the rainy season has just ended, it is expected that these plots will fall dry in the coming months. It is unclear whether the pond has become more shallow over the years due to lack of documentation. According to Elster et al. (1999), drying out of the top soil layer is a big risk for seedling growth, especially for *A.germinans*.

Abiotic variables, tree abundance and location

Land sites had a significantly smaller silt layer compared to Pond sites and Pond Adjacent sites. There was also a significant difference between Lagun Adjacent and Pond and Pond Adjacent. Silt buildup in the pond can be explained by runoff of sediment from the land. Van der Geest et al. (2020) mapped out watersheds, water flows and runoff areas for Bonaire which showed two runoff watersheds ending in Lagun, which could result in more silt buildup in this area (N. Roos, 2018). The relationship between seedling abundance and silt layer shows a negative trend, but it was not significant (Fig. 8a). Ellison (1999) reported several examples of mortality events caused by high siltation rates of mangroves around the Caribbean Sea with the same species. A major issue is root burial, which is described in her research as a cause for high mortality in *A.germinans*. The pond, according to Mangrove Maniacs, was also mostly populated with this species, and root burial could therefore have been the cause of the high mortality. It is important to find out whether the siltation rate is still high in the pond, as well as in other areas around Lagun to establish whether new trees would be able to survive.

Lagun Adjacent had the lowest conductivity compared to other locations, and Land the highest. Pond also showed a relatively high conductivity, but, contrary to my hypothesis, it was not significantly higher than other locations. Figure 11 shows a table containing average conductivity ranges and their assigned salinity. When converting the conductivity means of the data to fit the table (EC_e range), all locations are categorized as moderately saline, except for Lagun Adjacent, which is categorized as slightly saline. The equipment used for measurements might have contributed to issues as it was a relatively simple pocket meter and due to lack of data it is difficult to establish if these measurements are accurate.

However, considering the effect of runoff water and rainfall on soil salinity could still be explanatory factors for Lagun. Ouwersloot (2022) conducted an extended research on seagrasses as bioindicators for eutrophication and pollution in several bays of Bonaire, including Lagun. Results showed that Lagun was the most eutrophied, with high %N and %P found in seagrass tissues, which could be explained by terrestrial run-off of sediments. Less saline conditions in the pond and surrounding mangrove canopy could indicate high runoff of fresh and rain water from two areas adjacent to Lagun (Van der Geest et al. 2020). Jarecki & Walkey (2006) mentioned that salinity in shallow saline ponds is heavily influenced by environmental changes, and patterns in weather can change salt concentrations through rainfall and evaporation. When this research started, the rainy season was just coming to an end in Bonaire. In the months prior, frequent rain storms were recorded, which could have influenced salt concentrations and growth rates at Lagun (Krauss et al. 2007). However, Jarecki & Walkey (2006) also mentioned that groundwater levels near ponds would stay relatively constant, and found a declining salt concentration with greater distances from ponds. This is in contrast with my results. The relationship between tree abundance and conductivity was insignificant. As there is no previous data on salinity for Lagun, it is advised to continue research on salinity concentrations of soil and water, with more accurate measuring equipment. On the results of this research alone no hard conclusions can be drawn about the effects of salinity on location types and tree abundance.

Salinity class	$EC_{1:5}$ range for sands (dS/m)	$EC_{1:5}$ range for loams (dS/m)	$EC_{1:5}$ range for clays (dS/m)	EC_e range (dS/m)
Non-saline	0–0.14	0–0.18	0–0.25	0–2
Slightly saline	0.15–0.28	0.19–0.36	0.26–0.50	2–4
Moderately saline	0.29–0.57	0.37–0.72	0.51–1.00	4–8
Highly saline	0.58–1.14	0.73–1.45	1.01–2.00	8–16
Severely saline	1.15–2.28	1.46–2.90	2.01–4.00	16–32
Extremely saline	>2.28	>2.90	>4.00	>32

Fig. 11; Salinity (ppm) ranges for different soil types (Agriculture and Food, 2022)

Temperature of the pond was not higher compared to other locations contrary to the expectations, and the relationship between temperature and tree abundance was not significant. Pond temperatures were even the lowest compared to the other locations. This could, as mentioned above, be because of excessive rainfall and freshwater runoff (Jarecki & Walkey 2006). For seedling abundance, it did show a slight negative trend, which is also described by Alongi (2022), who mentioned that drastically increased temperatures could result in restricted secondary growth and tissue death. Again, the possibility for inaccurate measurements (temperature was also measured with the TDS&EC meter) is not unlikely. The meter could only be placed in the top layer of the soil, which is the most influenced by the sun, and therefore not an accurate prediction for the actual soil temperature in which mangroves grow. More measurements should be conducted with better equipment to base any conclusions on the difference in temperature at different locations.

Species composition and location

From the DCA results, there is a clear distinction notable between plots containing red and black mangroves. There was a significant difference for Lagun Adjacent plots in sand and silt layer thickness compared to the other locations, which were more populated with black mangroves. Ellison (1999) mentioned that there is a difference in tolerance of siltation for different mangrove species. Research on the difference between *A.germinans* and *R.mangle* in their tolerance for siltation could aid in specifying restoration measures for areas where they occur.

Shortcomings

A major problem for Lagun is the lack of documentation. There is no data from before the degradation on mangrove health, cover, soil temperature, soil salinity or soil composition, making it difficult to establish the actual causes of degradation and mortality. While habitat regeneration seems to be the most logical solution at this time, there is no data on pressures and their effect on the mangrove forest at Lagun. Continued monitoring and documentation is necessary to create a more detailed picture of the issues at Lagun. An intensive study on soil quality, also factoring in nutrient availability is necessary to find out in which areas the system is disturbed.

As mentioned there were some issues with the measuring equipment. The initial plan was to do all measurements with a HANNAH instrument, but due to absence of calibration fluid, measurements were not accurate. A TDS&EC meter was the solution, but this meant that some variables (like pH) could not be measured, and that measurements might be inaccurate.

Restoration measures

There are many different factors currently pressuring the system, which restricts it from rehabilitating. It is therefore important to first facilitate habitat rehabilitation in order to create a more optimal habitat (Van Bijsterveldt et al. 2022). One option to consider is the implementation of a technique called "pond reversion". It is mostly used to revert abandoned culture ponds back to mangrove areas, but the technique is applicable here (Primavera et al. 2004). With pond reversion, it is important to establish the issues that are preventing natural regeneration of mangrove forest, and to understand the hydrology and ecology for a specific site. Re-opening channels (which Mangrove Maniacs has already started implementing at Lagun), can help in increasing tidal exchange, which can mitigate stressors such as high salinity and temperatures (Van Loon et al. 2016; Van Zee, 2022). Establishment of seedlings in the pond was mostly based close to the reopened channel, which leads to belief that reopening of channels could allow for more recruitment. Brown et al. (2014) used relatively the same techniques (which consisted of the usage of hand-tools, breaking through dyke walls and re-opening channels), showed great success in restoring natural recruitment and growth.

Another stressor that needs to be addressed is the high siltation rate. By decreasing sediment inflow from uplands, siltation rates could decrease (Mekonnen et al. 2015). Sediment traps have been considered as an effective measurement for soil conservation (i.e. decreasing siltation in lowlands and wetlands), and are already implemented in some areas on Bonaire (Koster, 2013). However, maintenance of these traps is often lacking, which causes a decrease in their quality (Wösten, 2013). Another way to enhance soil conservation is by restoring vegetation in upstream areas. Vegetation has the ability to increase drainage and also functions as a natural sediment trapper. With this measure, it is also important to decrease grazing pressures from goats and donkeys (Wösten, 2013). This could be done with fencing for example. Decreasing siltation could help in restoring natural pond conditions which could be more favorable for mangrove establishment and growth.

Van Bijsterveldt et al. (2022) mentioned that habitat restoration combined with planting could increase the success of restoration efforts. *A.germinans* seedlings have more difficulty establishing in flooded areas because of their smaller size (Elster et al. 1999). Recruitment in the pond might therefore be an obstacle. Active planting of nursed seedlings once hydrology measures are initiated could have a positive effect on the rehabilitation of the mangrove cover. Ellison et al. 1999 mentioned that mangrove species are adapted to certain elevation levels, and that increased elevation caused by high sedimentation rates could make that area unsuitable for that species. Surveys analyzing the elevation of the pond, other locations around Lagun and healthy areas around Lac as comparison could give a more clear image as to where planting activities should be initiated for a high success rate.

Sargassum blooms started during the course of this research, and have caused issues in the past years for both Lac and Lagun (Ouwersloot, 2022). In 2010, the first encounter of Sargassum was reported at Lagun (Bonaire.nu, 2020; Franks et al., 2011). Sargassum is an algae that periodically washes up on shore due to climate change in the Caribbean. In high amounts, Sargassum clogs up beaches, channels and ponds (Chavez et al., 2020) When the algae starts to dry and rot, it creates toxic and anoxic environments which lead to high mortality rates in both mangroves and organisms associated with mangroves. Booms were supposed to be placed before the Sargassum season would start, but authorities failed to do so at Lagun, causing a major influx of Sargassum to already wash up on shore. Previously reopened channels were clogged up within a week, disrupting water circulation (Fig. 12). The booms have since been placed and cleaning efforts are put in place, mitigating the effects. It is important to protect the mangroves at Lagun from Sargassum, because of its negative effects on the systems' health (Dutch Caribbean Nature Alliance, 2019). However, since it is a problem with international causes, it is difficult to find a short-term solution. For now, the most important thing is for Mangrove Maniacs and local authorities to facilitate protection.

Fig. 12; Clogged up channels at Lagun due to Sargassum (Photo shot by Saar, 22-02-23)

There are many issues to consider at Lagun, including runoff of chemicals from the nearby landfill, washing up of trash from the ocean and the effect of grazing from donkeys and goats in the area, which I have not widely elaborated in this report (Ouwersloot, 2022). However, these issues do affect Lagun, and their relationship to mangrove health should be considered and further studied. For now, it is most important to study the quality of the pond and document changes to its quality, as well as implement efforts that stimulate habitat restoration. According to IPCC, water levels are supposed to rise faster around Bonaire and neighboring islands compared to other low-lying islands around the world (GREENPEACE, 2022). It is therefore of the utmost importance to take action in protecting the coast. Conservation and restoration of mangrove forests could be an important factor in coastal protection and prevent major flood and storm hazards in the future.

Conclusion

Hypersalinity, burial and high temperatures caused by increased siltation rates have been known issues leading to mangrove mortality around Lac Bay, Bonaire. Degradation around Lagun was analyzed to find out whether the same matters were present here. Through a vegetation and soil analysis the conditions of tree abundance, soil salinity, soil temperature and soil composition were established for different location types around Lagun (Land, Lagun Adjacent, Channel Adjacent, Pond and Pond Adjacent). Differences in tree and seedling abundance were found between these locations, but were only significant for seedlings, showing high abundance in Land plots compared to Pond plots. There was a negative trend found for seedling abundance and silt layer thickness, which could be an explanation for the low abundance of seedlings in the pond. There were significant differences found in conductivity and temperature for different locations, however, they contradicted the hypothesis that these values would be higher in the pond. An explanation could be excess runoff water from the rainy season, or inaccurate measurement equipment. Restoration measures around Lagun should focus on habitat regeneration first, to decrease stressors that pressure the system and prohibit natural recruitment. Reopening channels is one measure which was already initiated, but could be further explored for Lagun. It could help increase water circulation in the pond, which could lead to more favorable conditions for mangrove recruitment. Sediment trapping could decrease the siltation rate in the pond. Active planting can be paired with habitat restoration where needed, but an analysis should be conducted to find out what areas are optimal for planting. Besides efforts to reduce stressors around Lagun, it is important that more research is done on soil quality in the pond, and chemical compositions in adjacent mangroves. Furthermore, research about other issues, such as Sargassum, erosion, the effect of grazing and the landfill could create a more detailed picture for restoration measures needed at Lagun. Restoring and protecting mangroves on Bonaire is crucial because they provide coastal protection. Due to their wide variety of ecosystem services, restoration of mangrove forests is an important factor in mitigating the effects of climate change.

Literature

Hendricksen, j. (2022). Key insights for Mangrove Restoration Discovered on Bonaire. BioNews. Key Insights for Mangrove Restoration Discovered on Bonaire | Dutch Caribbean Biodiversity Database (dcbd.nl)

Adame, M. F., Neil, D., Wright, S. F., & Lovelock, C. E. (2010). Sedimentation within and among mangrove forests along a gradient of geomorphological settings. *Estuarine, Coastal and Shelf Science*, *86*(1), 21–30. https://doi.org/10.1016/j.ecss.2009.10.013

Alongi, D. M. (2002). Present state and future of the world's mangrove forests. *Environmental Conservation*, *29*(3), 331–349. https://doi.org/10.1017/S0376892902000231

Alongi, D. M. (2014). Carbon Cycling and Storage in Mangrove Forests. *Annual Review of Marine Science*, *6*(1), 195–219. https://doi.org/10.1146/annurev-marine-010213-135020

Alongi, D. M. (2022). Climate change and mangroves. In *Mangroves: Biodiversity, Livelihoods and Conservation* (pp. 175–198). Springer, Singapore. https://doi-org.proxy.library.uu.nl/10.1007/978-981-19-0519-3_8

Bosire, J. O., Dahdouh-Guebas, F., Walton, M., Crona, B. I., Lewis, R. R., Field, C., Kairo, J. G., & Koedam, N. (2008). Functionality of restored mangroves: A review. *Aquatic Botany*, *89*(2), 251–259. https://doi.org/10.1016/j.aquabot.2008.03.010

Cardoso-Mohedano, J.-G., Lima-Rego, J., Sanchez-Cabeza, J.-A., Ruiz-Fernández, A.-C., Canales-Delgadillo, J., Sánchez-Flores, E.-I., & Páez-Osuna, F. (2018). Sub-tropical coastal lagoon salinization associated to shrimp ponds effluents. *Estuarine, Coastal and Shelf Science*, *203*, 72–79. https://doi.org/10.1016/j.ecss.2018.01.022

Chávez, V., Uribe-Martínez, A., Cuevas, E., Rodríguez-Martínez, R. E., van Tussenbroek, B. I., Francisco, V., Estévez, M., Celis, L. B., Monroy-Velázquez, L.

V., Leal-Bautista, R., Álvarez-Filip, L., García-Sánchez, M., Masia, L., & Silva, R. (2020). Massive Influx of Pelagic Sargassum spp. on the Coasts of the Mexican Caribbean 2014–2020: Challenges and Opportunities. *Water*, *12*(10), 2908. https://doi.org/10.3390/w12102908

Das, S. C., Pullaiah, & Ashton, E. C. (Red.). (2022). *Mangroves: Biodiversity, Livelihoods and Conservation*. Springer Nature Singapore. https://doi.org/10.1007/978-981-19-0519-3

Davaasuren, N., Meesters, E. (2012). *Extent and health of mangroves in Lac Bay Bonaire using satellite data*. Imares Wageningen UR.

Debrot, A., Meesters, E., & Slijkerman, D. (z.d.). *Assessment of Ramsar site Lac Bonaire – June 2010*.

Debrot, A. O., Wentink, C., & Wulfsen, A. (2012). *Baseline survey of anthropogenic pressures for the Lac Bay ecosystem, Bonaire*.

Duarte, C., Geertz-Hansen, O., Thampanya, U., Terrados, J., Fortes, M., Kamp-Nielsen, L., Borum, J., & Boromthanarath, S. (1998). Relationship between sediment conditions and mangrove Rhizophora apiculata seedling growth and nutrient status. *Marine Ecology Progress Series*, *175*, 277–283. https://doi.org/10.3354/meps175277

Dutch Caribbean Nature Alliance. (2019). *Prevention and clean-up of Sargassum in the Dutch Caribbean* (p. 30). Dutch Caribbean Nature Alliance. http://dx.doi.org/10.25607/OBP-796

Ellison, J. C. (1999). Impacts of Sediment Burial on Mangroves. *Marine Pollution Bulletin*, *37*(8–12), 420–426. https://doi.org/10.1016/S0025-326X(98)00122-2

Elster, C., Perdomo, L., & Schnetter, M.-L. (1999). Impact of ecological factors on the regeneration of mangroves in the Ciénaga Grande de Santa Marta, Colombia. In R. S. Dodd (Red.), *Diversity and Function in Mangrove Ecosystems* (pp. 35–46). Springer Netherlands. https://doi.org/10.1007/978-94-011-4078-2_4

Franks, J. S., Johnson, D. R., Ko, D.-S., Sanchez-Rubio, G., Hendon, J. R., & Lay, M. (2011). *Afluencia sin Precedentes del Sargassum Pelágio a lo Largo de la Costa en Islas Caribeñas durante el Verano del 201*.

Gilman, E. L., Ellison, J., Duke, N. C., & Field, C. (2008). Threats to mangroves from climate change and adaptation options: A review. *Aquatic Botany*, *89*(2), 237–250. https://doi.org/10.1016/j.aquabot.2007.12.009

Govers, L. L., Lamers, L. P. M., Bouma, T. J., de Brouwer, J. H. F., & van Katwijk, M. M. (2014). Eutrophication threatens Caribbean seagrasses – An example from Curaçao and Bonaire. *Marine Pollution Bulletin*, *89*(1–2), 481–486. https://doi.org/10.1016/j.marpolbul.2014.09.003

Greenpeace (2022). Futuro Di Boneiru, Future of Bonaire. Stichting Greenpeace Nederland. 15pp.

Grote schoonmaak Lagun. (2020). *Bonaire.nu*. https://bonaire.nu/2015/07/22/grote-schoonmaak-lagun/

Hendricksen, j. (2022). Key insights for Mangrove Restoration discovered on Bonaire. Bionews. Key Insights for Mangrove Restoration Discovered on Bonaire | Dutch Caribbean Biodiversity Database (dcbd.nl)

Hendricksen, j. (2023). Mangrove and seagrass restoration on Bonaire. MSc, Wageningen Universiteit.

Jarecki, L., & Walkey, M. (2006). Variable hydrology and salinity of salt ponds in the British Virgin Islands. *Saline Systems*, *2*(1), 2. https://doi.org/10.1186/1746-1448-2-2

Koster, G. (2013). Mapping runoff and erosion to reduce urban flooding and sediment flow towards sea. MSc, Wageningen University.

Krauss, K. W., Keeland, B. D., Allen, J. A., Ewel, K. C., & Johnson, D. J. (2007). Effects of Season, Rainfall, and Hydrogeomorphic Setting on Mangrove Tree Growth in Micronesia. *Biotropica*, *39*(2), 161–170. https://doi.org/10.1111/j.1744-7429.2006.00259.x

Krauss, K. W., Lovelock, C. E., McKee, K. L., López-Hoffman, L., Ewe, S. M. L., & Sousa, W. P. (2008). Environmental drivers in mangrove establishment and early development: A review. *Aquatic Botany*, *89*(2), 105–127. https://doi.org/10.1016/j.aquabot.2007.12.014

Measuring Soil Salinity (2022). Agriculture and Food, https://www.agric.wa.gov.au/soil-salinity/measuring-soil-salinity

Mekonnen, M., Keesstra, S. D., Stroosnijder, L., Baartman, J. E. M., & Maroulis, J. (2015). Soil Conservation Through Sediment Trapping: A Review: INDIVIDUAL, COMBINED AND INTEGRATED SEDIMENT TRAPPING. *Land Degradation & Development*, *26*(6), 544–556. https://doi.org/10.1002/ldr.2308

Mitra, A. (2020). Ecosystem Services of Mangroves: An Overview. In A. Mitra, *Mangrove Forests in India* (pp. 1–32). Springer International Publishing. https://doi.org/10.1007/978-3-030-20595-9_1

Nagelkerken, I., Blaber, S. J. M., Bouillon, S., Green, P., Haywood, M., Kirton, L. G., Meynecke, J.-O., Pawlik, J., Penrose, H. M., Sasekumar, A., & Somerfield, P. J. (2008). The habitat function of mangroves for terrestrial and marine fauna: A review. *Aquatic Botany*, *89*(2), 155–185. https://doi.org/10.1016/j.aquabot.2007.12.007

Noor, T., Batool, N., Mazhar, R., Ilyas, N. (2015). *Effects of Siltation, Temperature and Salinity on Mangrove Plants*. European Academic Research. Vol. 11, issue 11.

Onderz. Form. I., Aquatic Ecology and Water Quality Management, Alterra - Earth informatics, PE&RC, van der Geest, M., Meesters, E., & Mücher, S. (2020). *Impact of terrestrial erosion on coral reef health at Bonaire: A plea for nature-inclusive ‘watershed-to-reef’ based coastal management*. Wageningen Marine Research. https://doi.org/10.18174/524688

Orihuela, B., Diaz, H., & Conde, J. E. (1991). Mass Mortality in a Mangrove Roots Fouling Community in a Hypersaline Tropical Lagoon. *Biotropica*, *23*(4), 592. https://doi.org/10.2307/2388397

Ouwersloot, B. (2022). Seagrass as bioindicator for eutrophication and pollution in the coastal bays of Bonaire, Caribbean Netherlands. MSc biological sciences, University of Amsterdam.

Peterson, J.M., Bell, S.S. (2012). Tidal events and salt-marsh structure influence black mangrove (*Avicennia germinans*) recruitment across an ecotone. Department of Integrative Biology, University of south Florida. *Ecology*, 93(7), pp. 1648-1658.

Primavera, J. H., Rollon, R. N., & Samson, M. S. (2011). The Pressing Challenges of Mangrove Rehabilitation. In *Treatise on Estuarine and Coastal Science* (pp. 217–244). Elsevier. https://doi.org/10.1016/B978-0-12-374711-2.01010-X

Raijmakers, J. (2022). *Map mangrove planting sites & COMPARE and evaluate MANGROVE RESTORATION TECHNIQUES*. Van hall Larenstein, university of applied sciences.

Rhyma Purnamasayangsukasih, P., Norizah, K., Ismail, A. A. M., & Shamsudin, I. (2016). A review of uses of satellite imagery in monitoring mangrove forests. *IOP Conference Series: Earth and Environmental Science*, *37*, 012034. https://doi.org/10.1088/1755-1315/37/1/012034

Richards, D. R., & Friess, D. A. (2016). Rates and drivers of mangrove deforestation in Southeast Asia, 2000–2012. *Proceedings of the National Academy of Sciences*, *113*(2), 344–349. https://doi.org/10.1073/pnas.1510272113

Roos, N. (2018). *EROSION AROUND KRALENDIJK, BONAIRE*. MSc, Vrije Universiteit Amsterdam.

Shafique, T., Khan, M. A., Fatima, S. U., & Alamgir, A. (2022). Multivariate and geospatial monitoring of water and soil quality impact on planted mangroves growth pattern at Indus Delta: A pilot study. *Journal of Coastal Conservation*, *26*(4), 29. https://doi.org/10.1007/s11852-022-00873-4

Su, C.-J., Hsieh, S.-Y., Chiang, M. W.-L., & Pang, K.-L. (2020). Salinity, pH and temperature growth ranges of *Halophytophthora* isolates suggest their physiological adaptations to mangrove environments. *Mycology*, *11*(3), 256–262. https://doi.org/10.1080/21501203.2020.1714768

Suárez, N., & Medina, E. (2005). Salinity effect on plant growth and leaf demography of the mangrove, Avicennia germinans L. *Trees*, *19*(6), 722–728. https://doi.org/10.1007/s00468-005-0001-y

van Bijsterveldt, C. E. J., Debrot, A. O., Bouma, T. J., Maulana, M. B., Pribadi, R., Schop, J., Tonneijck, F. H., & van Wesenbeeck, B. K. (2022). To Plant or Not to Plant: When can Planting Facilitate Mangrove Restoration? *Frontiers in Environmental Science*, *9*, 690011. https://doi.org/10.3389/fenvs.2021.690011

van Zee, R. (2022). *The role of creeks for tidal exchange in the mangrove forest of Lac Bay, Bonaire*. MSc thesis. University of Twente.

Wösten, J.H.M. (2013). Ecological rehabilitation of Lac Bonaire by wise management of water and sediments. Alterra report 2448. Alterra Wageningen, UR.

Appendix 1. Satellite imagery of Lagun

Satellite images were obtained with Google Earth Pro. Imagery with the least amount of cloud cover was selected. The years that had the most clear images were 2009, 2011, 2014, 2018 and 2022.

a. 2009

b. 2011

c. 2014

d. 2018

e. 2022

Lagun, 01-22
Legenda
J the laguna beach
Google Earth
100 m

Appendix 2. Lac Bay Monitoring

Monitoring plant growth at two sites around Lac Bay, Bonaire

Introduction

Lac Bay contains the largest area of mangrove forest on Bonaire. However, due to erosion and high sedimentation rates, channels in the back area of the forest started to close up, causing high rates of salinity and temperature. Mortality rates spiked causing strong degradation. Mangrove Maniacs, a non-profit organization on Bonaire, executes research in the mangroves and implements many restoration efforts to restore the damaged parts around Lac Bay. Recently, their main focus has been tore-open tidal channels to the more damaged back area of the forest and reconnect several ponds to increase water circulation and promote the growth of red mangroves in those areas (Van Zee, 2022). Besides the reopening of the channels, they experiment with different planting techniques to see what could stimulate more growth (Hendricksen, 2022).

In 2022, they aired a pilot planting using BESE elements and burlap to mimic root structure of mangroves (Hendricksen, 2023; Raijmakers, 2022). In Lac Bay, there is already a study going on testing whether certain regeneration techniques impact mangrove growth positively. I will continue monitoring these efforts to answer the following research question: *Which restoration measure (BESE or channel re-opening) stimulates the most mangrove growth?*

Because reopening tidal channels solves many issues that were caused by the closing of these channels (high temperatures,high salinity, low water circulation, less sediment output and more sediment buildup), I expect it will have many benefits for mangrove growth, and that it could facilitate successful rehabilitation. I think that the installation of burlap and BESE-elements can promote growth, but that overtime more measures should be taken focusing on restoring hydrology. Therefore I hypothesize that the re-opening of channels stimulates higher growth rates compared to BESE-elements.

Materials and Methods

Study site

The pilot site and channel site are located in the more degraded part of Lac bay (AP. fig. 1). The pilot site is situated close to a big pond as well as the road Kaminda Sorobon, and therefore easily accessible. The channel site is located in one of the re-opened channels by Mangrove maniacs and is accessible by boat from Lac Cai, and by foot from Kaminda Sorobon.

Ap. fig. 1; pilot site and channel site shown on map.

Monitoring
Seedlings were monitored at the pilot and channel site. Plant growth was measured every two weeks by taking the length of the first root to the shoot (where leaves start to grow). Branches, yellow leaves and water submersion were also noted when observed. Water quality (salinity, temperature, pH) was measured every two weeks using a HANNA Instruments multiparameter HI198912. Fish occurrence was only measured for the pilot site with a GHOST Drift camera every month for 3-5 hours. A rebar pin was used to stick the camera in the mud facing the entrance of the small channel leading to the pilot site. 30 minutes of footage was taken from the original footage to analyze.

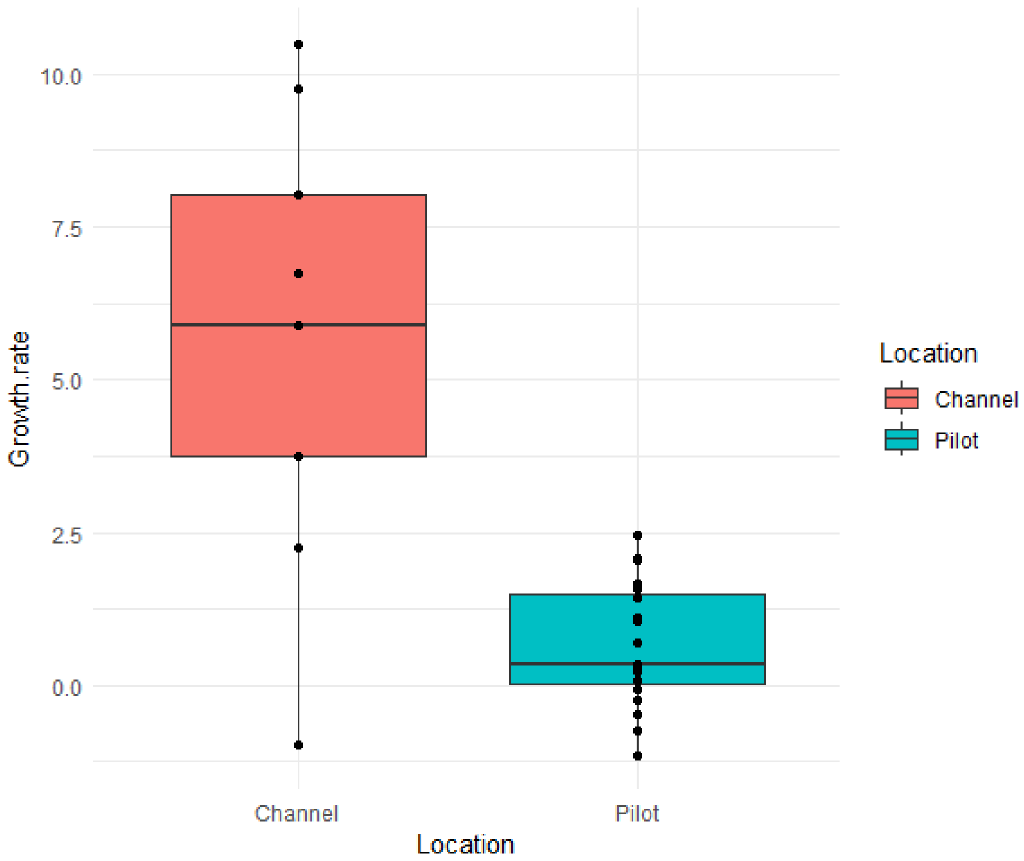
Data
Self obtained data was combined with data already available from previous months. Plant growth measurements were compared. Water quality measurements for the pilot site were obtained from the data that was available from the past months. The measurements will continue for both the pilot and the channel site, and water quality for the channel will be analyzed later in the process by another intern at Mangrove Maniacs, since there is little data present now. Raw data, and an explanation for tag numbers can be found here.

NOTE: control site data was not used in this report because all the seedlings have died in that area.

Statistical analysis
To test if there is a difference in growth rate between the pilot and channel site, a Welch's T-test was performed according to the assumptions (normally distributed, $P>0.05$; variances not homogeneous, $P<0.05$).

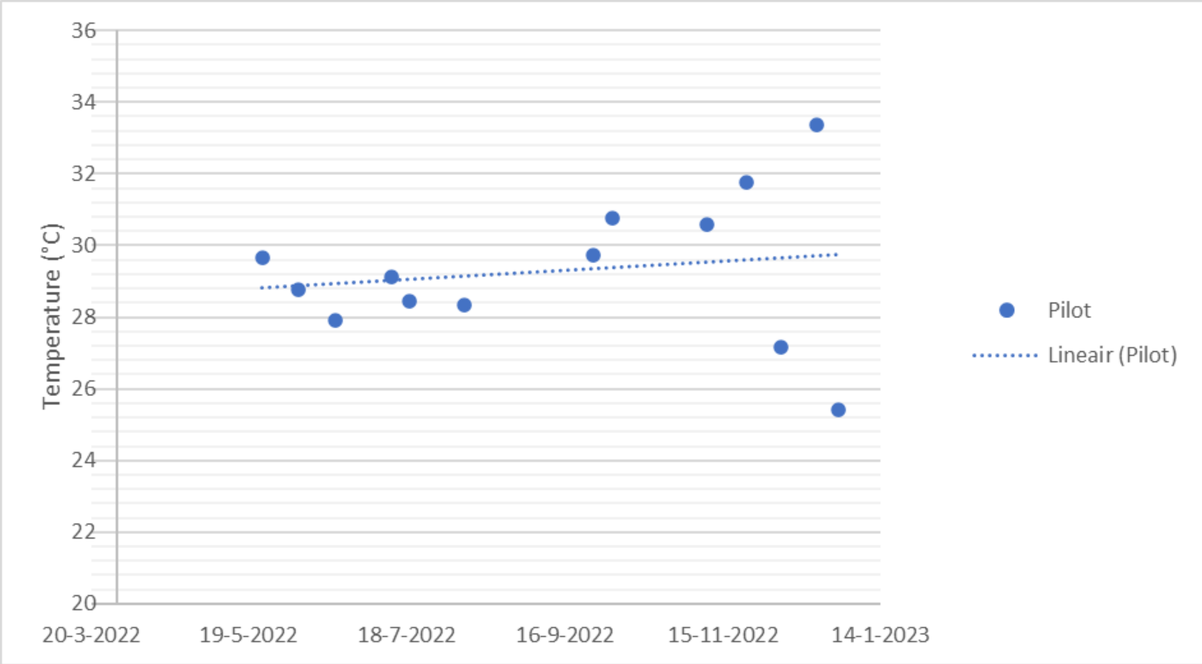
Results

The mean growth rate in the channel site was 5.76 (SD = 3.64), whereas at the pilot site the mean growth rate was .665 (SD = 1.02). A Welch independent t-test showed that this difference was statistically significant [t = 4.12, df = 8.59, p = .002] (AP. fig. 2).

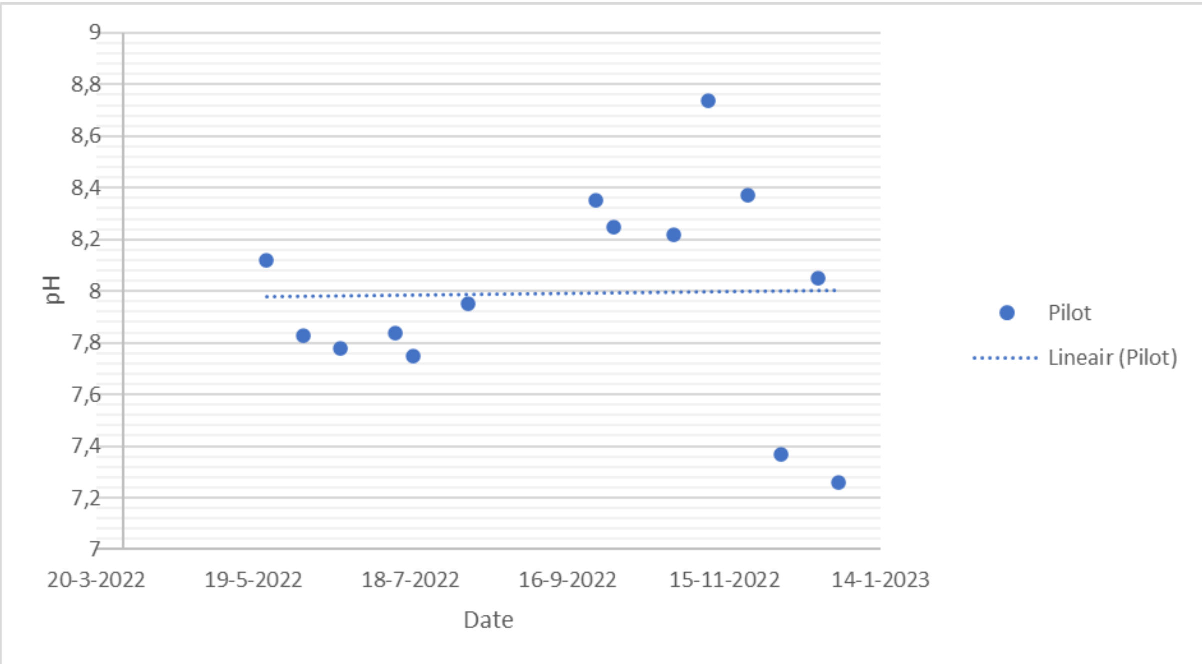


AP. fig. 2; Growth rate of seedlings at channel site and pilot site displayed in a box plot.

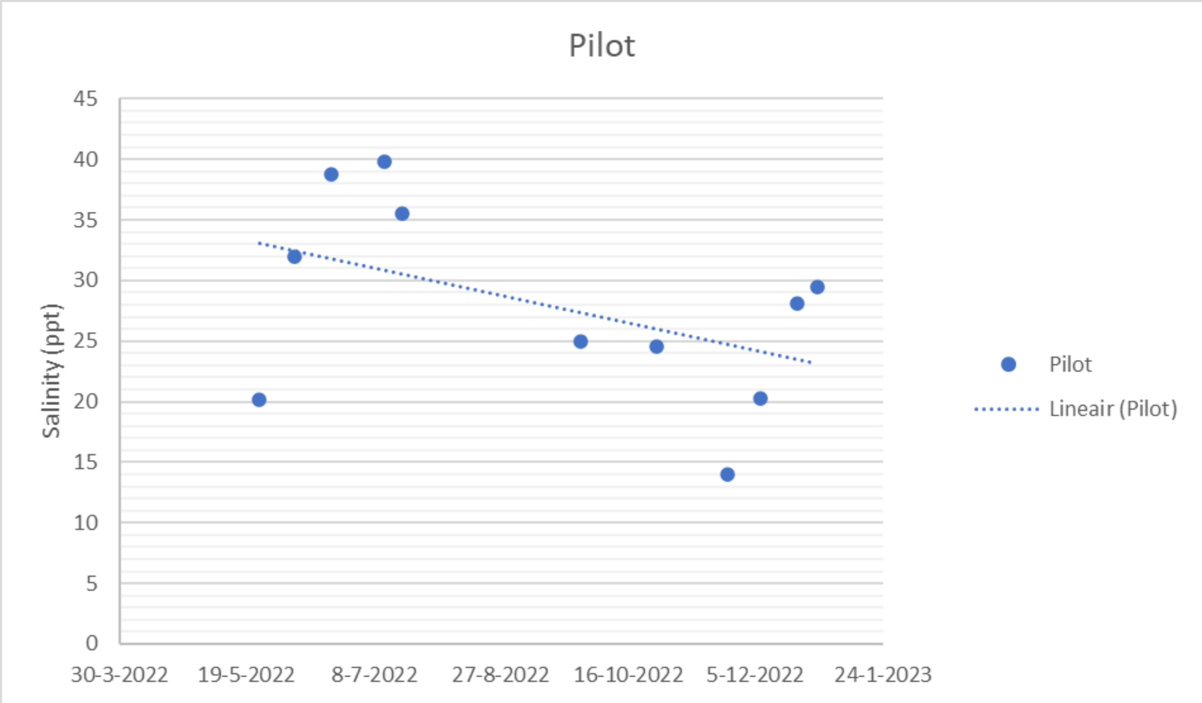
Water quality measurements over time are shown in graphs that are obtained from the raw data of Hendricksen (2023). Temperature is shown in AP.fig.3, pH in AP.fig.4 and salinity in AP.fig.5. There is a small increase notable in temperature over time. pH does not fluctuate much, and salinity shows a gradual decrease.



AP. fig. 3; Water temperature (°C) at the pilot site over time. Graph obtained from raw data of Hendricksen (2023).



AP. fig. 4; Water pH at the pilot site over time. Graph obtained from raw data of Hendricksen (2023).



AP. fig. 4; Water salinity (ppt) at the pilot site over time. Graph obtained from raw data of Hendricksen (2023).

Discussion and conclusion

Growth rate seems to be higher at the channel site compared to the pilot site. This could have something to do with environmental conditions. The channel site is a bit more shaded, and next to a channel with a relatively good current, because it has been re-opened by Mangrove Maniacs. Water quality measures should be compared for both sites in the future to see which variables differ between the two sites. it could give information about optimal growth conditions for the *R.mangle*. It should be noted that the channel site is relatively new and therefore does not have a lot of data yet. It is important to continue monitoring plant growth at this site for more accurate results. A more in depth statistical analysis on the relationship between the water quality variables and plant growth could provide more insight on the most pressing matters.

Some plants had lower measurements at the last monitoring compared to earlier measurements. This could be due to different people measuring the plants, but also because of small fluctuations in sediment height. The data is therefore not completely accurate.

There is a slight increase in temperature noticeable over time at the pilot site. Hendriksen (2023) mentioned that this could have something to do with the time of measuring (morning temperatures were lower compared to afternoon). However, since the rainy season has ended, temperatures might be expected to rise again. Measurements should in the future be conducted around the same time, and keeping track of increases compared to weather conditions could provide valuable information for possible system pressures.

pH remained relatively steady, fluctuating around 8.0. pH measurements could not be taken during my research because the instrument needed to be calibrated (meter showed values around 13.0). For now, pH does not seem to be an issue at the pilot site. Salinity at the pilot site showed a decrease, which could be beneficial to mangrove growth in that area.

During monitoring, it was clear that the BESE-elements and burlap were in the process of breaking down. Continued maintenance is necessary to keep the structure intact, and Mangrove Maniacs expressed doubts about its resilience and success. The goal of Mangrove Maniacs is to eventually connect all the back ponds with each other again to increase circulation. This could provide better growth conditions in the future, and might provide more possibilities for mangrove recruitment with minimal upkeep.

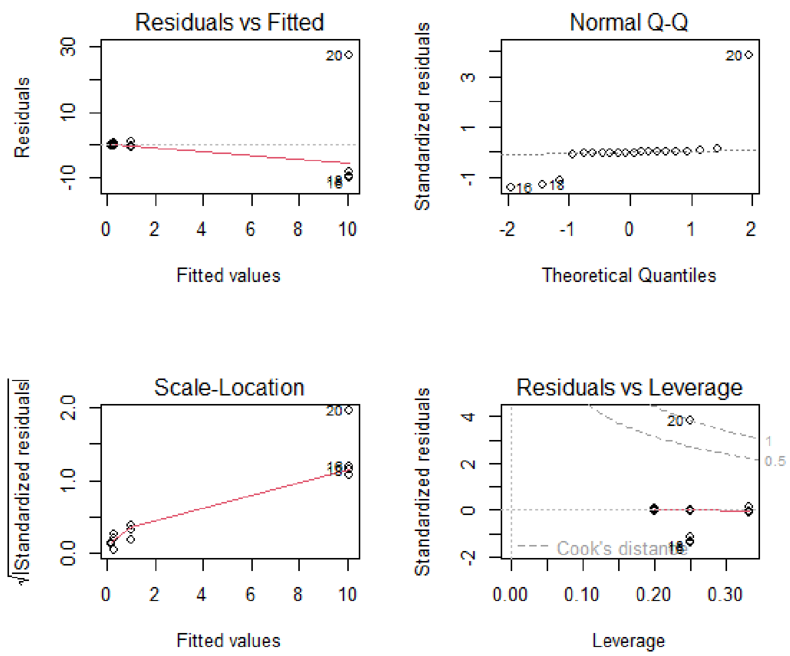
Appendix 3. Materials

- 4 ropes of 5 meters each
- 4 pvc tubes
- Black marker and pencil
- Small shovel
- 20 glass jars
- Measuring tape (30 m)
- Plastic zip-lock bags
- TDS & EC meter(hold)
- Plastic slate
- Ruler (30 cm)
- Measuring cup (1000 mL)
- Demineralised water (~4000 mL)

Appendix 4. Assumption figures

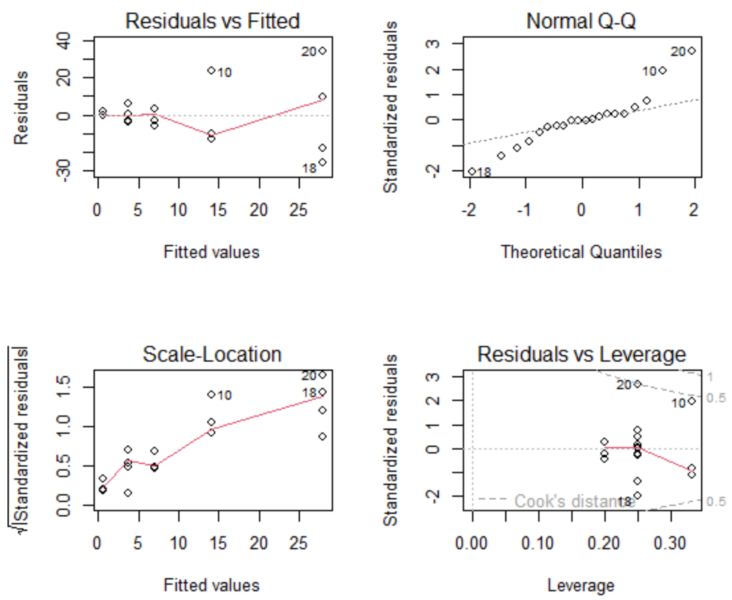
A. Assumptions Kruskal-Wallis for Adult tree abundance per location

No extreme outliers and variances were homogenous (P>0.05)



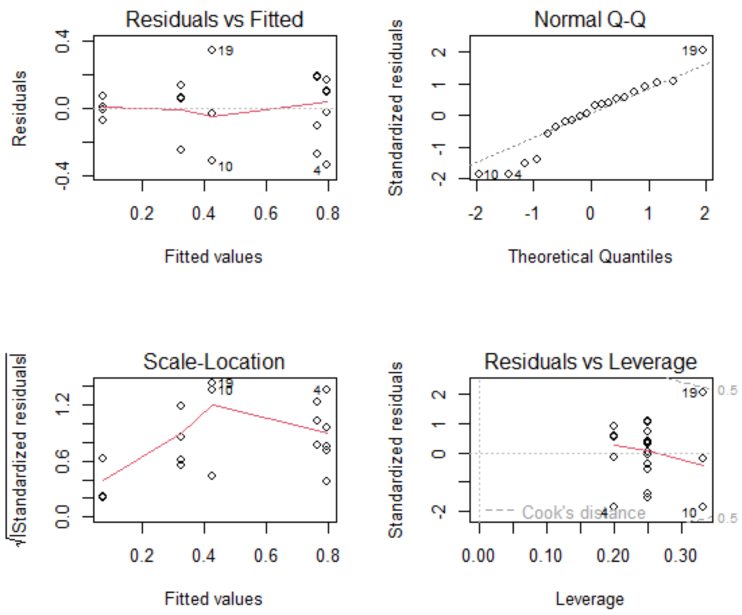
B. Assumptions Kruskal-Wallis for seedling abundance per location

No extreme outliers and variances were not homogenous (P<0.05). Data was transformed.



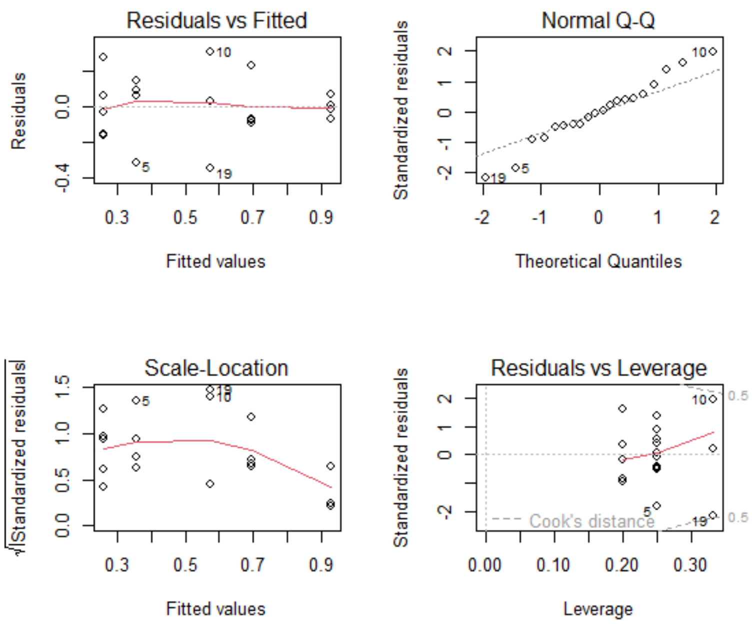
C. Assumptions Kruskal-Wallis for silt layer per location

No extreme outliers and variances were homogenous (P>0.05)



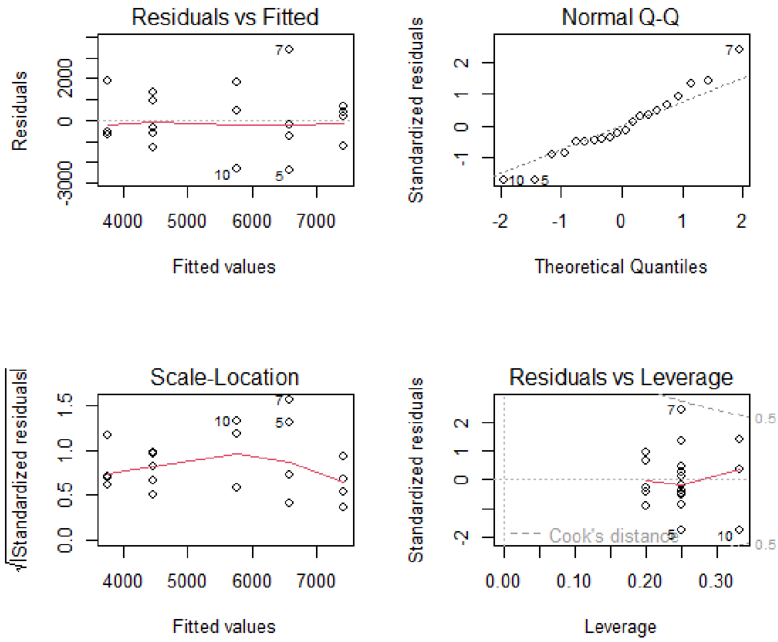
D. Assumptions One-way ANOVA for sand layer per location

No extreme outliers, residuals were normally distributed (P>0.05), and variances were homogenous (P>0.05)



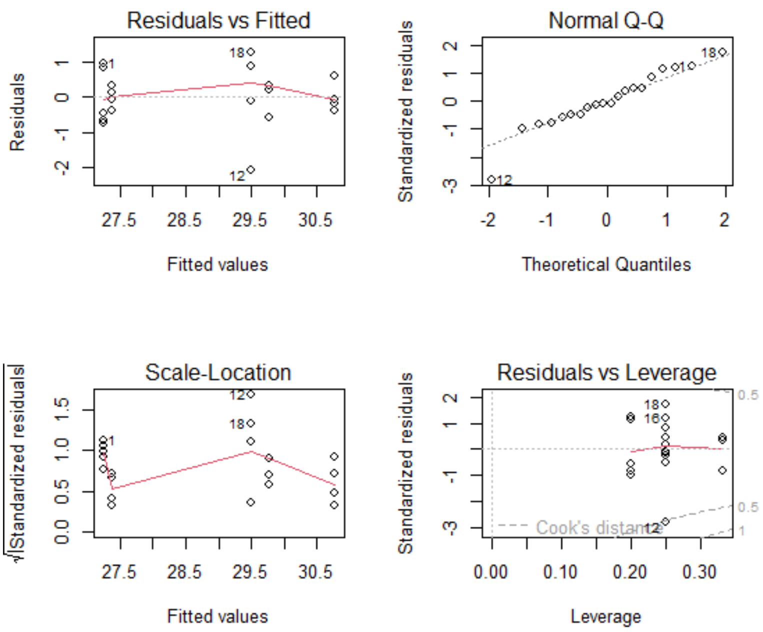
E. Assumptions Kruskal-Wallis for conductivity per location

No extreme outliersand variances were homogenous (P>0.05)



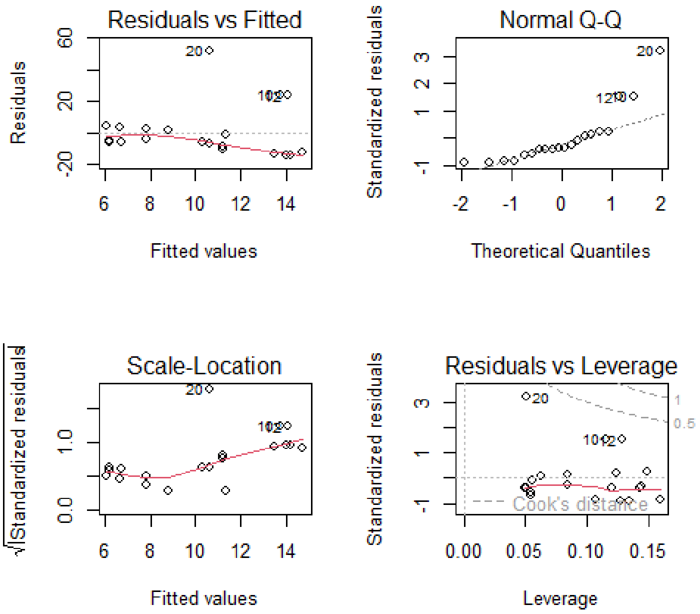
F. Assumptions Kruskal-Wallis for temperature per location

No extreme outliers and variances were homogenous (P>0.05)



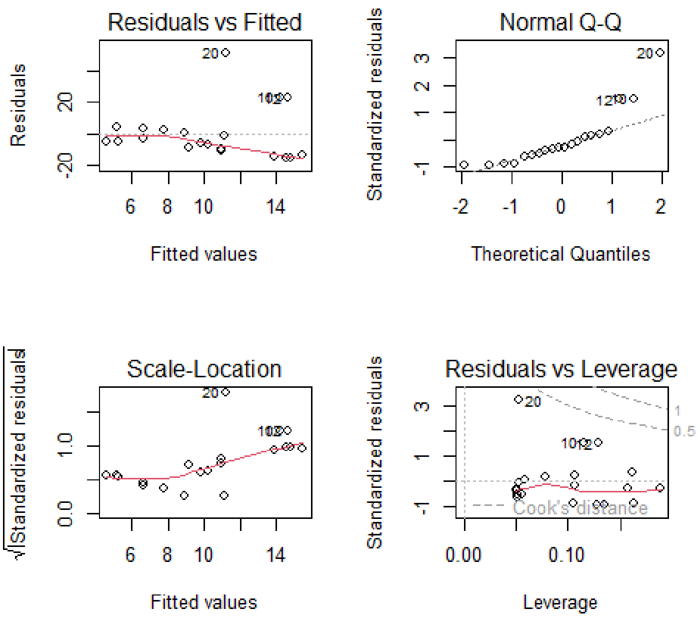
G. Assumptions GLM for silt and seedling abundance

No extreme outliers and variances were homogenous (P>0.05)



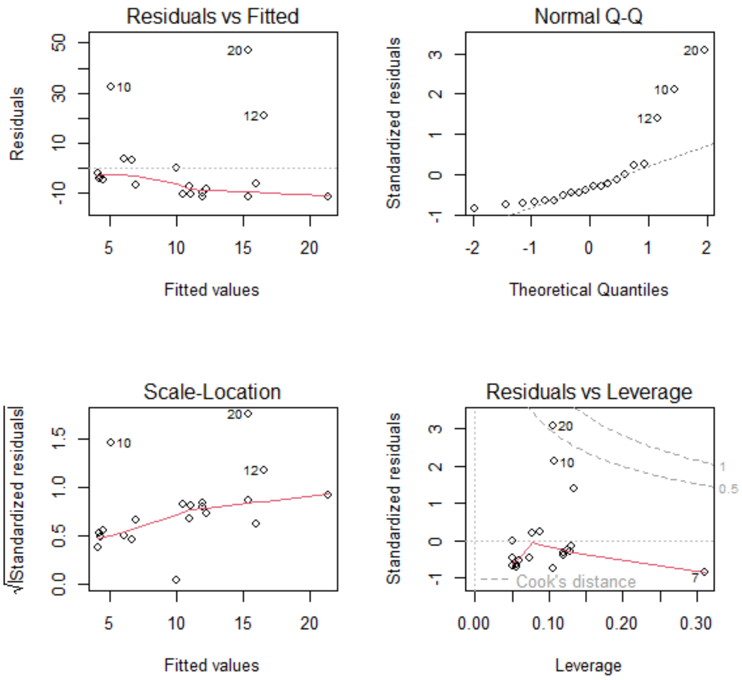
H. Assumptions GLM for sand and seedling abundance

No extreme outliers and variances were homogenous (P>0.05)

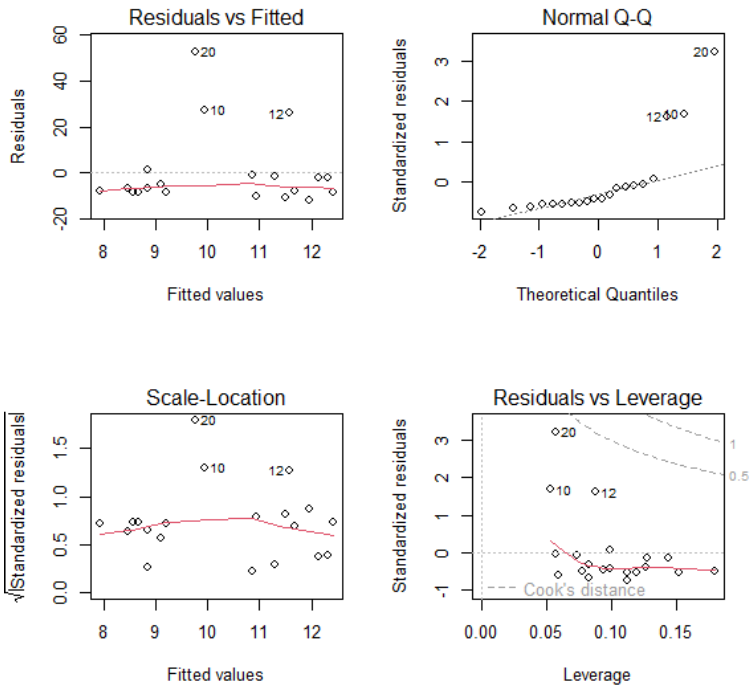


I. Assumptions GLM for conductivity and seedling abundance

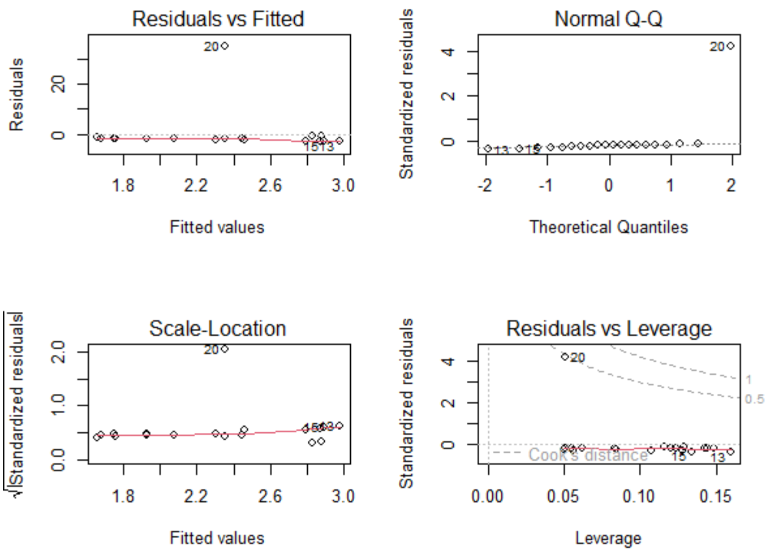
No extreme outliers and variances were homogenous (P>0.05)



J. Assumptions GLM for temperature and seedling abundance
No extreme outliers and variances were homogenous (P>0.05)

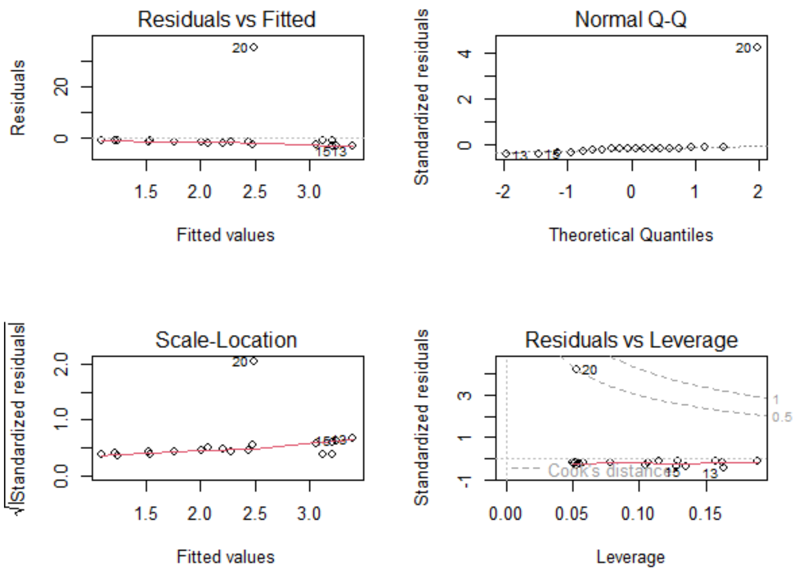


K. Assumptions GLM for silt and adult tree abundance
No extreme outliers and variances were homogenous (P>0.05)



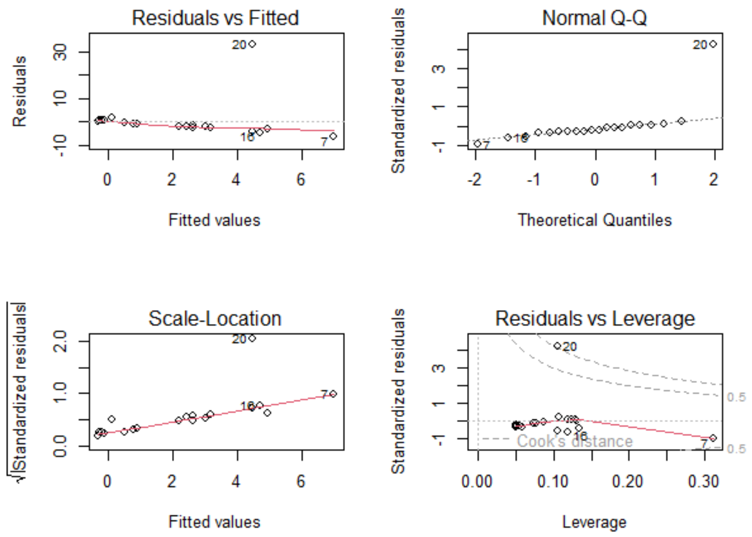
L. Assumptions GLM for sand and adult tree abundance

No extreme outliers and variances were homogenous (P>0.05)



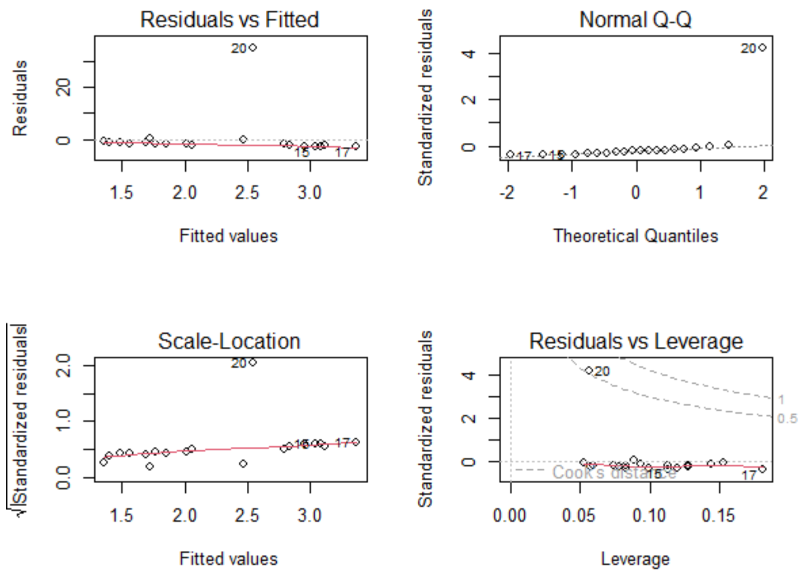
M. Assumptions GLM for conductivity and adult tree abundance

No extreme outliers and variances were homogenous (P>0.05)



N. Assumptions GLM for temperature and adult tree abundance

No extreme outliers and variances were homogenous (P>0.05)



Appendix 5. Logbook

Tekst	Weekday	Date	Start time	Duration	Day accumulated
Saar - Introduction and site visit	vrijdag	13-01-2023	10:00	06:00	06:00
Saar - Working on research question	zondag	15-01-2023	11:00	03:00	03:00
Saar - Visit Lagun	maandag	16-01-2023	10:30	01:30	01:30
Saar - Working on proposal	maandag	16-01-2023	12:00	04:00	05:30
Saar - Working in mangroves	dinsdag	17-01-2023	08:00	04:00	04:00
Saar - Working on proposal	woensdag	18-01-2023	10:00	06:00	06:00
Saar - Working on proposal	donderdag	19-01-2023	10:00	04:00	04:00
Saar - Working on proposal	donderdag	19-01-2023	15:00	03:00	07:00
Saar - Working on Proposal	vrijdag	20-01-2023	09:00	07:00	07:00
Saar - Making material list	maandag	23-01-2023	12:00	02:00	02:00
Saar - Research about monitoring and sampling	maandag	23-01-2023	14:00	02:00	04:00
Saar - Working in mangroves	dinsdag	24-01-2023	08:00	04:00	04:00
Saar - Site exploration Lagun	woensdag	25-01-2023	10:00	03:00	03:00
Saar - Satellite analysis Lagun	woensdag	25-01-2023	13:00	01:00	04:00
Saar - getting materials	woensdag	25-01-2023	14:00	01:00	05:00
Saar - Writing introduction	donderdag	26-01-2023	10:00	05:00	05:00
Saar - Prep materials Lagun	donderdag	26-01-2023	15:00	01:00	06:00
Saar - Writing introduction	donderdag	26-01-2023	19:00	02:15	08:15
Saar - Webinar blue carbon	vrijdag	27-01-2023	11:00	02:00	02:00
Saar - Prepare materials for Lagun	vrijdag	27-01-2023	13:00	04:00	06:00
Saar - Writing introduction	zaterdag	28-01-2023	08:00	03:00	03:00
Saar - Plot analysis Lagun	maandag	30-01-2023	08:00	04:00	04:00
Saar - Docum. data Lagun	maandag	30-01-2023	13:00	02:00	06:00

Saar - Working in mangroves	dinsdag	31-01-2023	08:00	04:00	04:00
Saar - First analysis Lac	dinsdag	31-01-2023	09:00	02:00	06:00
Saar - Docum. Data Lac	dinsdag	31-01-2023	13:00	02:00	08:00
Saar - Plot analysis Lagun	woensdag	01-02-2023	08:00	04:00	04:00
Saar - Docum. data Lagun	woensdag	01-02-2023	13:00	02:00	06:00
Saar - Taking soil samples Lagun	donderdag	02-02-2023	08:00	03:00	03:00
Saar - 1st soil sample analysis	donderdag	02-02-2023	11:00	04:00	07:00
Saar - World Wetland Day	donderdag	02-02-2023	17:00	04:00	11:00
Saar - Plot analysis Lagun	vrijdag	03-02-2023	08:00	04:00	04:00
Saar - Docum. data Lagun	vrijdag	03-02-2023	13:00	02:00	06:00
Saar - Outplanting Lagun	zaterdag	04-02-2023	09:00	01:30	01:30
Saar - Plot analysis Lagun	maandag	06-02-2023	08:00	04:00	04:00
Saar - Docum. data Lagun	maandag	06-02-2023	13:00	02:00	06:00
Saar - Working in mangroves	dinsdag	07-02-2023	08:00	04:00	04:00
Saar - Plot analysis Lagun	woensdag	08-02-2023	08:00	04:00	04:00
Saar - Docum. data Lagun	woensdag	08-02-2023	13:00	02:00	06:00
Saar - Plot analysis Lagun	donderdag	09-02-2023	08:00	04:00	04:00
Saar - Docum. data Lagun	donderdag	09-02-2023	13:00	01:00	05:00
Saar - writing methods	donderdag	09-02-2023	14:00	03:00	08:00
Saar - Soil samples from Lagun	vrijdag	10-02-2023	08:00	04:00	04:00
Saar - Docum. data Lagun	vrijdag	10-02-2023	13:00	02:00	06:00
Saar - soil analysis Lagun	maandag	13-02-2023	08:00	06:00	06:00
Help Daphne met algae collection	maandag	13-02-2023	14:00	03:00	09:00
Saar - Working in mangroves	dinsdag	14-02-2023	08:00	04:00	04:00
Saar - 2nd analysis Lac	dinsdag	14-02-2023	09:00	02:00	06:00
Saar - Docum Data Lac	dinsdag	14-02-2023	13:00	02:00	08:00
Help Daphne met algae collection	woensdag	15-02-2023	08:00	08:00	08:00

Saar - Soil analysis Lagun	donderdag	16-02-2023	08:00	08:00	08:00
Saar - Soil analysis	vrijdag	17-02-2023	08:00	08:00	08:00
Saar - soil analysis	zaterdag	18-02-2023	08:00	04:00	04:00
Saar - Statistical analyses	maandag	20-02-2023	08:00	09:00	09:00
Saar - Working in mangroves	dinsdag	21-02-2023	08:00	04:00	04:00
Saar - Statistical analyses	woensdag	22-02-2023	08:00	08:00	08:00
Saar - Statistical analyses	donderdag	23-02-2023	08:00	08:00	08:00
Saar - Statistical analyses	vrijdag	24-02-2023	08:00	08:00	08:00
Saar - Writing results	maandag	27-02-2023	08:00	08:00	08:00
Saar - Working in mangroves	dinsdag	28-02-2023	08:00	04:00	04:00
Saar - 3rd analysis Lac	dinsdag	28-02-2023	09:00	02:00	06:00
Saar - Docum. Data Lac	dinsdag	28-02-2023	13:00	02:00	08:00
Saar - Statistical analyses	woensdag	01-03-2023	08:00	04:00	04:00
Saar - Writing Results	woensdag	01-03-2023	12:00	04:00	08:00
Saar - Writing results/discussion	donderdag	02-03-2023	08:00	08:00	08:00
Saar - Writing discussion	vrijdag	03-03-2023	08:00	08:00	08:00
Saar - submitting first draft	zaterdag	04-03-2023	12:00	01:00	01:00
Saar - Fofoti help	zondag	05-03-2023	16:00	02:00	02:00
Saar - Writing report	maandag	06-03-2023	08:00	07:00	07:00
Saar - Working in mangroves	dinsdag	07-03-2023	08:00	04:00	04:00
Saar - Writing report	woensdag	08-03-2023	08:00	09:00	09:00
Saar - Prepare presentation	woensdag	08-03-2023	19:00	02:00	11:00
Saar - Writing report and prepare presentation	donderdag	09-03-2023	08:00	07:00	07:00
Saar - Presentation evening	donderdag	09-03-2023	19:00	02:00	09:00
Saar - seagrass monitoring	vrijdag	10-03-2023	08:00	06:00	06:00
Saar - Finishing report	vrijdag	10-03-2023	15:00	02:00	08:00
Saar - BonDoet reforestation	zaterdag	11-03-2023	08:00	04:00	04:00
Saar - Finishing report	zaterdag	11-03-2023	13:00	03:00	07:00