MANGROVE AND SEAGRASS RESTORATION ON BONAIRE

5 JANUARY 2023

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Internship with Mangrove Maniacs
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Acknowledgement

I would like to thank Sabine Engel for her guidance during this internship with Mangrove Maniacs, on the Dutch Caribbean island Bonaire. She made it possible for me to join a broad range of activities, see different places of the island, and meet a lot of people. She has been very kind and helpful, from answering my questions, giving me rides, to offering a working place at her own house. I am also thankful for the freedom I had to join activities outside the internship (e.g. coral mapping, beach clean ups, sea turtle net-capture surveys, Greenpeace presentation & discussion), which were complementary in my learning process about the island's people, environment and issues.

Also Jessica Johnson has been of great help and a real pleasure to work with. She was always there to answer my questions or provide me with information, data or materials. She made it possible to publish my article on DCNA's BioNews and Nature Today. Besides, I want to thank Marjolijn Christianen for this opportunity and her pleasant guidance from WUR, as well as for the two weeks of fieldwork with her, Fee Smulders and Karin Didderen on seagrass restoration on Klein Bonaire and in Lac Bay. Those two weeks were truly a cherry on top of the cake of this internship. The volunteers from Mangrove Maniacs have also been very kind and welcoming to me. I enjoyed their enthusiasm and passion for the hard work in the mangroves, which I quickly took over. I would also like to thank the volunteers and other students that helped me with my experiments or monitoring which I was not able to do alone. My special thanks goes out to Dedrie for her help and enthusiasm, and most importantly for letting me join her catamaran the 'Woodwind' multiple times to get to Klein Bonaire for my seagrass research. It was always a pleasure to be on board and get support from the crew! Getting the opportunity to work abroad and to experience lots of fieldwork has steered and confirmed the interests for my future career in marine ecology and restoration. But it has also given me valuable friendships, memories & love for this beautiful Caribbean island.

Summary

Vegetated coastal ecosystems provide important ecosystem services on which humans depend. Mangrove and seagrass ecosystems function as a nursery for fish, sequester large amounts of carbon and protect our coasts. Mangroves and seagrasses worldwide are threatened by human disturbances like coastal development, tourism, pollution, and climate change. Therefore, the protection of these valuable ecosystems is crucial and understanding underlying dynamics becomes increasingly important. Monitoring restoration efforts of mangroves and seagrasses provides more knowledge on effective restoration measures. On the Dutch Caribbean island of Bonaire, both large areas of mangrove forest and seagrass beds are present. Nature organisations like Mangrove Maniacs and STINAPA work together on mangrove and seagrass restoration. However, there are still knowledge gaps on the most suitable restoration measures for certain areas and there is a lack of monitoring. Therefore, this four month professional internship with Mangrove Maniacs focussed on monitoring mangrove and seagrass restoration efforts. In consultation with the internship host, activities included monitoring a new mangrove restoration pilot in the mangrove forest of Lac Bay, a reforestation area near Lac Bay and a new seagrass restoration experiment at Klein Bonaire. Besides, helping to set up a regional blue carbon network, analysing data and conducting a literature review were also part of this internship, next to joining the weekly Tuesday morning of channel maintenance with the Mangrove Maniacs. With this internship research, I was able to provide new insights on mangrove and seagrass restoration on Bonaire which could help steering future research and restoration plans of the host organisation.

Content

1. Introduction

Vegetated coastal ecosystems provide important ecosystem services on which humans depend. Mangroves and seagrass ecosystems function as an important nursery for juveniles of reef fish (Nagelkerken et al., 2002), are important for carbon sequestration and storage, also called blue carbon (Nellemann & Corcoran, 2009) and protect our coasts (Hemminga & Duarte, 2000; Massel et al., 1999; Mazda et al., 1997). Despite their high value, seagrass and mangrove ecosystems are rapidly degrading due to human disturbance (Valiela et al., 2001). Therefore, the protection of seagrass and mangroves has been suggested as climate change mitigation strategies (Macreadie et al., 2017; Murdiyarso et al., 2015). Understanding the dynamics of these crucial ecosystems thus becomes increasingly important in order to draft recovery programs (Bosire et al., 2008).

Local restoration projects are initiated to reverse the loss of seagrass and mangroves, like on Bonaire in the southern Caribbean, the main study location of this project. On Bonaire, mangrove restoration was recently ranked as the most important adaptation option against coastal flooding (Tiggeloven et al., 2022). Here, the major concentration of mangroves and seagrass beds can be found in the shallow lagoon of Lac Bay (Figure 1). This bay is a designated Ramsar wetland (protected under the Ramsar Convention (1971) due to its international and ecological significance) of about seven hundred hectares, separated from the open ocean by a shallow coral reef barrier. It is also recognised as an Birdlife International IBA (Important Bird Area) and plays a critical function as fish nursery for the reefs of the island (STINAPA, 2022a). The bay is a part of the Bonaire National Marine Park which extends to a depth of sixty meters surrounding the whole island, including the island of Klein Bonaire (Figure 1). Also on Bonaire, several (human) disturbances are putting a pressure on the coastal ecosystems. Disturbances in Lac Bay include trampling of seagrass by tourists, the increase of the invasive seagrass species *Halophila stipulacea*, fishing, Sargassum blooms, beach litter contamination, human-mediated
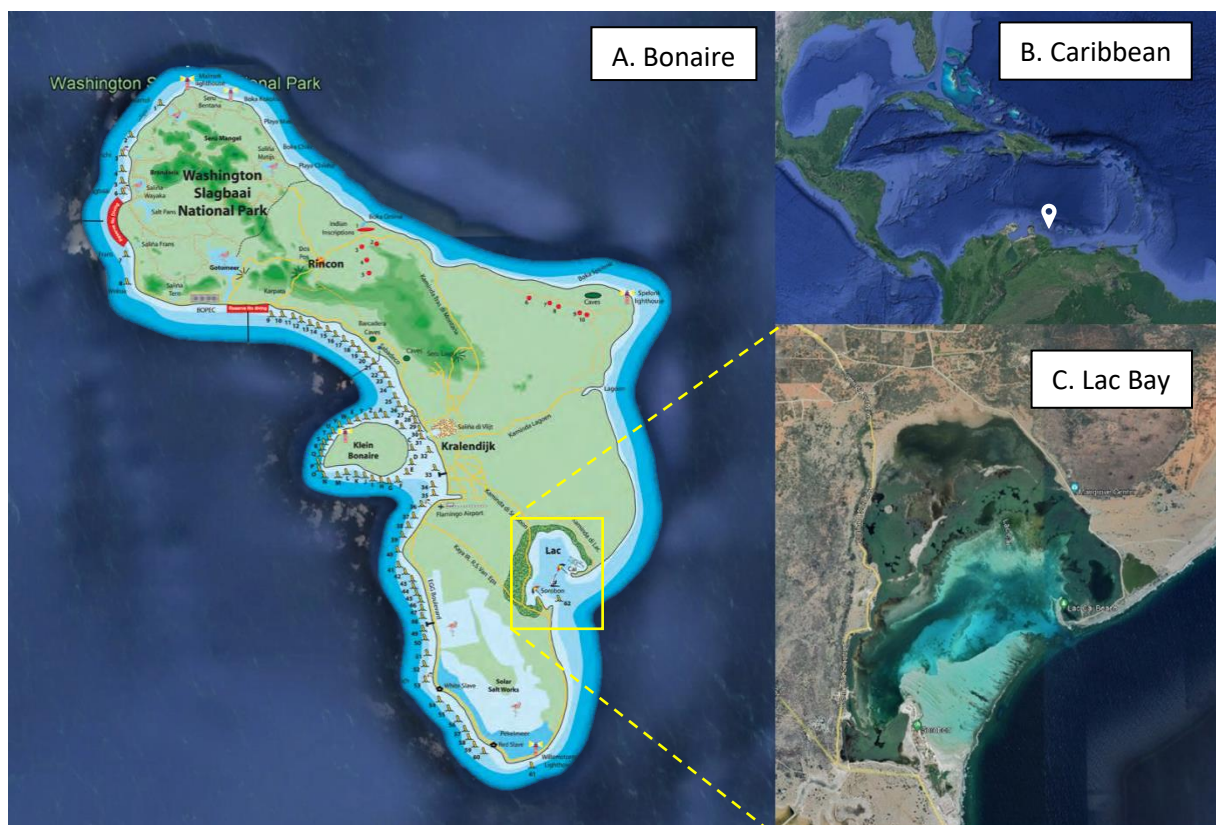

Figure 1 Geographical location of the island Bonaire (A) in the Caribbean (B), including Lac Bay (C) and Klein Bonaire, all part of the Bonaire National Marine Park, indicated by the light blue area around the island.

eutrophication and sediment input due to erosion caused by overgrazing of livestock, heavy rainfall, and traffic (Debrot, 2012).

Several organisations work to restore and preserve these important coastal ecosystems on Bonaire, next to the overall nature management of protected areas conducted by STINAPA (Stichting Nationale Parken Bonaire, who manages the preservation and conservation of Washington Slagbaai National Park and Bonaire National Marine Park). Mangrove Maniacs, the host of this internship project, plays a key role in mangrove restoration by developing and maintaining channels in the forest and thereby improving the water circulation and health of the forest. They monitor restoration efforts (either by students or volunteers) and raise awareness by organising outreach activities such as presentations or outplant events. Seagrass restoration in Lac is currently initiated in a 1.5 year RESEMBID project of STINAPA (2022b) and includes for example outplanting of seagrass using BESE-elements® (Biodegradable Ecosystem Engineering Elements, a porous 3D structure made out of potato starch) and monitoring, in addition to placing lines and signs in Lac to prevent people from trampling the seagrass.

Although restoration efforts are already being taken on Bonaire, there are still knowledge gaps (Table 1) about the identification and assessment of some stressors, about the most effective way to restore seagrass or mangroves, the most suitable location or type of restoration and about results of earlier taken measures for restoration. Therefore, monitoring is crucial in research: to be able to reveal new insights and evaluate certain restoration methods.

Table 1 Existing knowledge gaps per internship activity.

Internship activity	Knowledge gap	Literature
Mangrove Maniacs: hydraulic restoration	Monitoring: What is the current water quality status throughout the mangrove forest in Lac? What has been the effect of digging channels on the water quality and mangrove growth and survival?	(López-Portillo et al., 2017; van Zee, 2020; Wosten, 2013)
Pilot: restoration and monitoring of degraded mangrove forest area *	What is the best way of restoring degraded areas of mangrove forest? Does a pond with BESE-elements and burlap improve the water quality and thus conditions for mangroves to grow?	
Reforestation with buttonwood plants	Is planting buttonwood in a fenced-off area a successful reforestation measure? What is the effect of rain? Does it decrease the sediment input into Lac Bay?	(Debrot, 2012; van Zee, 2020)
Mangrove outplanting along the coast as coastal protection	Which mangrove species is best to use for planting along the coast? What is the most successful method (on sand, using rocks, BESE-elements)?	(Lanjouw, 2022)
Genetic population connectivity of red mangroves *	Are there different genetic populations of red mangroves in the Caribbean region? What are consequences of importing & mixing populations?	(Arbeláez-Cortes et al., 2007; Basyuni et al., 2017)

Seagrass restoration & monitoring *	What is the current status of seagrass beds in Lac Bay? What is the best way of seagrass restoration in Lac and at Klein Bonaire? What are the most important pressures on seagrass?	(Engel & Johnson, 2022)

This professional internship, therefore, focussed on the monitoring and data-analysis of mangrove and seagrass restoration efforts on Bonaire. Some of the activities were a continuation of previous work done by Mangrove Maniacs or other students (e.g., monitoring outplants), but also new activities and insights were developed during this internship (marked with an asterisk above). Chapter 3 gives a complete overview of the internship activities.

The goal of this internship was to expand the current knowledge on mangrove and seagrass restoration (Table 1). In terms of personal development, the goals were to gain more knowledge on the importance and issues related to vegetated coastal ecosystems, as well as gaining more data-collection experience in the field and steering my future career by developing a professional working attitude, working with people outside the university, identifying my strengths (and weaknesses) and further develop my writing and networking skills. I evaluate these personal learning goals in a separate reflection report, which is only accessible to my supervisors. If appropriate, I may share this report upon request.

2. Description of the internship

2.1 The organization Mangrove Maniacs

Mangrove Maniacs is a group of volunteers that were supporting mangrove restoration in a 'Natuurgelden Project' that ran from 2015. Mangrove restoration continued after the project and the Mangrove Maniacs acquired a formal foundation status in 2021. They work on mangrove research and restoration in Lac Bay, Bonaire, but also on the southwest coastline of the island. The organization is led by a board of five people, taking care of activities, finances, social media, and outreach events (such as presentations, outplant events or open days). The Mangrove Maniacs exist of a group of around 30 active volunteers, of which between 6 to 12 volunteers join for the weekly restoration work in Lac Bay. Every Tuesday morning, they work together to maintain and reopen important channels within the mangrove forest of Lac Bay. This will help to restore the water circulation, decrease salinity levels in the landside of Lac Bay, and build resilience of the mangroves. By combining research, monitoring and physical labour, the Mangrove Maniacs work to better understand the complex environments of the mangroves and help return the mangroves to their previous natural state. Changes in the status of this important habitat are researched and monitored in collaboration with Stichting Internos (chaired by Sabine Engel), Coastal Dynamics (owned by Jessica Johnson) and students from international universities working on either a thesis research or internship. These results can provide feedback to governmental policy makers (here: managers of STINAPA) or any interested stakeholder. Beside the channel maintenance and restoration, and research activities, the Mangrove Maniacs also grow new mangrove trees in their natural nurseries in Lac Bay. These young mangroves can then be outplanted in degraded and coastal areas, expanding healthy mangroves around the island. This can help prevent erosion and provide future coastal protection.

Next to the abovementioned activities, the Mangrove Maniacs are active in outreach and awareness events, because they believe cultivating a sense of ownership among residents and visitors will be key in protecting the mangroves for the future. Examples of outreach to the wider public are coastal outplant events, update presentations and special days like Mangrove Day or Wetlands Day. This also helps them to gather more volunteers. Beyond the boundaries of their own island, Mangrove Maniacs is also active in the organization of setting up a new blue carbon network in the Eastern Tropical Pacific, the Gulf of Mexico and the Caribbean: Tropical Restoration Network (TRN). After hosting a regional Workshop on Mangrove Restoration in October 2021, a new Mangrove Restoration Workshop is now planned to be held early 2023 in Costa Rica.

2.2 Map with all internship locations

Because of the diversity of this internship, fieldwork has been executed on several locations on the island. The map below (Figure 2) provides an overview of all important locations where data has been collected or part of the internship work was done.

Figure 2 Overview of all internship locations on Bonaire. The smaller detailed map shows Lac Bay, where most of the activities took place. Locations: 1. KB = seagrass restoration experiment Klein Bonaire; 2. Lagun = secondary mangrove area; 3. RF = reforestation area with buttonwoods, called 'Fofoti'; 4. Pilot = mangrove restoration experiment; 5. MM = work with Mangrove Maniacs; 6. RESEMBID = seagrass restoration in Lac; 7. LS = Lac Survey (yellow polygon), monitoring seagrass, Halimeda *and conch; 8. SW – SP = southwest coast Salt Pier, most northern point of mangrove monitoring; 9. MPE = mangrove outplant event; 10. SW – MB = southwest coast Margate Bay, most southern point of mangrove monitoring (yellow line).*

3. Internship activities

I worked on mangrove and seagrass restoration by executing a range of different activities that I present below. These activities included joining the Mangrove Maniacs to help with their channel maintenance, I worked on my own pilot, monitored buttonwoods, mangroves, seagrass, and conch, analysed data, published an article, did a literature review, gave a presentation, educated STINAPA rangers and much more. This chapter gives an overview of my most important internship activities, including (links to) results. During the internship, me and my supervisor Sabine Engel kept track of the activities using the online tool Trello (Appendix I).

3.1 Mangrove Maniacs: channel maintenance & outreach events

Channel maintenance

Every Tuesday morning between 8:00 and 12:00, I worked together with a group of volunteers from the Mangrove Maniacs. My role was the same as the other volunteers: digging channels to improve the water circulation (Figure 3) and collecting propagules of red (*Rhizophora mangle*) and black mangroves (*Avicennia germinans)* for in the nursery, where I sometimes worked as well. The nurseries are a natural area on the side of the channels, with shallow water, where the propagules are planted in biodegradable bags. The bags are filled with mud that is collected from the channels by using crates. In the nursery these propagules grow out to bigger plants, after which the mangroves are ready to be outplanted (in a degraded area or along the southwest coast for coastal protection). My work in the channels and nursery was sometimes alternated with setting out a route for a new channel, installing or reading sensors (measuring salinity, temperature, depth, etc.) that are located throughout the channels and lagoons in the mangrove forest, or a visit to a different mangrove area (Lagun) for a beach clean-up (when there were too many mosquitos). Lastly, Mangrove Maniacs received help from around 80 Dutch Army soldiers, divided over three days in December, who came out with us to clear a new part of the forest for a new channel.

Figure 3 Weekly work in the mangrove channels with Mangrove Maniacs. Photo source: Monique Grol.

Outreach events

Several events have been organised by Mangrove Maniacs during my internship with the goal of public outreach and creating community awareness about mangroves and mangrove restoration on Bonaire. First, we organised a **public outplant event** on the southwest coast of Bonaire on September 23, 2022. Outplantings are regular events organised by Mangrove Maniacs to help increasing coastal protection, while at the same time educating volunteers. In the preparation phase of this event, I organised all the snacks for the drink afterwards and during the event, I helped with explaining to volunteers and planting mangroves with them. *R. mangle* was used in the shallow water because of its higher resilience to wave action using rocks to secure the plant that was still in its biodegradable bag. *A. germinans* was planted on the beach by digging holes in the sand. In total, a record-breaking number of 1,300 mangroves were outplanted and 75 people joined to help.

A second event took place on the 20th of October, when we hold a public **presentation night** about the BEST2.0+ restoration project of mangroves and seagrass in Lac Bay (Figure 4). The group of around 20 people present were invited via social media. Here, Sabine Engel and Jessica Johnson (Mangrove Maniacs), Daan Zeegers (Sea Turtle Conservation Bonaire), Judith Raming (STINAPA) and I (intern) gave a presentation about mangroves and seagrass in Lac and the work we do. I presented my work done so far at that time including some preliminary outcomes.

Lastly, during the **open day from LVV** on the 30th of October, we were present with the Mangrove Maniacs at one of the stands. Sabine, Jessica, some other volunteers, and I stand behind the stand to tell visitors of the open day about what we do and how they could be involved as a volunteer

Sabine Engel, Mangrove Maniacs; Danne Zeegers STCB; Judith Raming, STINAPA; Jessica Johnson, Coastal Dynamics B.V. and project coordinator for BEST 2.0+ and RESIMBID ; Josien Hendricksen, Intern

Figure 4 Article about the presentation night of Mangrove Maniacs in The Bonaire Reporter Oct. 26 - Nov. 9, 2022.

as well. I prepared the 'showcase', a large box with plexiglass displaying some plant species and materials, by printing labels and collecting the plant material. To involve young kids as well and give them a practical mangrove experience, they could plant a mangrove propagule in a bag with mud and play a mangrove memory game. This open day was meant to involve and educate locals from all ages in mangrove restoration on Bonaire.

Next to these events, I was part of the initial phase of setting up a **blue carbon network** in the Eastern Tropical Pacific, the Gulf of Mexico and the Caribbean: Tropical Restoration Network (TRN). I compiled a contact list of organisations in the region that work on mangrove and/or seagrass restoration, who were later invited to join the network. I joined meetings with the co-organisers from the University of Costa Rica and was part of the kick-off event that announced a Mangrove Restoration Workshop to be held early 2023 in Costa Rica.

3.2 Pilot Isla Yuwana

The pilot area is a location north of the island Isla Yuwana, which is in the back of the mangrove forest in Lac Bay (Figure 2 in Chapter 2, Figure 15/16 in Appendix III) and is used as an experimental site for mangrove restoration methods. From Isla Yuwana and further north, the mangrove forest starts degrading. Mangrove roots are very dense and can stabilize sediments and filter (Carlton, 1974), so in this degraded area Mangrove Maniacs wanted to create this 'ecosystem service' using BESE-

elements®. The pilot location was chosen because this area would degrade further if left alone and because it is easily accessible via the road ('Kaminda Sorobon'). A pond was made by the Mangrove Maniacs and the sides were secured with vertically placed BESE-elements®. Red and black mangrove propagules from the nursery were planted behind this biodegradable border of the pond. This was all done before the start of this internship. However, using the BESE-elements® alone did not function very well, so as suggested by Sabine Engel, I added burlap to the pilot as an attempt to further stabilize the sediment. This experiment combining BESE-elements® with burlap had the purpose to mimic the root structure of mangroves. Over time, roots of new healthy mangroves should take over the filtering and stabilizing function once the installation is degraded. This method was used for the first time, since BESE-elements® for mangrove restoration have only been used in a horizontal position before (Lanjouw, 2022) and use of burlap was new as well. The aim was to find out if this measure would stimulate mangrove growth compared to if no measure was taken. The research question was:

Does the installation of burlap in combination with BESE-elements® in a pond stimulate mangrove restoration, compared to an area where no measure is taken?

Figure 5 Installation of burlap at the pilot site with the help of five volunteering students.

Monitoring

After installation of burlap at the pilot site (Figure 5, 30th of September), mangrove plant growth, water quality parameters (salinity, depth, temperature, DO), and fish occurrence were regularly measured on the pilot site, as well as on a control site. Water quality measures help indicating the health of the location, for example a decrease in temperature or salinity could indicate a recovery from a degraded to a healthier mangrove forest. The same applies to fish occurrence: more fish means a healthier area. Monitoring was done simultaneously at the pilot and control site, to compare the results of a site with intervention and a site without. The complete protocol (Appendix III) explains the material and methods in detail and also includes a map of the area.

Water quality parameters were measured every two weeks using a Hanna Instruments multiparameter HI98912. Plant growth was measured every month taking the length from the first root to the green tip where new leaves start growing and observational notes were taken as well (plant under water, having side branches, or yellow leaves). Fish occurrence was measured every month by placing GHOST Drift cameras. The links to the raw data collected can be found here:
➔ Excel with monitoring data

➔ Folder of monitoring photos (videos are stored on an external hard disk due to the large files)

Results & Discussion

- Water quality

With the 2-week interval, six data points were collected for each parameter, however, water quality measurements at the pilot site have already been taken since May 2022 by Mangrove Maniacs, so at this site it is easier to see a trend than at the control site (Appendix IV: graphical output for temperature, salinity and pH change over time). Temperature at the pilot has been slowly increasing, although there in a fluctuation for both sites in the data since November 2022. This is due to the time of the monitoring: low temperatures were found in the morning, and higher temperatures in the afternoon. It is therefore recommended for future monitoring to take measurements always around the same time. Salinity has been slowly decreasing at the pilot site and was roughly the same at the pilot and the control site. pH fluctuated over time around a value of 8.0, but a trend was not found.

- Plants

Most mangroves at the pilot survived (Table 2) and were developing new leaves or roots. However, lots of rainfall during the rainy season of October-November 2022 may have caused the death of some plants at the pilot. Five out of the seven plants that were dead at the final monitoring were earlier observed to be (partly) under water. The propagules planted at the control site quickly died or I was unable to find them back in the mud. Only one mangrove was found alive during the last monitoring. Therefore, calculating a mean growth rate was not possible.

Table 2 Results of monitoring mangrove propagules at the pilot and control site.

	# propagules start (11-10-'22)	# propagules end (29-12-'22)	Survival rate (%)	Mean growth rate (cm/month)
Pilot	30	23	76.667	0.1078
Control	12	1	8.3333	N.A.

- Fish

At the pilot site, 5-20 fish individuals were sighted per period of 30 minutes, both smaller and larger fish: yellow fin mojarra (*Gerres cinereus*), barracuda (*Sphyraena barracuda*) and tarpon (*Megalops atlanticus*) (Figure 6). However, sometimes the water was too turbid to retrieve any fish data. This occurred after heavy rainfall. Camera footage taken at the control site was not useful at all because of too murky water (only one crab sighted on a day with better visibility). This makes it hard to compare the two sites in terms of fish health. Based on visual observations from above water, few fish were seen near the control site, but this was still less than at the pilot itself. For future monitoring of fish, I would recommend choosing a different control site with better visibility, next to postponing filming days after heavy rainfall.

Figure 6 Fish sightings at the pilot site: yellow fin mojarra (Gerres cinereus), barracuda (Sphyraena barracuda) and tarpon (Megalops atlanticus).

- Observations

During monitoring, I noticed that the burlap had a lot of algae grown on top of it, which made the material very heavy. Either the heavy burlap attached to the BESE-elements®, or the pressure of sediment coming in from the sides, caused some of the BESE-elements® to break. Attaching the burlap was also a bit hard, which is why it got loose on some points (Figure 7). I tried to reattach this where possible. The bottom of the burlap was not attached to the BESE-elements® but buried underneath. This did not stay in place since sediment came moving inwards of the pond. Besides, the control site might not have been the best location to compare the pilot to. The soil here consisted of a thick layer of muddy clay (Figure 7) and mainly black mangroves were growing nearby (although dying as well), while red mangroves were used to plant and monitor. The different soil composition and little amount of clear water flowing by has impacted the survival of the planted mangroves here.

Lastly, comparison of the two sites is difficult because multiple factors differed between pilot and control: digging out a pond, placing BESE-elements® and placing burlap or not, as well as the soil composition. Because of time limitation, no interventions were taken at the control site. Comparison between any intervention at all or not is possible but indicating which of the three measures contributed most is not possible. If this is a desired outcome, I would recommend both a change in site selection and method: choose a control site with comparable soil composition and take the intervention there of digging a pond and placing BESE-elements®, but no burlap. This will give better insight in the use of burlap itself in mangrove restoration.

Figure 7 Photos during monitoring. Left: the burlap has gotten loose from the BESE sheets on the pilot site. Right: the soil on the control site consists of thick black mud.

Conclusion

To conclude, the mangrove growth and survival, water quality and fish cover overall were better at the pilot site than at the control site. However, proper comparison with the control site was impossible because of differences in method and soil composition. Based on this experiment and due to the heavy rainfall, which influenced the monitoring, it is still hard to draw a conclusion about the effectiveness of BESE-elements® with burlap in mangrove restoration. Although, it can be concluded that taking this complete intervention at the pilot stimulated mangrove restoration, knowing that this used to be a degraded area. This experiment showed that creating an open area for water flow, in this case combined with BESE-elements® and burlap has a added value for mangrove restoration in degraded areas. Nevertheless, considering the fact that installing the burlap was labour intense and parts of the

installation already broke down during the monitoring period, I would not recommend using this method on a large or long-term scale. With better attachment of the burlap, proper site selection for visual fish surveys and analysing soil composition for a more similar site selection, this experiment could be improved for further research and mangrove restoration efforts in Lac bay.

3.3 Reforestation Fofoti

The northern part of the mangrove forest in Lac Bay (also called Awa di Lodo) is currently experiencing a die-off. Unsustainable overgrazing by livestock (mainly goats) has resulted in a depletion of ground cover vegetation. Wind, vehicle traffic and rainwater run-off therefore cause a high influx of sediment into Awa di Lodo. The sediment build-up clogs lagoons and creeks, reducing the hydrological connectivity between the front and back of the forest, creating hypersaline conditions and causing the trees to die (Debrot, 2012; van Zee, 2020).

To fight this die-off, an area north of Lac Bay of 5.5 ha was fenced off in September 2019 for a reforestation project called Fofoti (Figure 8). 'Fofoti' is the local name for the buttonwood (*Conocarpus erectus*). Up to November 2021, 600 buttonwood trees were planted in total. The purpose of this reforestation project is to restore vegetation, reduce erosion and increase the biodiversity in this area. Part of my internship activities were watering the plants at this location and monitoring the plant survival. The research question was:

What is the survival rate of the planted buttonwood trees in the reforestation area 'Fofoti'?

I monitored this site once at the beginning of my internship (October 4, 2022) and once at the end (December 23, 2022) and compared survival rates. Plants were identified as either having green or brown leaves or being snapped (broken off and no leaves at all, just a dead branch). The percentage green plants from total was calculated as %alive (=survival rate) and the percentage snapped from total was calculated as %dead. Because of the heavy precipitation this rainy season, watering the plants was only needed once during my internship.
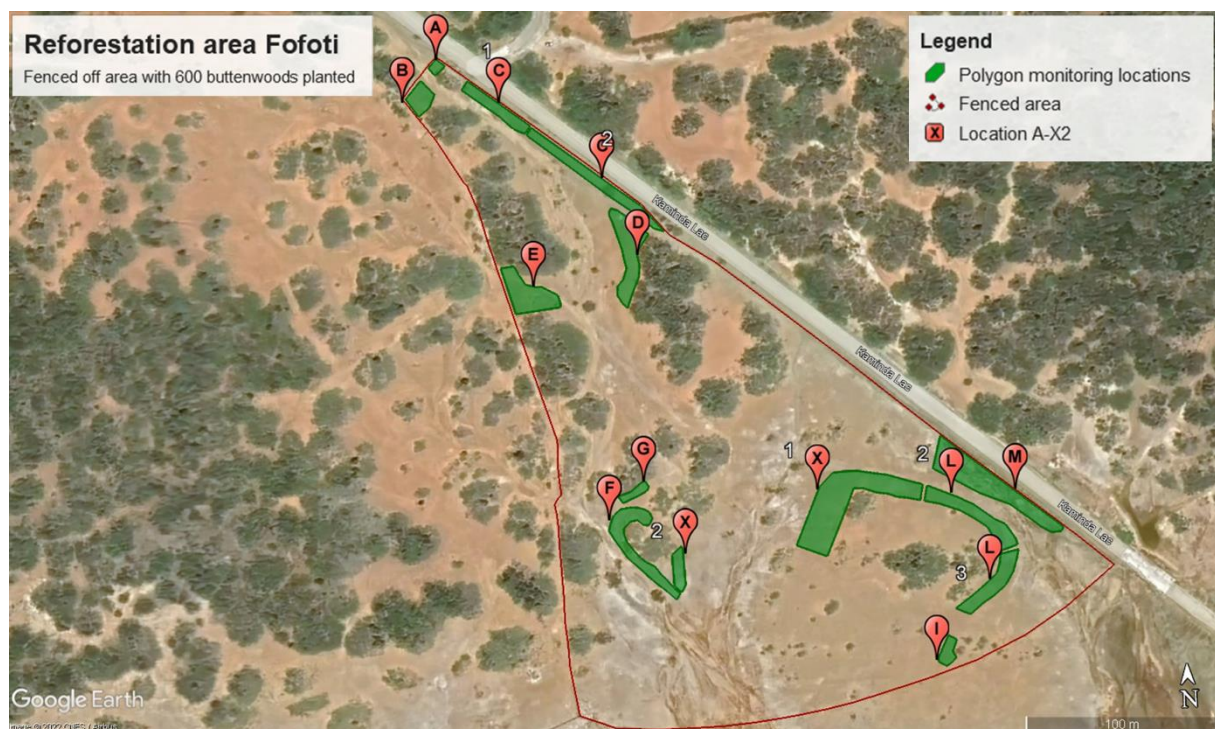

Figure 8 Location of reforestation project 'Fofoti'. Green polygons represent the areas where buttonwood trees are planted, indicated with a letter (A-X2). Some letters are double and have a small indicator 1, 2, or 3.

Results & Discussion

During the first monitoring, 499 out of the 600 planted trees were still there. From the 499 trees, 65.5% had green leaves (thus noted alive). So, from the initial 600 trees, this was a survival rate of 54.5%. Between the first and the final monitoring, precipitation levels were high due to the rainy season (Figure 9). This probably caused some of the trees that were first noted as brown or snapped to restart growing, because survival rates at the final monitoring were found to be higher at almost all plots (Figure 10). From the 600 planted trees, 472 were still found from which 74.7% had green leaves (Figure 11). From the initial 600 trees, this was a survival rate of 58.5%.
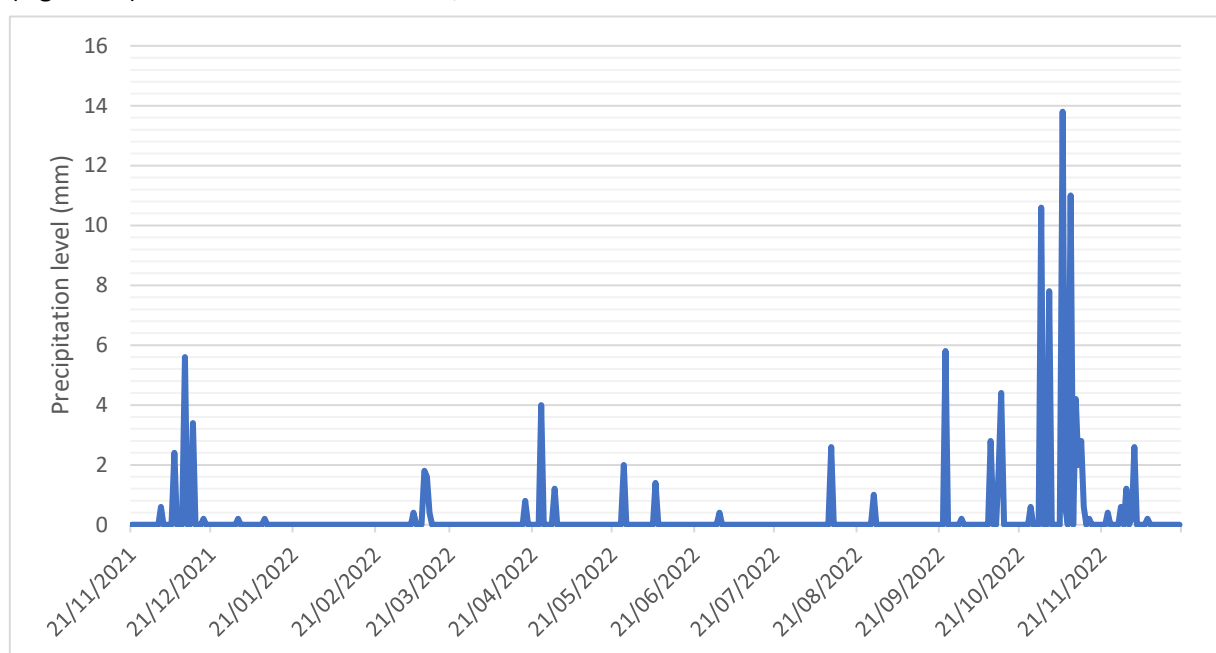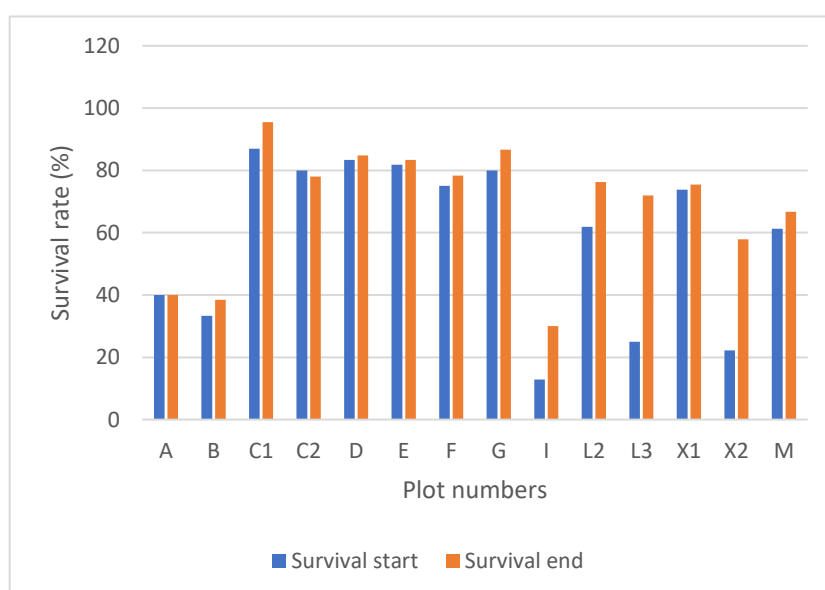

Figure 9 Cumulative amount of rain per day at reforestation site 'Fofoti' during 2022.

All data can be found here. Photos of the area during monitoring can be found in this folder.

Figure 10 Survival rates of buttonwoods at the different plots. Start monitoring: 4 Oct 2022, final monitoring: 23 Dec 2022.

Figure 11 Green buttonwood trees, after the rainy season of 2022.

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Small gullies were visible in the sediment spread over the whole reforestation area that flowed from the hinterland into Lac Bay. This means that this would indeed be a suitable area for reforestation since the new vegetation can help stabilizing the sediment. Location I and X2 are closest to Lac, dealing with the most water run-off, and had the lowest survival rates (Figure 8 and 10). Therefore, it is important that locations north of this area first grow enough vegetation so less run-off will end up at these most southern plots, where reforestation is now still difficult. Recommendations for placing dams, planting trees and maintenance on gates are already done by the company BonBèrdè.

3.4 Monitoring southwest coast

Together with Jessica Johnson, I monitored mangroves that were outplanted along the southwest coast of Bonaire. These mangroves are taken from the nurseries in Lac Bay and are planted here to form a 'green wall' and function as a form of coastal protection once they are bigger (Spalding et al., 2014; Tiggeloven et al., 2022). Some of the mangroves were planted using rocks for stabilization (red mangroves) or were dug into the sand (black mangroves) by volunteers during events like on the 23rd of September (see 3.1). Other mangroves were previous experiments from other students, like the BESE-pilot from Shamyi Lanjouw early 2022 (Lanjouw, 2022).

During a first inventory (September 5, 2022) with Sabine north of Salt Pier, we observed something that looked like a difference in mangrove growth between the plots with and without BESE-elements® (Figure 12). From the long-term monitoring data, I was only able to identify the two set-ups 'Natural Pond' and 'Coral 2' from Shamyi's plots located at Margate Bay and mean survival rates for these two site set-ups together were 57.4% for with BESE-elements® and 79.6% for control. This does not align with our observation, although this was at a different location along the coast. When more time allows, a better identification of the site set-ups, locations and labels should be executed to draw a conclusion about the use of BESE-elements® for mangrove restoration along a high-wave energy coastline. Results so far indicate that long-term monitoring of this experiment could be valuable and give new insights.

A full monitoring of the sites was done by Jessica and me on November 1, 2022 for all locations between Red Slave and Salt Pier.

Figure 12 Surprised by the long-term outcome of the mangrove-BESE experiment near Salt Pier.

3.5 Data analysis & literature review

Another part of this internship consisted of analysing data previously collected by Mangrove Maniacs, as well as conducting a literature review. These analyses together were called 'Project Portfolio', referring to the portfolios created for each project which include a short overview of the research question(s), method, results and implications. Links to data, portfolios and if applicable, publications, can be found in Table 3, beside the full portfolios of each project in Appendices VI, VII, VIII and IX. The portfolios about mangrove aerial root/trunk growth and propagule growth formed input for an article published on DCNA's BioNews and Nature Today (Appendix X). The topic of my literature review was about the genetic population connectivity of red mangroves, at the request of Octogroup. This literature review will be sent out to the MPA Help list of over 11,000 global MPA practitioners in early January 2023.

Table 3 'Project Portfolio: an overview of all links to raw data, the portfolios themselves and, if applicable, a link to the published news article.

Project	Link to data	Portfolio overview	Published
Mangrove aerial root/trunk growth	Mangrove Monitoring Project_Bonaire 2020_incl graphs JH	Portfolio - Mangrove root & DBH data (JH_Oct 2022)	DCNA BioNews Nature Today
Mangrove propagule growth	Mangrove propagule growth_incl graphs JH	Portfolio - Propagule growth data (JH_Oct 2022)	DCNA BioNews Nature Today
Red mangrove genetic population connectivity	Non-open-access literature used in review	Portfolio - Genetic population connectivity R. mangle	Will be sent to MPA Help list – Jan '23
Water quality data-analysis	WQ monitoring 2021-2022	Portfolio – WQ data analysis (JH_Dec 2022)	

3.6 Seagrass restoration & monitoring

Lac Bay

During the week of November 28, 2022, I worked on seagrass restoration in Lac Bay together with Jessica Johnson, Sabine Engel, Fee Smulders, Marjolijn Christianen, Karin Didderen and others as part of STINAPA's RESEMBID project in Lac. We harvested turtle grass (*Thalassia testudinum*) from a healthy area at Sorobon and replanted them using BESE-elements®. Part of this fieldwork was also giving a workshop to STINAPA rangers to teach them about seagrass and how to monitor this new experimental site in Lac Bay (Figure 13). I had a supporting role during this week of fieldwork and helped harvesting seagrass, digging in BESE-elements® and training the rangers.
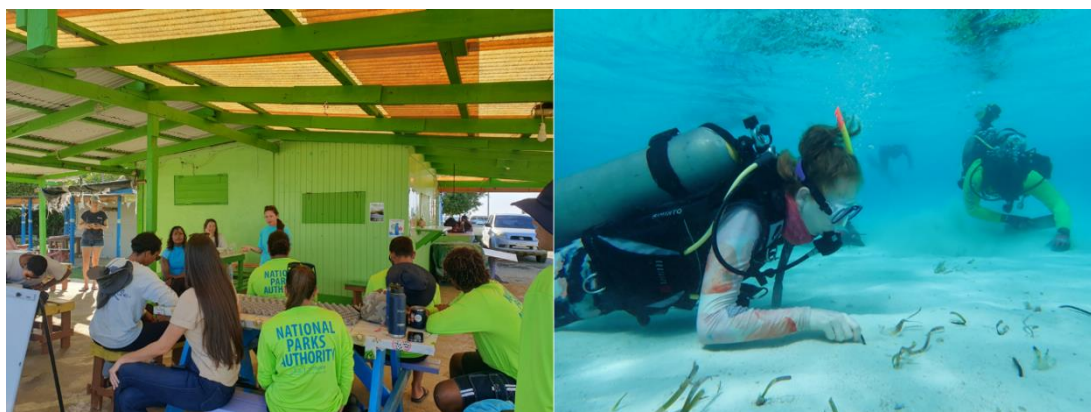

Figure 13 Training STINAPA rangers and digging in BESE-elements® with seagrass in Lac Bay.

Monitoring conch and seagrass

A yearly survey of seagrass, Halimeda and Queen Conch cover in Lac Bay is executed by Stichting Internos and funded by STINAPA to continue a qualitative seagrass survey in Lac Bay, which was first conducted by Hummelinck and Roos in 1969. Since then, additional surveys were conducted in 1999, 2007, and on a regular basis since 2011 (2011, 2013, 2015, 2017, 2018, 2019, 2020, 2022). Raw data from each survey are uploaded to the Dutch Caribbean Biodiveristy Database (DCBD) and have been referenced by a number of scientific publications, most notably the seagrass and sea turtle research by Christianen and Smulders from Wageningen University and Research (WUR). The results of these surveys give more insight in the responses of seagrasses in Lac Bay to threats like decreasing water quality (from wastewater and sunscreens), trampling (by tourists), smothering (by large influxes of sargassum), and the invasion of the species *Halophila stipulacea* which is spreading since its first documentation in 2010 and could outcompete the local species of seagrasses.

Data is collected from 49 plots, by measuring the seagrass and Halimeda cover six times in a 1x1m grid and by counting the number of Queen Conch found in a 30x30 m transect and by measuring their length. Some of the plots are very shallow and those were done while snorkelling. Diving gear is needed for the deeper locations. A more detailed background, methodology and results of the previous survey (April 2022) can be found here for seagrass and Halimeda and here for Queen Conch. During my internship, Rens Jonker and I did part of the fieldwork for the survey of 2022-2023. We were able to measure 11/49 plots. Photos and data of this survey can be found in this folder.

Klein Bonaire

The second site where I worked on seagrass restoration and monitoring is the island of Klein Bonaire. First, I went to Klein Bonaire (October 5, 2022) to take photos and observations of the old experiment that was still there since 2021. Almost no seagrass was growing at the experimental site, only small amounts of *Halodule wrightii*. There was no difference visible between plots with or without BESE-elements® or with or without cage (turtle exclosure). Some BESE-elements® were moved or broken because of wave action and sediment movement. However, these results might have been due to improper installation of the BESE-elements® and therefore it was decided to re-do the experiment.

During the field visit of Fee Smulders (November 21, 2022), Fee and I removed the old BESE-elements®, prepared the new set-up together by collecting all materials and with the help of three volunteers, we re-installed the experiment. An overview of the set-up and the different used treatments can be found in the protocol written by Smulders (Appendix V).

Installation

On November 25, we installed new BESE-elements® with Thalassia shoots. This was only done at the plots with a BESE treatment (see protocol). Beforehand, we organised a boat ride with STINAPA and gathered some volunteers to help us in the field. *Thalassia testudinum* shoots were collected on the same morning from Sorobon, Lac Bay. After a few hours, we took the boat to Klein Bonaire and planted the seagrass, by putting the Thalassia shoots in the BESE-elements® and digging the BESE-elements® under the sediment by using dive gear and a shovel. Intermediate results showed a loss of Thalassia shoots in plots of all treatments and visual observations were made of grazing sea turtles and (parrot) fish, immediately after installation (Figure 14).

As a result, we decided one week later to install small cages as fish exclosures as well (Figure 15). On all cage treatments (plot 2, 10, 13, 14, 16), six new Thalassia shoots were planted in the sediment, placing the fish exclosure on top and securing this with tiewraps and rebar pins.

Figure 14 Left: turtle grazing seagrass in an open plot. Right: turtle trying to graze the seagrass in a cage plot.

Figure 15 Fish exclosure (small cage) with Thalassia shoots, within a turtle exclosure (big cage).

Monitoring

During the remainder of my internship, I went back every week to monitor the site according to the protocol made by Smulders (Appendix V). I organised rides to the island with the Woodwind and Sea Turtle Conservation Bonaire, and sometimes got help with monitoring by a volunteer. The data collected were put in an Excel file and a folder for photos of the plots. Footage collected with Ghost Drift cameras is stored on an external hard drive because of the large files, however interesting screenshots of turtles and fish are stored in the same photo folder mentioned above.

Results & Discussion

Thalassia shoots only survived in the cage treatment, and then specifically within the small fish cages. The average number of Thalassia shoots decreased a bit over the weeks (Table 4), which could be due to smalles species still able to penetrate the cage, or because of accidental tearing off leaves during the monitoring. Camera footage shows that even after disappearance of the Thalassia at most plots, the density of grazing fish and sea turtles in this area is still high (Figure 16). Because of this high grazing pressure, it does not seem like the Thalassia gets a chance to grow back easily outside the small cages. The fish cages themself get quickly covered by algae, so regular maintenance would be needed to ensure enough light penetration.

Table 4 Average number of Thalassia testodinum *shoots per treatment.*

Treatment	25/11/2022	08/12/2022	16/12/2022	23/12/2022	28/12/2022
BESE	15	0	0	0	0
Cage	15	8.6	8.2	8	7.4
Cage + BESE	15	0	0	0	0
Control	15	0	0	0	0
Grand Total	**15**	**2.15**	**2.05**	**2**	**1.85**

Figure 16 Fish grazing algae in a cage plot.

At the final monitoring, grazing marks on Thalassia leaves, *Halodule wrightii* occurrence and sediment movement were also measured (Appendix V). For the Thalassia leaves in the small cages, no grazing marks (neither turtle nor fish) were found. Halodule cover was found to be highest in the cage and control treatments (low in treatments with BESE-elements®) and slightly decreased since the start measurement (Table 5). Sediment accumulation was observed within the small cages.

Table 5 Average number of Halodule wrightii *shoots in 0.5 x 0.5m quadrant per treatment, before and after installation of the experiment.*

Treatment	20/11/2022	28/12/2022
BESE	1.4	0.8
Cage	33.6	23.8
Cage + BESE	0.4	3.2
Control	24	32.2
Grand Total	**18.85**	**15.00**

Conclusion

Depending on the sea turtle density and the amount of seagrass already present at a certain location, a suitable restoration method should be considered. In this case, a high density of turtles and no natural presence of Thalassia,anymore results in a high grazing pressure of both turtle and fish and only the small fish exclosures allowed Thalassia to grow. Implications of these results for future seagrass restoration initiatives include using fish exclosures on a larger scall (high level of depletion/maintenance) and identifying restoration areas with a higher natural presence of seagrass which could reduce the grazing pressure. Although seagrass restoration on Bonaire will remain a challenge, this experiment provided new insights on the novelty of using fish exclosures.

4. General conclusion

A variety of conservation and research efforts regarding mangrove and seagrass restoration already takes place on Bonaire, either by Mangrove Maniacs, STINAPA, or students. I was able to participate in these restoration activities during my internship or organise them myself. I learned that Mangrove Maniacs is already quite far with community engagement and identifying reasons for degrading mangrove forest instead of only initiating reforestation efforts which are usually not successful if not combined with other activities (Lovelock et al., 2022; Lovelock & Brown, 2019; Rodríguez-Rodríguez et al., 2021). Simultaneously opening channels in the mangrove forest, doing reforestation projects, educating locals and volunteers and doing research on best restoration methods are all activities that help to conserve the health of the mangroves. However, challenges for mangrove restoration on Bonaire remain. There are still some knowledge gaps for best restoration methods in Lac Bay as well as for planting mangroves along the coastline as coastal defence. The list of questions below is a start for further research to overcome these knowledge gaps.

For seagrass restoration, it can be concluded that grazing pressure determines the success of a restoration site, and this is currently too high for regrowth of Thalassia at Klein Bonaire. A more balanced ecosystem with more natural predators present (sharks) could help reducing this pressure and thus help restoring the seagrass (Christianen et al., 2023). In Lac Bay, different pressures are present (invasive species, excess of nutrients, trampling, Sargassum) and therefore different measures should be taken, which is already part of STINAPA's management plan. However, monitoring the RESEMBID project will give more results on the success of seagrass restoration in Lac Bay.

There were some weaknesses in the results that could have affected the outcomes of my internship activities. First, a proper site selection was not always done before the start of an experiment. For the pilot at Isla Yuwana, another control site could have resulted in better mangrove growth at the control due to soil composition or more fish data due to a better visibility. The seagrass restoration experiment was already installed at Klein Bonaire before I came here, but a different location could have resulted in a lower grazing pressure and better growth of the seagrass (e.g., in Lac Bay). Secondly, access to data or information of research that was done before me was sometimes incomplete or the data were hard to analyse or interpret if I was not part of the process. I received help from my supervisors for this but did not always feel able to draw the right conclusions due to little knowledge. Finally, minor errors could have occurred in data handling or installation of experiments due to human mistake (either me or helping volunteers). Leaves were sometimes accidently broken off while monitoring, materials were forgotten or not installed secure enough. However, this will only have had a minor impact on the results.

To conclude, my general recommendations for mangrove and seagrass restorations would be to monitor external factors (like soil composition, water quality, grazing) before starting a new restoration site somewhere. Based on this information and depending on the desired outcome of the research or restoration site, a suitable site can be selected. Although new insights will probably be developed by trying out new methods and locations, this could help the success of mangrove and seagrass restoration.

Some remaining research questions for future mangrove and seagrass restoration (could be added to the 'wish list' of Mangrove Maniacs):

- What is the effect of sun versus shade on mangrove growth?
- Which mangrove species, red or black, is most resilient regarding changes in salinity, tide, wave action? Which species is best to use for planting at which location?

- Lab experiments to exclude multiple factors present in the field: what is the effect of salinity on survival/growth of red/black mangroves or on aerial root/trunk growth?
- What is the difference in soil composition on the pilot and control site near Isla Yuwana?
- How much sediment is flowing into Lac Bay via reforestation area Fofoti? How much is captured by the installed sediment trapped and can this be improved? What are the best areas to plant more buttonwood? What will be their survival rate in the dry season?
- Seagrass restoration at Klein Bonaire: how will the seagrass in the plots with fish exclosures develop? Is this method feasible on larger scale or useful at other locations on Bonaire?
- Seagrass in Lac: finishing the yearly survey. Did the cover of different seagrass species, Halimeda and conch in Lac changed and how? What is the reason for this?
- Monitoring outplant of RESEMBID project by rangers: what is the survival and growth rate of planted seagrass in Lac Bay? What is the best way to continue this restoration project?

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Appendices

Appendix I. Overview of weekly activities & Trello

Week 1 (05-09):

- Introduction to MM activities
- MM work in the channels
- Tour along different pilots and outplant sites
- Reading literature
- Volunteering: beach clean up & mapping corals

Week 2 (12-09):

- Start meeting with supervisors
- Meeting with local co-workers
- Meeting about seagrass restoration project
- Making contact list for Blue Carbon Network
- MM work in the channels
- Making planning for different activities
- Tour to SW coast outplant sites
- Buy materials for pilot Isla Yuwana

Week 3 (19-09):

- Processing data of mangrove root/stem growth research
- MM work in the channels – placing tidal sensors with Jessica
- Thalassia snorkel survey & process notes
- Monitor mangrove outplants SW coast
- Presentation: Climate Change Effects on Bonaire
- (Preparation for) Outplant event 23/09

Week 4 (26-09):

- Mail & planning
- Blue Carbon network meetings
- Processing data of mangrove root/stem growth research
- MM work in the channels – reading WQ sensors with Jessica
- Test method for pilot Isla Yuwana
- Snorkelling Klein Bonaire with Sabine
- Deploy experiment Isla Yuwana with volunteering students
- Make outline internship report

Week 5 (03-10):

- Literature research
- Monitor pilot Isla Yuwana
- Monitor Fofoti
- Process data
- MM work in the channels
- Snorkelling Klein Bonaire with Carmen
- Meeting with Jessica & Sabine

Week 6 (10-10):

- MM work in the channels
- Data analysis (root/propagule data)
- Pilot IY work: label/measure plants, monitor fish, analyse, write protocol
- Make presentation slides BEST2.0+
- Meeting with Sabine & Jessica

Week 7 (17-10):

- MM work in the channels
- Finish portfolio: root/stem & propagule data
- WQ data analysis
- Presentation evening BEST2.0+
- Kick-off meeting RESTROP

Week 8 (24-10):

- Meeting with Sabine
- MM work in the channels
- Pilot: plant trees at control site, do WQ measurements
- Progress Evaluation Meeting
- (Preparation for) LVV Open Day
- Writing BioNews article
- Monitoring SW coast

Week 9 (31-10):

- Work on internship report, reflect on learning goals
- Meeting with Sabine
- Finish literature review genetics
- Finish writing BioNews article
- Training seagrass & conch monitoring Lac
- Full monitoring SW coast with Jessica

Week 10 (07-11):

- Volunteering: turtle netting with STCB
- Working on internship report
- Monitor plants/WQ/fish at pilot Isla Yuwana
- Seagrass & conch monitoring Lac
- Preparation field work Klein Bonaire
- Process feedback on BioNews article

Week 11 (14-11):

- Seagrass & conch monitoring Lac
- MM work in the channels (incl. monitoring nurseries)
- Analyse WQ data, update all graphs
- Preparation field work Klein Bonaire

Week 12 (21-11):

- MM work in the channels

- Meeting with Fee, Sabine, Jessica
- Monitor seagrass experiment Klein Bonaire (with Fee)
- Break down old seagrass experiment Klein Bonaire (with Fee)
- Prepare & set up new experiment Klein Bonaire (with Fee)
- WQ measurement at pilot Isla Yuwana

Week 13 (28-11):

- Field work seagrass Lac (with Fee & Marjolijn), harvesting & installation BESE
- Training STINAPA Rangers about seagrass
- Installing small cages (fish exclosures) at Klein Bonaire

Week 14 (05-12):

- MM work in the channels
- Monitor plants/WQ/fish at pilot Isla Yuwana
- Monitor seagrass at Klein Bonaire
- Writing report
- Day off because of family visit

Week 15 (12-12):

- Days off because of family visit
- MM work in the channels
- Writing draft version internship report + reflection learning goals
- Meeting seagrass monitoring RESEMBID
- Monitor seagrass at Klein Bonaire

Week 16 (19-12):

- WQ data analysis
- MM work in the channels
- Final monitoring Fofoti + data-analysis
- Monitor seagrass at Klein Bonaire
- Process feedback on draft internship report

Week 17 (26-12):

- Christmas break
- MM work in the channels
- Final monitoring seagrass Klein Bonaire
- Final monitoring pilot IY
- Writing reflection on learning goals
- Writing final internship report

Week 18 (02-01):

- Writing final internship report, editting
- Preparing final presentation
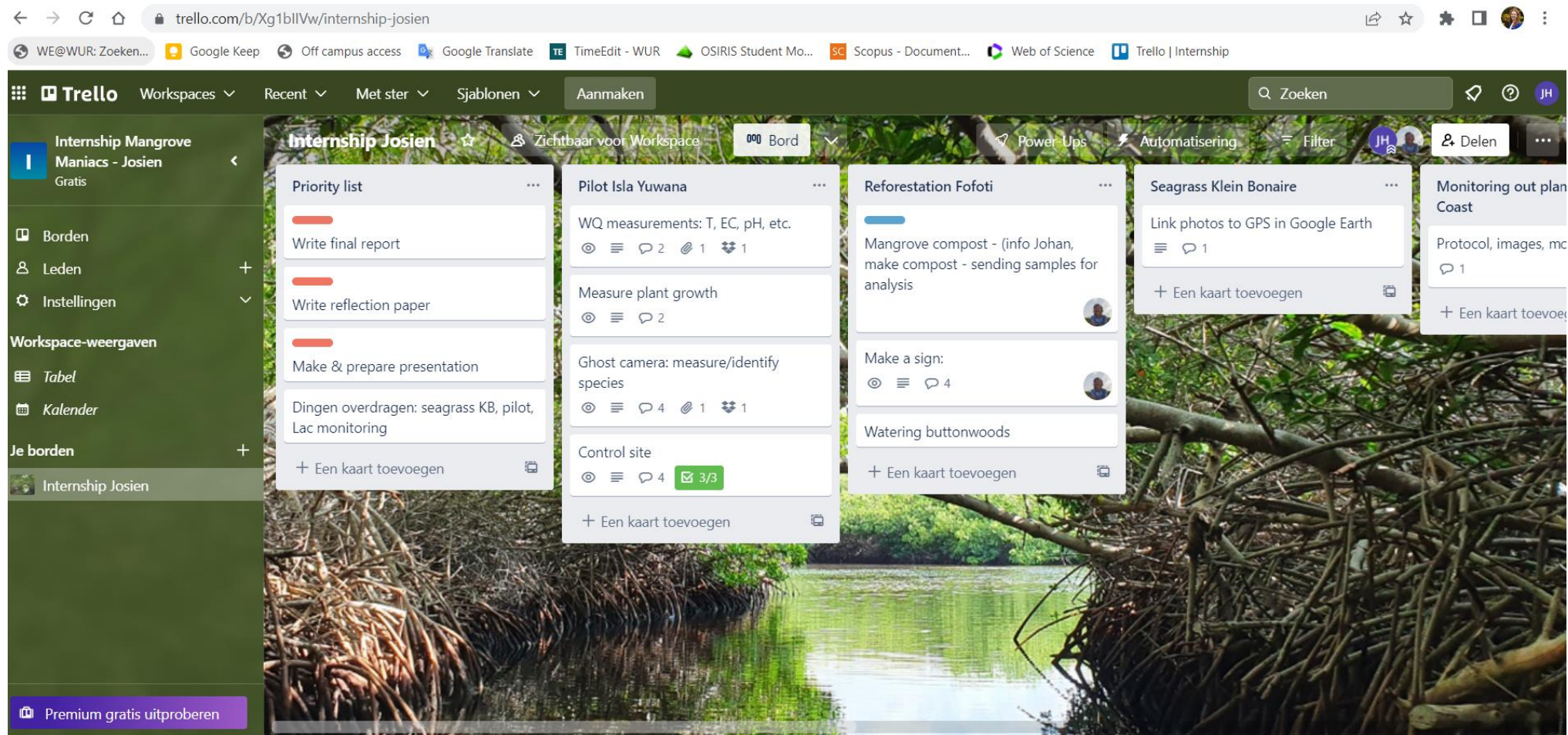
Figure 17 Trello interface - the website used for keeping track of the internship activities together with the internship host. Check lists, notes, files, links, etc. can be added to a shared board to collect all information in one place.

Appendix II. Relevant links to research output

➢ **Protocols**

Pilot Isla Yuwana: https://www.dropbox.com/scl/fi/ymk06u2rm4iistig115gg/Protocol-pilot-Isla-Yuwana-material-method.docx?dl=0&rlkey=f8exrljl6oaapw0y0ttg6dkk4

➢ **Portfolio files**

Water quality data analysis: https://www.dropbox.com/scl/fi/t7dqd9v1fdnbkbynnhrov/Portfolio-WQ-data-analysis-JH_Dec-2022.docx?dl=0&rlkey=014lxuekp1ueu48e2xy3sc7ij

Mangrove root growth: https://www.dropbox.com/scl/fi/l2ad3ke1lbq9zisrzlc74/Portfolio-Mangrove-root-DBH-data-JH_Oct-2022.docx?dl=0&rlkey=rpw5s00rh1aqs5pa9dgf0op33

Propagule monitoring: https://www.dropbox.com/scl/fi/vwslx5kk9zy0s1mib8n0x/Portfolio-Propagule-growth-data-JH_Oct-2022.docx?dl=0&rlkey=g6smvrihy2i1ikbhf8js62om0

Literature research genetics: https://www.dropbox.com/scl/fi/qu5psis9gl4opfz0d4fcv/Portfolio-Genetic-population-connectivity-R.-mangle.docx?dl=0&rlkey=yph6ce5hoo15xn9o301kps0d2

➢ **Published articles**

https://dcnanature.org/mangrove-monitoring/

https://www.naturetoday.com/intl/en/nature-reports/message/?msg=30132 (English)

https://www.naturetoday.com/intl/nl/nature-reports/message/?msg=30132 (Dutch)

https://bonairereporter.com/back_issues/2022/202221.pdf (Mangrove Maniacs presentation night)

➢ **Presentation slides**

https://www.dropbox.com/scl/fi/ti8jhte1h6ljmlykuhtki/Presentation-Josien*20102022*-Internship-Research-updates.pptx?dl=0&rlkey=j29djicne9m8ov4ebx4e63sxb

Appendix III. Protocol pilot site Isla Yuwana

Materials

- 24 red mangrove propagules from the nursery
- Mix of 30 labelled red/black mangroves (already planted)
- BESE-elements (already installed)
- Burlap, 30 meters, cut in pieces of 1,5 x 1,0 m
- 10 rebar pins
- Scissor
- Rope
- Labels
- Hole puncher
- Hanna Instruments multiparameter HI98912
- GHOST Drift camera
- Measuring tape
- Writing slate

Method

Installation

On 30 September 2022, burlap was installed at the pilot site (Figure 1; 12.115827, -68.240796) by a group of six WUR students, guided by intern Josien Hendricksen. The BESE + burlap mimic the root structure of mangroves and are installed to prevent sediment from going into the little pond (that was dug out in an earlier experiment, together with installing the BESE and planting mangrove propagules). In the end, the idea is that the roots of the outplanted mangroves will take over this structure once degraded.

Burlap was cut in pieces of 1.5 x 1.0 m and with metal rebar pins and rope they were attached to the BESE elements. Two pieces of burlap were attached to one metal pin by cutting a hole in the burlap with a scissor. Rope was only used to attach the top pieces to the BESE elements, since the BESE are

Figure 18 The pilot site is located at the red pin, also shown by the yellow box with dotted line in the zoomed-in picture. The island on the bottom right is Isla Yuwana.

very fragile and easily break when too much pressure is put on them. On the bottom, the burlap was not attached but only dug into the mud underneath the BESE because it was too hard to see anything at that depth.

A control site was chosen a bit north of the pilot site (Figure 2; 12.117571, -68.239354). Red flagging tape attached to the trees point out the location at the site itself. This location was chosen because it also connects to a large water body and is in a degrading area, so roughly the same environmental conditions apply compared to the pilot site. However, at the control site, no human interference measures were taken (digging a pond, using BESE sheets and attaching burlap). At this site, 24 red mangrove propagules were planted of which 12 were labelled to measure.

Figure 19 Location of control site at the red pin relative to the pilot site (orange pin).

After installing burlap at the pilot site, the mangrove propagules that were already planted there before by the Mangrove Maniacs were labelled (L1-6, M1-6, MM1-6, R1-6 and RR1-6, see Table 1 and Figure 3 below). These mangroves were a combination of red and black mangroves. Different patterns of hole punching were used to distinguish the labels from each other, since writing with a marker would quickly disappear due to exposure to salt water and sunlight.

Table 1 Explanation of label names

Label name in datasheet	Explanation of location on the label
L (1-6)	Holes on the left side of label
M (1-6)	Holes in the middle of label
R (1-6)	Holes on the right side of label
MM (1-6)	Holes overlapping in the middle of label
RR (1-6)	Holes overlapping on the right edge of label

R2, MM2, RR2.

<u>Monitoring</u>

To monitor any changes in the pilot and control site, three things are measured: water quality parameters (salinity, depth, temperature, DO), plant growth, and fish occurrence. Water quality measurements are taken every two weeks using Hanna Instruments multiparameter HI98912 and downloaded at a regular basis. Plant growth is measured every month (starting 11 October, 2022) by taking the length of the plant from the start of the first root to the green tip where the top leaf starts to grow. Notes about special observations are also taken (e.g., plant completely under water, yellow leaves, side branch). Fish occurrence is measured by installing a GHOST Drift camera every month for 3-5 hours. A rebar pin is used to stick the camera in the mud (at the pilot site, there is one sticking out from the side at the entrence you can use). Within the camera footage of 3-5 hours, 30 minutes are taken to analyse closely. This should be a timeframe when most sediment is settled and light is optimal.

Note: when doing maintenance/measuring plants and filming with the GHOST camera, make sure not to walk through the entrance to stir up all the sediment (or start your 30min frame later).

Links to data

- *Link to Excel datasheet:*

https://www.dropbox.com/scl/fi/6452keipv0v09tkpwqy1f/IY_mangrove-growth-monitoring-2022.xlsx?dl=0&rlkey=earg26pfjd20lqoaji78gr72d

- *Link to screenshots of fish:*

https://www.dropbox.com/scl/fo/mcel0h6t913l6v18hhzp7/h?dl=0&rlkey=27htegcn4rx52tbb8saisjcsj

- *General pictures of the site:*

https://www.dropbox.com/sh/06y2dtc4pnad7ns/AACO0_vw9UDaydtOERarGTX7a?dl=0

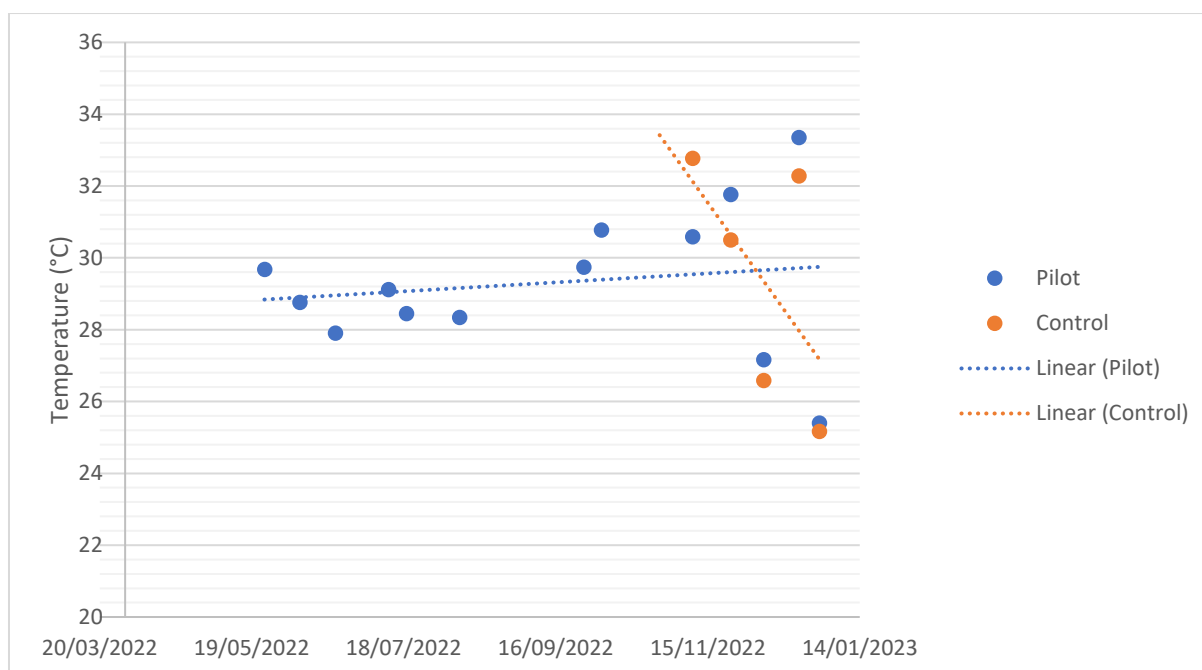# Appendix IV. Additional graphs

Pilot Isla Yuwana:

Figure 21 Temperature change over time at the pilot and control site near Isla Yuwana, Lac Bay.
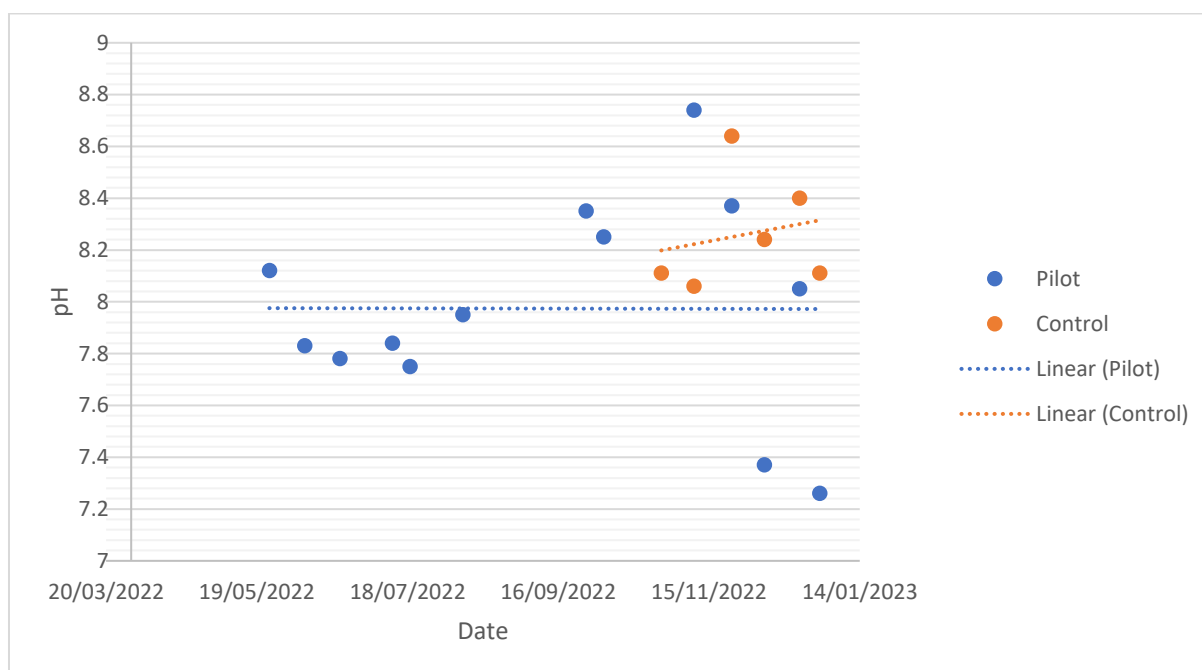

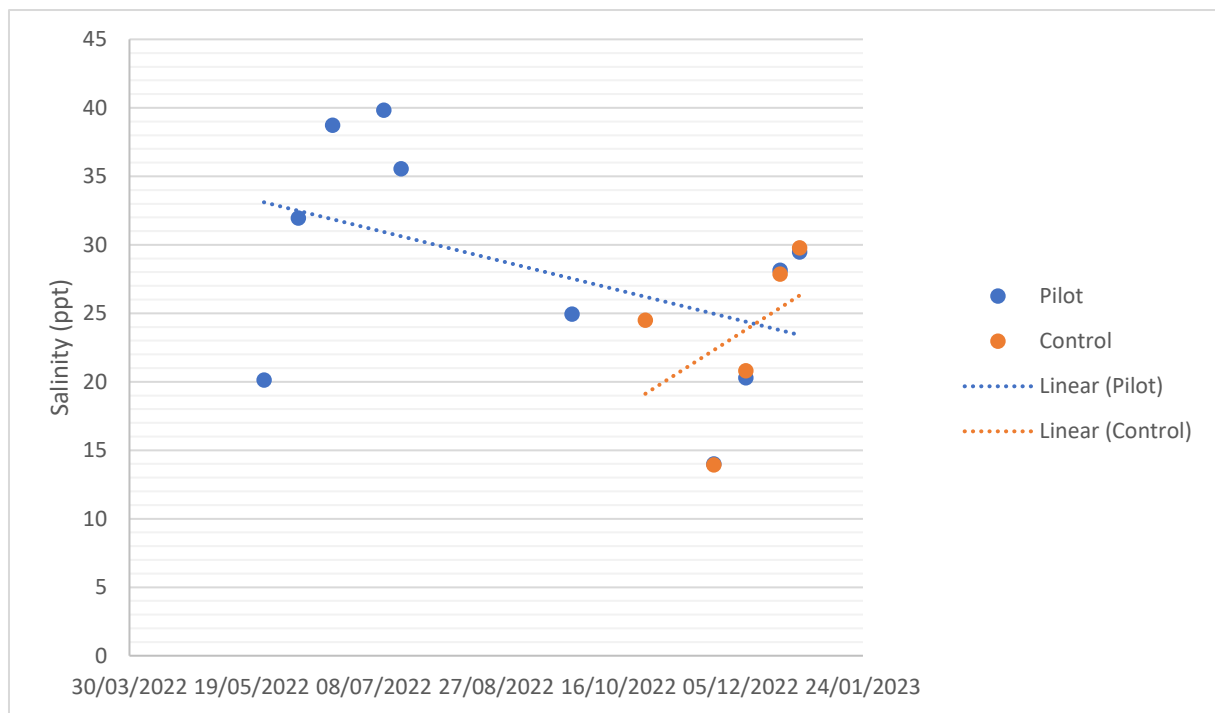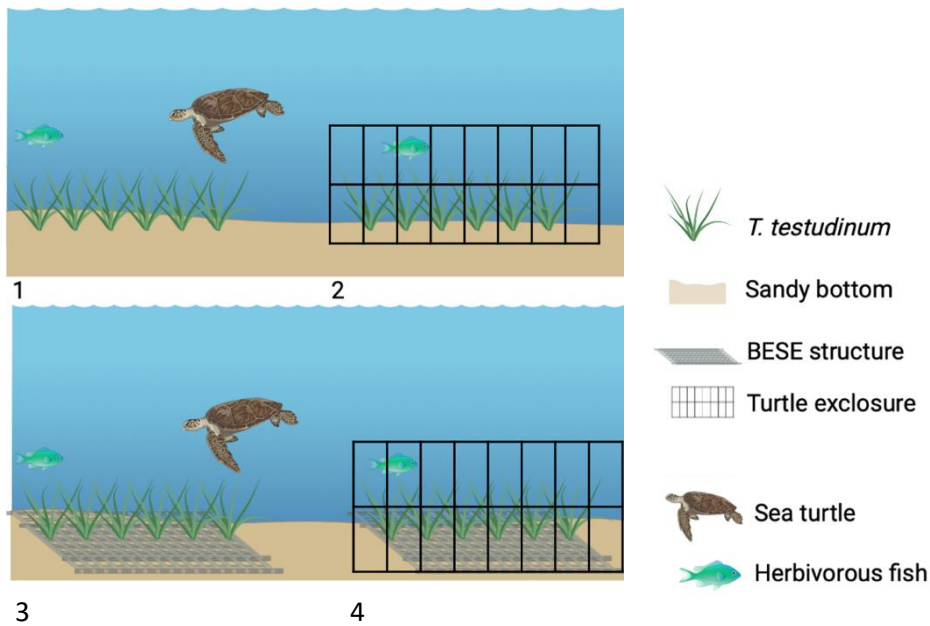*Figure 22 pH change over time at the pilot and control site near Isla Yuwana, Lac Bay.*

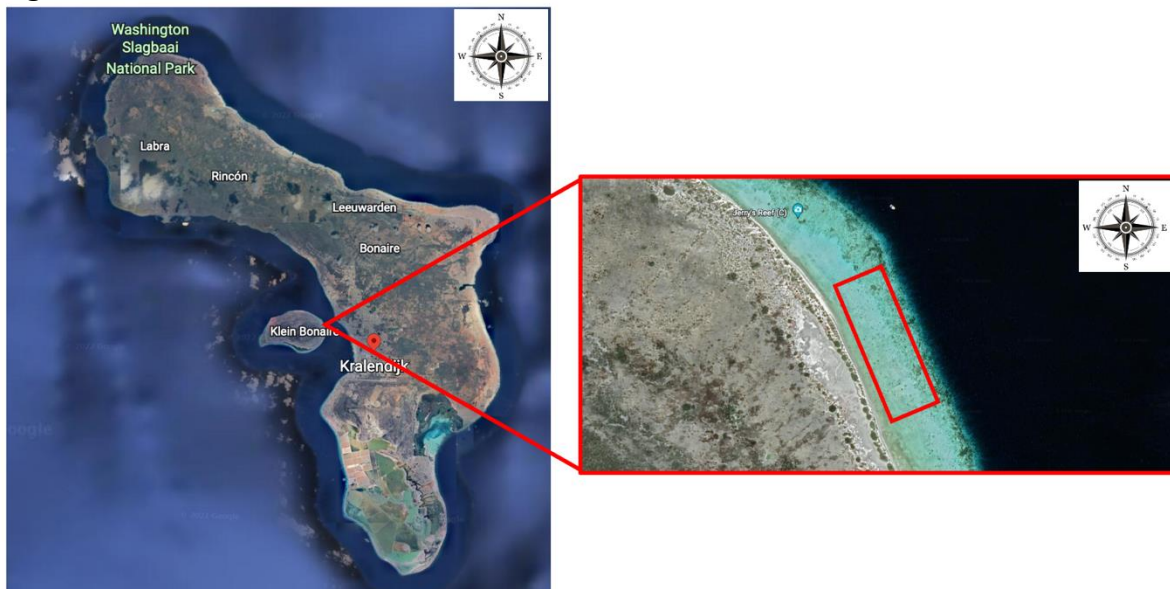*Figure 23 Salinity change over time at the pilot and control site near Isla Yuwana, Lac Bay.*

Impact of turtle grazing and BESE on *T. testudinum* restoration success – Experimental set up
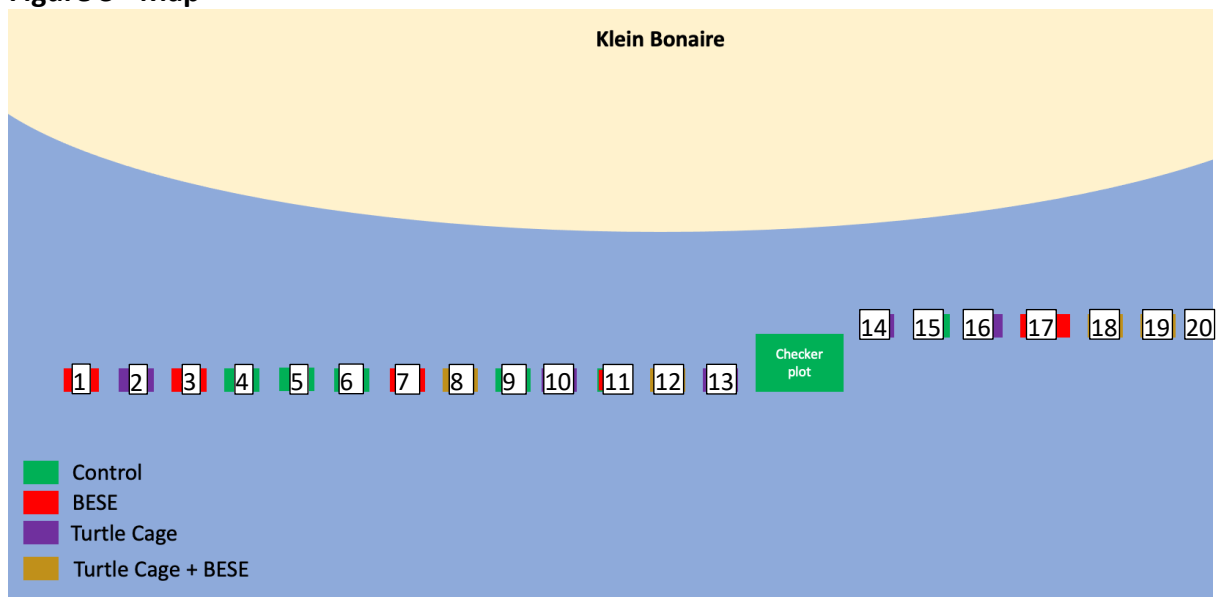
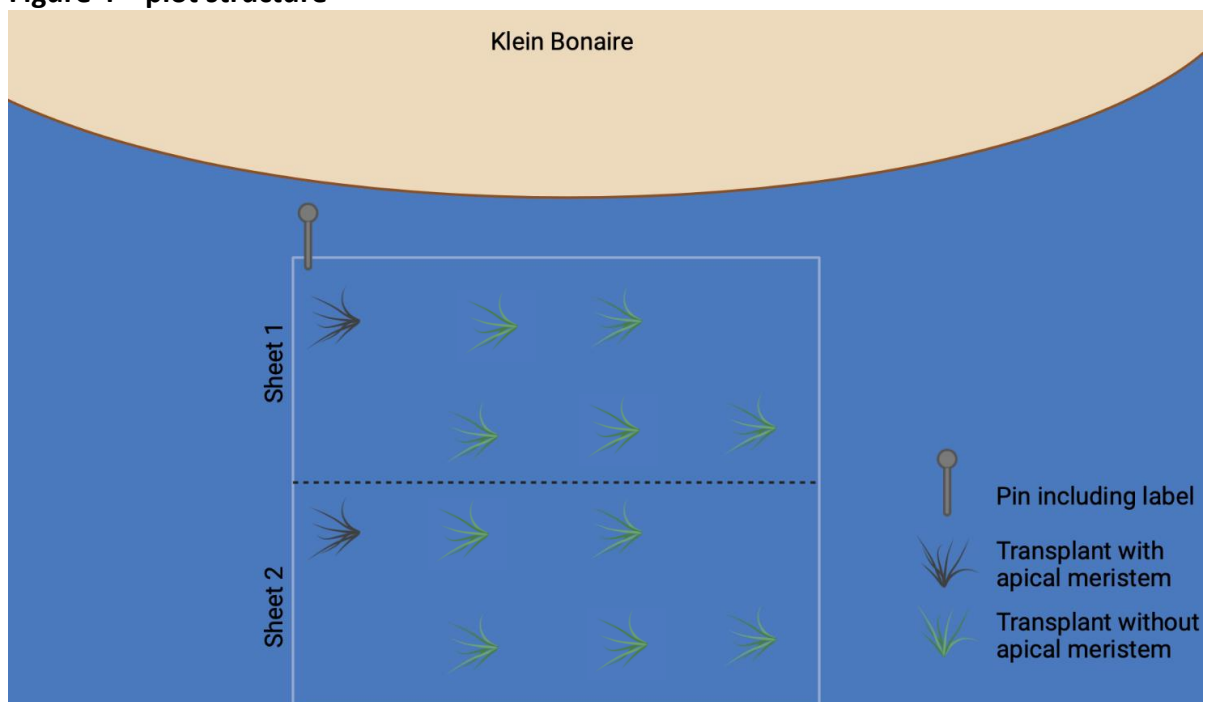**Figure 1 – Treatments: (1) Control, (2) Cage, (3) BESE, (4) BESE + cage**

Figure 2 – location

Figure 3 - Map

Figure 4 – plot structure

Plots and treatments are set up as follows:

- Each plot consist of ~1m^2 with 12 *T. testudinum* fragments per plot (10 non-apical, 2 apical, see figure 4). Each plot has one rebar pin where a label can be attached.
- Control plots: 12 fragments are buried in the sediment
- BESE plots: 2 BESE sheets are placed next to each other to form ~1m^2.
- Cage plots: 12 seagrass fragments are placed in the imaginary middle 1m^2 of the cage. This way, the turtles cannot reach the seagrass leaves from the side of the cage. Additionally 5 fish exclosures are placed at the top right 0.25m2 (near the label) with 3 fragments inside.
- Cage + BESE sheets: 2 BESE sheets are buried in the middle of the cages

Monitoring protocol

- For each plot (1 to 20), count the number of *T. testudinum* shoots with green leaves. Even if it is a tiny bit of green. For this, you need to wave away the sand to see properly. Do not count brown stumps.
- For plots with fish exclosures (plot 2, 10, 13, 14, 16), write this down separately (i.e. plot 2: total: 12 shoots; turtle excl: 3 shoots; fish exclosure: 9 shoots)
- If there are any shoots, measure the length of the shoot, up to 5 shoots per plot
- Leave cameras pointing at each of the 4 (or a subset) of treatments: Drift camera SD card needs to be emptied and camera fully charged. Best if you go in the morning, it can still film for the full afternoon. We always try to have about 1/2 of seafloor in view, and 1/2 water, so you capture as much as you can on camera, not just the plot but a little bit of the surroundings (see screenshots below). Before you insert in the sediment, film the label of the plot. Lay down next to the camera as you position it, so you know the angle is right. Try to prevent glare with regards to sun.

End monitoring protocol

- For each plot (1 to 20), count the number of *T. testudinum* shoots with green leaves. For this, you need to wave away the sand to see properly.
- Additionally, count the number of *H. wrightii* shoots in each plot
- For plots with fish exclosures (plot 2, 10, 13, 14, 16), write this down separately (i.e. plot 2: total: 12 Tt shoots; turtle excl: 3 Tt shoots; fish exclosure: 9 Tt shoots)

- If there are any shoots, measure the length of the shoot, up to 5 shoots per plot
- Of up to Thalassia 5 leaves per plot write down number of fish grazing marks (crescent shape) or write down if the leaf looks turtle grazed.
- See if you can measure outward expansion: from the middle of the BESE plot to the furthest shoot outside the BESE.
- Leave cameras pointing at each of the 4 (or a subset) of treatments: Drift camera SD card needs to be emptied and camera fully charged. Best if you go in the morning, it can still film for the full afternoon. We always try to have about 1/2 of seafloor in view, and 1/2 water, so you capture as much as you can on camera, not just the plot but a little bit of the surroundings (see screenshots below). Before you insert in the sediment, film the label of the plot. Lay down next to the camera as you position it, so you know the angle is right. Try to prevent glare with regards to sun.

Mangrove monitoring in Lac Bay

Background & purpose

Long-term monitoring of mangroves in Lac Bay, Bonaire, will give us insights in the health of the mangrove forest, which is dying because of high salinity levels. To restore the mangrove forest, two channels (called Coco and Pedro) are made in landward direction. It is expected that this will reduce the salt concentration in the hinterland and could restore mangrove growth in this specific part of Lac. A monitoring plan for mangrove growth was developed to study if this measure has the intended effect.

Research questions

- Is there a difference in aerial root growth of *Rhizophora mangle* between different plots from the channels Coco and Pedro (Lac Bay, Bonaire) between January 2018 and August 2020?
- Is there a difference in DBH growth of *Rhizophora mangle* between different plots from the channels Coco and Pedro (Lac Bay, Bonaire) between October 2016 and September 2018?

Method

For long-term growth, the diameter at breast height (DHB; ± 1.3 m above ground surface) was measured, by first measuring the perimeter at this height. For short-term growth the aerial root length was measured, which could give an indication of changing salt concentrations (Gill & Tomlinson, 1971). Nine monitoring plots were installed, of which five in channel Coco and four in channel Pedro (Figure 1). Within each plot, six to eight trees were chosen to measure. *Rhizophora mangle* was the dominant species in most plots and the easiest accessible. *Avicennia germinans* was also occasionally found but not in both channels, so no comparison was possible here and this species was left out of the data analysis. The measurement interval for both perimeter and aerial root length was one month (with a gap of more than a year for the perimeter data after Oct 2016). Once an aerial root touched the water or died, a new root was chosen to measure instead.

Our interest was mainly in mean growth differences between the different locations and not the growth pattern over time, which is why the
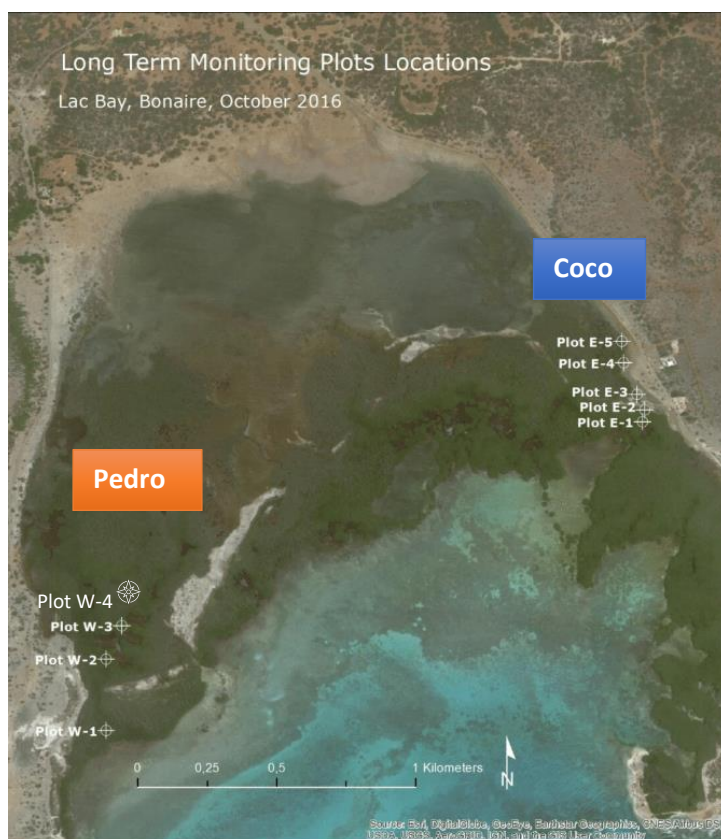

Figure 24 Long-term monitoring plots of mangroves in Lac Bay, Bonaire. Plot E1-E5 are the eastern channel, also called Coco. Plot W1-W4 are the western channel, also called Pedro.

difference in length between the start and end date was calculated. From this, the mean growth rate (cm/month) was calculated per location. Negative growth rates were removed from the calculation, because this is assumed not to be possible.

Results

The mean aerial root growth of the mangroves was lower in the Coco channel than in the Pedro channel (Figure 2). The mean growth in plot E1 to E5 ranged from 2.86 to 3.86 cm/month (overall mean Coco 3.24 cm/month), while the mean growth in plot W1 to W4 ranged from 3.94 to 7.29 cm/month (overall mean Pedro 5.64 cm/month).
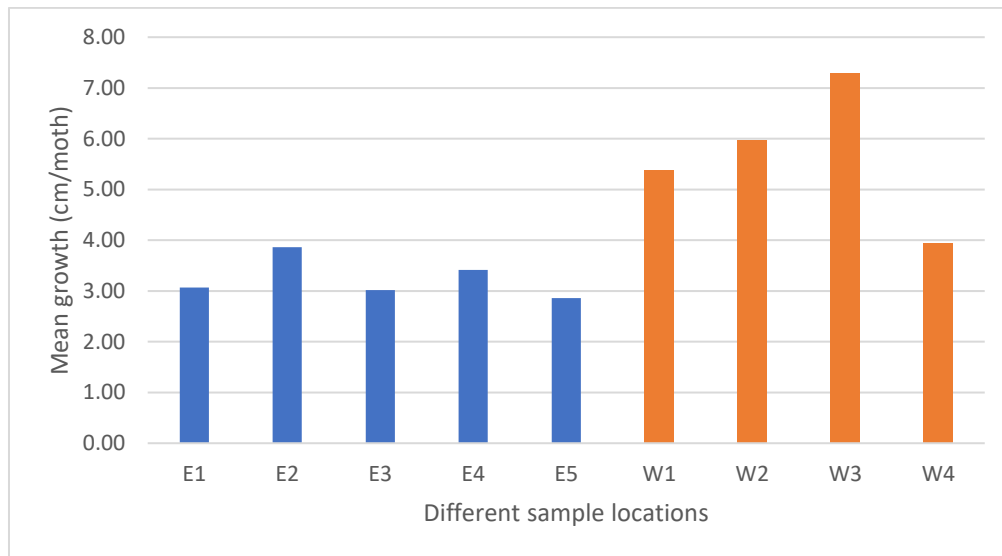

Figure 25 Mean aerial root growth of Rhizophora mangle *in two different channels (Coco (E1-E5) and Pedro (W1-W4)) in Lac Bay, Bonaire, between January 2018 and August 2020. The blue bars represent Coco and the orange bars Pedro.*

The mangrove DBH growth shows a different trend. In general, the mangroves in channel Pedro had a lower mean growth rate (0.08 cm/month) than in channel Coco (0.09 cm/month). However, location W4 differs a lot from the other Pedro locations and had the highest growth rate of all (0.17 cm/month).
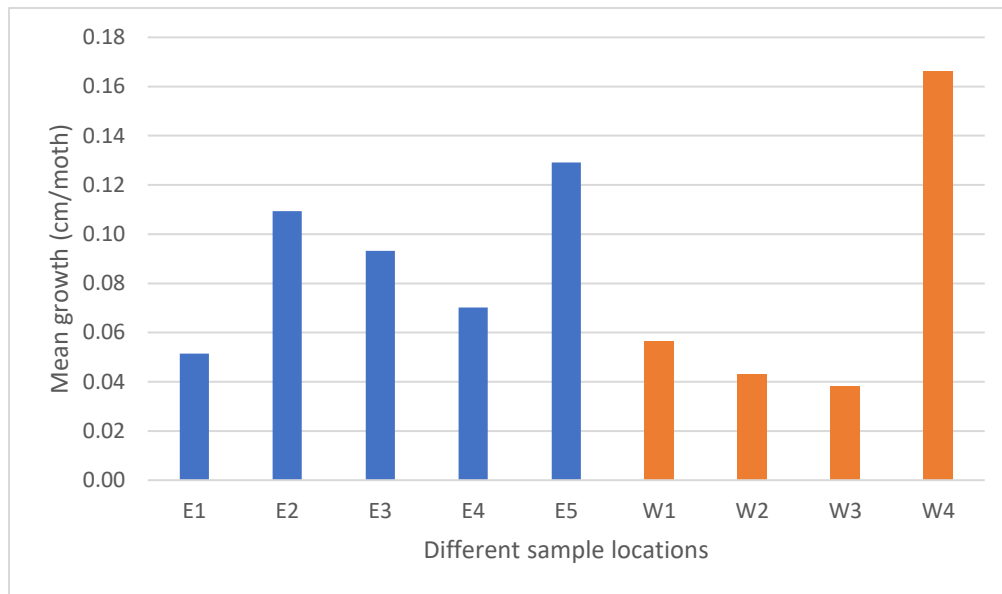
Figure 26 Mean DBH growth of Rhizophora mangle *in two different channels (Coco (E1-E5) and Pedro (W1-W4)) in Lac Bay, Bonaire, between October 2016 and September 2018. The blue bars represent Coco and the orange bars Pedro.*

Comparing the two channels, the mangroves in Coco had a lower aerial root growth rate but a higher DBH growth rate and thus a larger increase in biomass compared to the mangroves in Pedro. The mangroves in Pedro had a higher aerial root growth rate and lower DBH growth rate, except for location W4.

Note: for the DBH data, begin and end measurements were taken but sometimes the perimeter was larger in between (April/May 2018) and decreased again after. This could either be errors in the measurements or a seasonal change.

Implications

The channel Coco is next to a degrading area, having a higher sun exposure than at Pedro because of a less dense canopy. This could be the reason that that the mangroves in this area had a lower aerial root growth rate, because shade promotes lateral root growth compared to high light intensity (Gill & Tomlinson, 1977). Light response flexibility (''light-demanding" or "shade-tolerant") may however change with plant age (Farnsworth & Ellison, 1996). The DBH growth of trees at Coco suggest that mangroves in high sun exposure do keep increasing their biomass, although aerial root growth is minimal.

The Pedro channel is a healthier area, which is likely to be the reason for the higher observed aerial root growth. For the trees in this area, it is likely that most energy went into growing aerial roots and less energy was left to increase biomass. This aligns with the observation that trees at Pedro do not grow very tall. According to research of Kraus and Allen (2003), the height of *R. mangle* was also higher in a shaded area compared to an unshaded area. Location W4 showed lower aerial root growth and much higher DBH growth than W1-W3, which could be explained because this location was much further landward than W1-W3 (see Figure 1) and experienced different environmental conditions.

Next to light intensity, another explanatory factor could be water fluctuations and thus salinity. Mangrove growth is enhanced in lower salinity, with DBH and leaf development having larger differences between high and low salinity than root growth (Smith & Snedaker, 1995). A lower growth rate could thus indicate higher salinity levels. To decrease salt concentrations, new channels might be needed in the forest of Lac Bay to further improve the water circulation.

Water quality measurements like salinity but also measurements on depth, water flow, temperature, DO, and light intensity/UV could give further explanation of why the mangroves grow better in a certain area than in another. Next to monitoring DBH and aerial root length, the canopy cover or number of leaves tell something about the growth and health of a mangrove tree. All this information helps steering future mangrove restoration in Lac Bay.

Link to raw data

- *Report of in-detail method description:*
Mangrove Monitoring Bonaire - Vogel & Houtsma (2016)

- *Excel-sheet with all measurements and graphs:*
Mangrove Monitoring Project_Bonaire 2020_incl graphs JH.xlsx

References

Farnsworth, E. J., & Ellison, A. M. (1996). Sun-shade adaptability of the red mangrove, Rhizophora mangle (Rhizophoraceae): Changes through ontogeny at several levels of biological organization. *American Journal of Botany, 83*(9), 1131-1143. doi:https://doi.org/10.1002/j.1537-2197.1996.tb13893.x

Gill, A. M., & Tomlinson, P. B. (1971). Studies on the Growth of Red Mangrove (Rhizophora mangle L.) 2. Growth and Differentiation of Aerial Roots. *Biotropica, 3*(1), 63-77. doi:10.2307/2989707

Gill, A. M., & Tomlinson, P. B. (1977). Studies on the Growth of Red Mangrove (Rhizophora mangle L.) 4. The Adult Root System. *Biotropica, 9*(3), 145-155. doi:10.2307/2387877

Krauss, K. W., & Allen, J. A. (2003). Influences of salinity and shade on seedling photosynthesis and growth of two mangrove species, Rhizophora mangle and Bruguiera sexangula, introduced to Hawaii. *Aquatic Botany, 77*(4), 311-324. doi:https://doi.org/10.1016/j.aquabot.2003.08.004

Smith, S. M., & Snedaker, S. C. (1995). Salinity Responses in Two Populations of Viviparous Rhizophora mangle L. Seedlings. *Biotropica, 27*(4), 435-440. doi:10.2307/2388955

Propagule Growth of Red and Black Mangroves

Background & purpose

The goal of this research was to measure the effect of salinity on mangrove propagules of the species *Rhizophora mangle* and *Avicennia germinans*. Monitoring was started by two WUR bachelor students, Eva and Annis (Dec 2020 to February 2021) and was taken over by Jessica Johnson afterwards. The study ended February 2022.

Research question

What is the impact of salinity on mangrove propagule growth and survival?

Method

Propagules of the two species *Rhizophora mangle* and *Avicennia germinans* were planted at five different locations at Lac Bay, Bonaire, in December 2020. These locations were named Isla Yuwana, Kaminda Sorobon, Pedro, Taco and Rand (Figure 1). The number of propagules planted differed per location (Table 1). Per species and per location, three randomly selected mangroves were labelled, and their length was measured over a period of 15 months. The number of dead mangroves was also counted, from which the survival rate (%) was calculated, and specific observations were written down. Besides, salinity and waterflow direction was measured.

At some locations, all plants died during the experiment, so new propagules were planted on April 29, 2021 (indicated in Table 1 as 'new black' and 'new red').
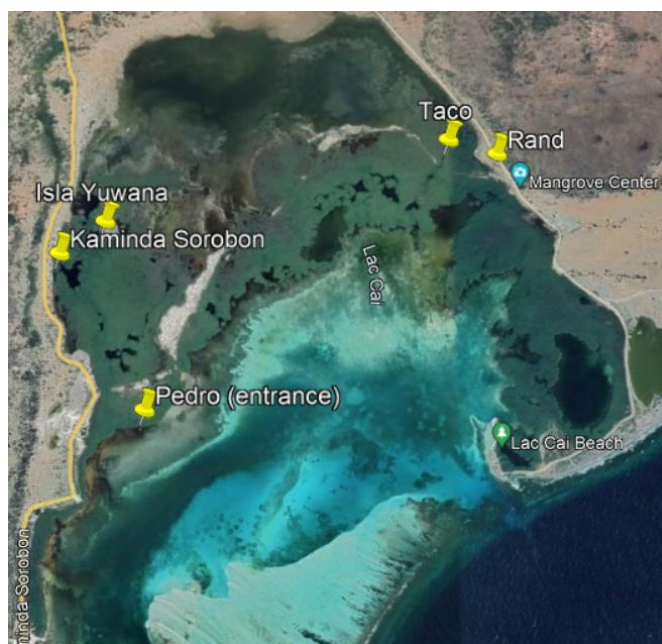

Figure 27 Five different measurement locations. Both red and black mangroves were planted at 'Isla Yuwana', 'Kaminda Sorobon', 'Pedro', 'Taco' and 'Rand' (near the Mangrove Center), Lac Bay, Bonaire.

Table 6 Number of mangrove propagules planted per location and per species.

Location	# black mangroves	(new black)	# red mangroves	(new red)
Isla Yuwana	40		32	
Kaminda Sorobon	17	16	40	16
Pedro	40		40	
Taco	23	17	32	19
Rand	25	15	25	

Results

- Salinity levels have decreased over all five locations.
- Salinity level at location Rand was highest (mean 49.25 ppt).
- Black mangrove propagules had either 20% (Isla Yuwana, Pedro) or 0% survival (Kaminda Sorobon, Taco, Rand).
- Red mangrove propagules had a much higher survival rate (70-85%) for almost all locations, except Rand.
- Sudden drops in survival occurred around April 2021, probably because of high water levels (black mangroves) or disturbance by a grazor (red mangroves).
- Propagule growth rate was higher for red mangroves than for black mangroves
- Highest growth rates were found for locations Taco (0.54 and 1.31 cm/month for black and red respectively) and Pedro (0.80 and 1.44 cm/month for black and red respectively).

The graphs below show a decreasing trend in salinity over all five locations (Figure 2), with a slightly lower salinity at location Pedro and the highest mean salinity at location Rand (Figure 3).
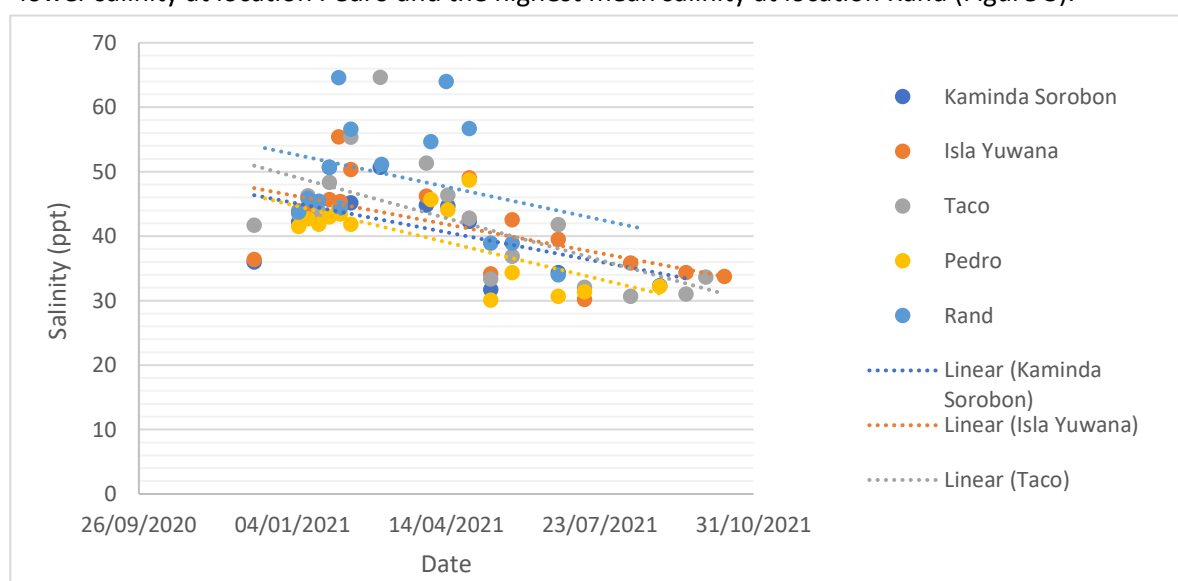

Figure 28 Salinity levels at different sample locations, from December 2020 to February 2022. The dots show the actual data points, while the dotted lines give the linear trend line per location.
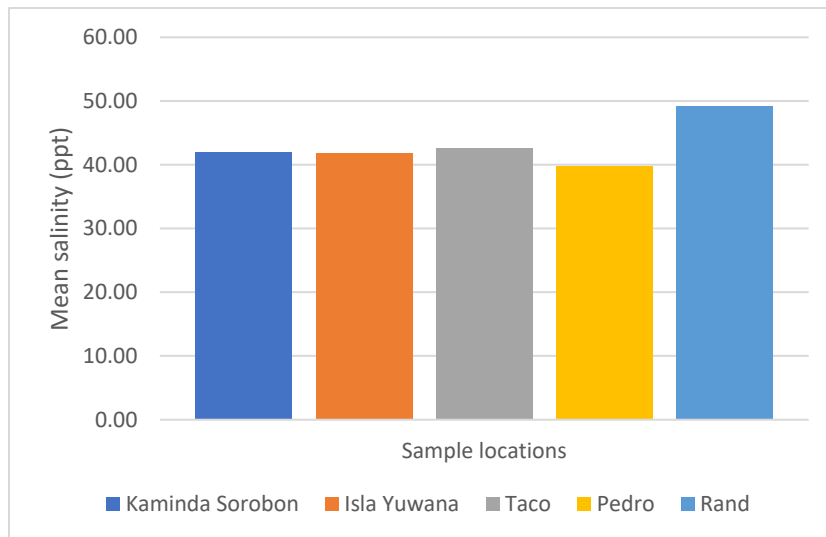
Figure 29 Mean salinity levels per sample location.

With a decreasing salinity, the black mangrove propagules also had a decrease in survival (Figure 4). Locations Kaminda Sorobon, Taco and Rand experienced a sudden drop in survival in April 2021, after which all plants at these locations died. New propagules were outplanted in April 2021, but these also all died by January 2022. The newly planted mangroves are not included in Figure 4.
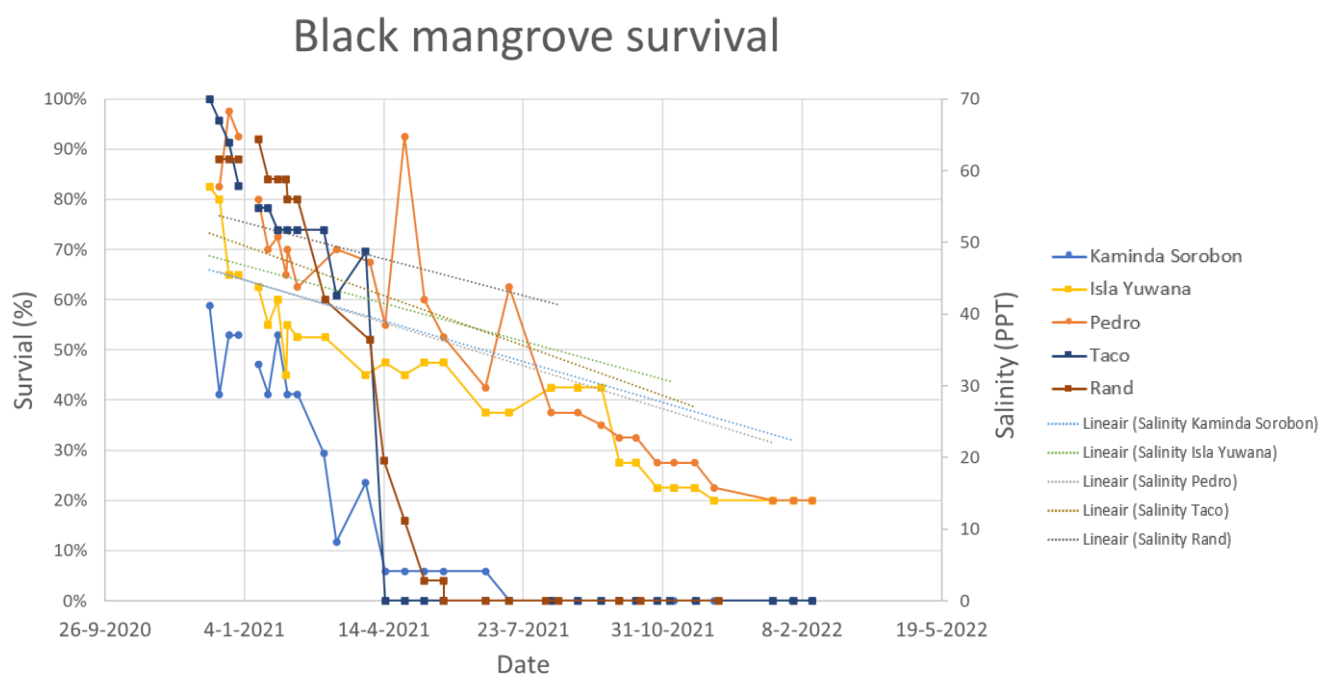

Figure 30 Black mangrove survival (%) between December 2020 and February 2022 at five different sample locations. Salinity trend lines are also shown by the dotted line (secundair y-axis).

From the red mangroves, 70-85% survived for locations Kaminda Sorobon, Isla Yuwana, Pedro, and Taco (Figure 5). Locations Kaminda Sorobon and Taco also had respectively 16 and 19 newly planted propagules outplanted in April 2021 (Table 1), which all survived till the end of the experiment (not included in Figure 5).
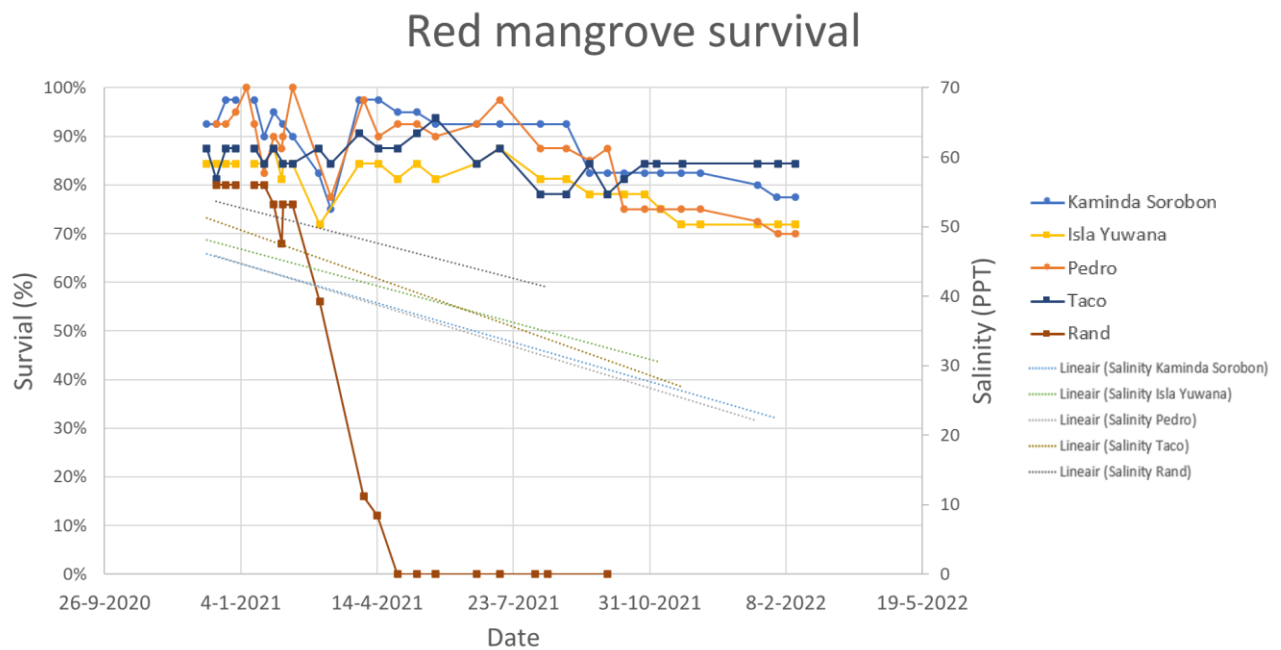
Figure 31 Red mangrove survival (%) between December 2020 and February 2022 at five different sample locations. Salinity trend lines are also shown by the dotted line (secundair y-axis).

Figure 6 shows the mean growth rate for every location. The locations were all plants died also had a negative mean growth rate, because the length of the plants decreased before they were observed as death. The growth rate of red mangroves was at all locations higher than the growth rate of black mangroves. The highest growth rates were observed at Taco (0.54 and 1.31 cm/month for black and red respectively) and Pedro (0.80 and 1.44 cm/month for black and red respectively).
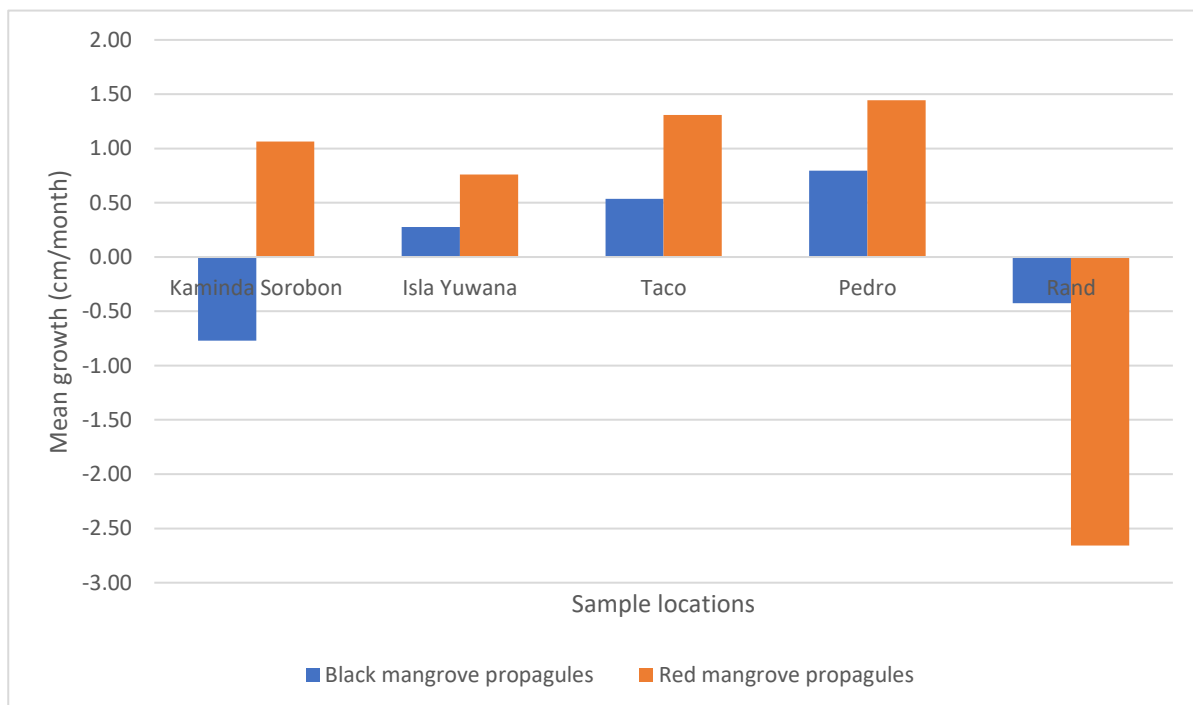

Figure 32 Mean growth rate (cm/month) for the five different sample locations. Blue bars indicate the black mangrove propagule growth and the orange bars the red mangrove propagule growth. A negative growth rate is not deemed possible so these are either measurement errors or the plant was already dying off.

Implications

The decrease in salinity over time shows the importance of channel maintenance in the mangroves. Simultaneously with this study, the Mangrove Maniacs worked on clearing channels to improve the water circulation of the mangrove forest in Lac Bay. The work of the Mangrove Maniacs helps maintaining lower salinity levels, which is favourable for the growth of the mangroves (Smith & Snedaker, 1995).

Red mangroves had a higher survival rate and mean growth rate than black mangroves. This could be because red mangroves have a relatively high resilience for changes in water level and salinity (Krauss & Allen, 2003). The sudden drop in black mangrove survival could be explained by flooding of the channels that occurred around the same time. Black mangroves cannot grow when they are constantly submerged by water, unlike red mangroves. This could be a reason to prefer red mangroves for outplants in environments more susceptible to high water levels (tides, sea level rise). The sudden drop in red mangrove survival at location Rand could be explained by disturbance of a grazer, probably a donkey or a goat. Erosion has been identified as a major pressure on mangroves, which is worsened by the grazing of free-ranging goats and donkeys (Tiggeloven, Buijs & van Oosterhout, 2022). So for outplants close to land accessible to grazers, it would be advisable to fence off the area.

The differences in growth rate could be explained because Pedro seems to be the healthiest area of the five locations, based on observations. Pedro had the lowest mean salinity level (although there were no big differences) and highest mean growth rate for both black and red mangroves. Other factors like the level of UV-intensity could have played a role here as well. In general, the higher growth rate of red mangroves could be explained by their strategy of fast growth under a wide range of environmental conditions (Krauss & Allen, 2003).

Link to raw data

- *Excel propagule growth:*
https://www.dropbox.com/scl/fi/th4wivaob2mdg08gidje3/Mangrove-propagule-growth_incl-graphs-JH.xlsx?dl=0&rlkey=235ood9tr9pnmecoarauxtti5

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Genetic Populations of *Rhizophora mangle* in Colombia and Bonaire

Background & purpose

In November 2020, a lot of mangroves in Colombia have been destroyed by a hurricane. During this hurricane, called Iota, over 95 percent of red mangroves have died on the Colombian island of Providencia (Figure 1) (Quiñones, 2022). The restoration of the mangrove forest is a challenge, because they have a general scarcity of red mangrove propagules for the outplanting of new mangroves (Quiñones, 2022). A solution could be to import mangrove propagules from other, healthy locations, such as Bonaire (Figure 1). However, it is still unknown if there exist different genetic populations of red mangroves in the Caribbean region and what the consequences or risks of importing a different genetic population for restoration purposes would be. The goal of this literature research is to find out if there is a connection between the genetic populations on Bonaire and in Colombia to come up with an advise for restoration of mangroves in Colombia.
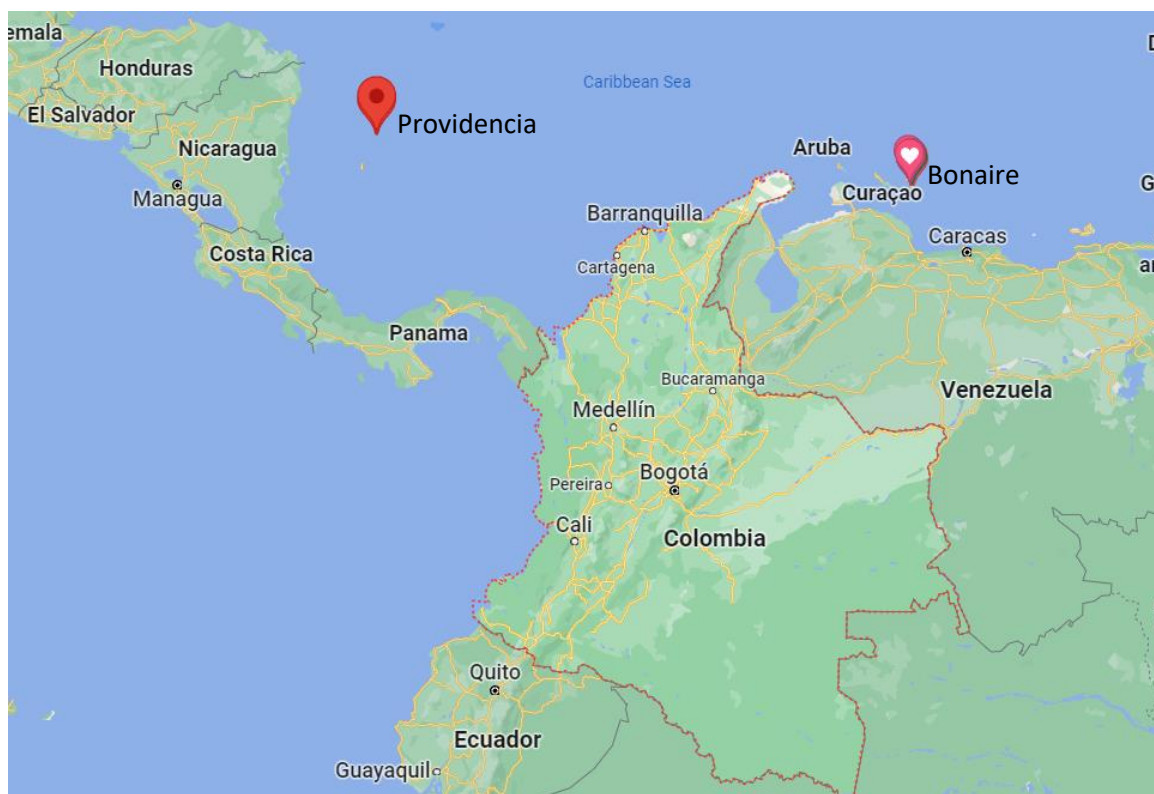

Figure 33 Map of part of South-America and Caribbean region including Colombia, and the islands Providencia (left pin) and Bonaire (right pin).

Research questions

- Is there a connection between the genetic populations of *Rhizophora mangle* (red mangrove) on Bonaire and in Colombia?
- Could *R. mangle* propagules from Bonaire be used for mangrove restoration in Colombia and what would be the consequences/risks involved in terms of mixing genetic populations?

Method

Literature search on Google Scholar and Scopus by using search words as: Rhizophora mangle, R. mangle, red mangrove, genetic population, gene flow, population connectivity, Bonaire, Colombia, Caribbean region.

Results

- *Is there a connection between the genetic populations of Rhizophora mangle (red mangrove) on Bonaire and in Colombia?*

When determining population connectivity, regional ocean currents are an important factor (Kennedy et al., 2016). In general, it is expected that island populations have a greater gene differentiation than populations along a continuous coastline due to their geographic isolation (Losos & Ricklefs, 2009). This would imply a different genetic structure of *R. mangle* on Bonaire, which is an island, compared to mainland of Colombia. Kennedy et al. (2016) found a complex expansion history of *R. mangle* in the Caribbean basin and Florida, with three discrete population clusters separating the Caribbean mainland, the Caribbean islands and Florida itself. They also looked at trans-Atlantic long-distance dispersal (LDD) and compared the genetic structure of populations from Northwest Africa (Senegal) and the two Caribbean Islands St. Kitts and Puerto Rico and found a genetic similarity, supporting genetic exchange across the Atlantic (Kennedy et al., 2016). LDD could be limited by major dispersal barriers, like the Panamanian Isthmus which forms a land barrier between the Pacific and the Caribbean Sea. However, this limitation is species dependent, *Rhizophora* is for example known to be more mobile and having longer surviving propagules than *Avicennia* (Triest, 2008).

A broad range of literature about mangrove genetics and dispersal was analysed by Triest (2008). He identified areas of gene flow and possible geographical barriers (Figure 2). The map and literature review of Triest (2008) show high levels of gene flow between populations of Mexico-Costa Rica and in the East Pacific of Colombia, supported by ocean currents (Arbeláez-Cortes et al., 2007; Cerón-Souza et al., 2005; Dodd & Afzal Rafii, 2002).
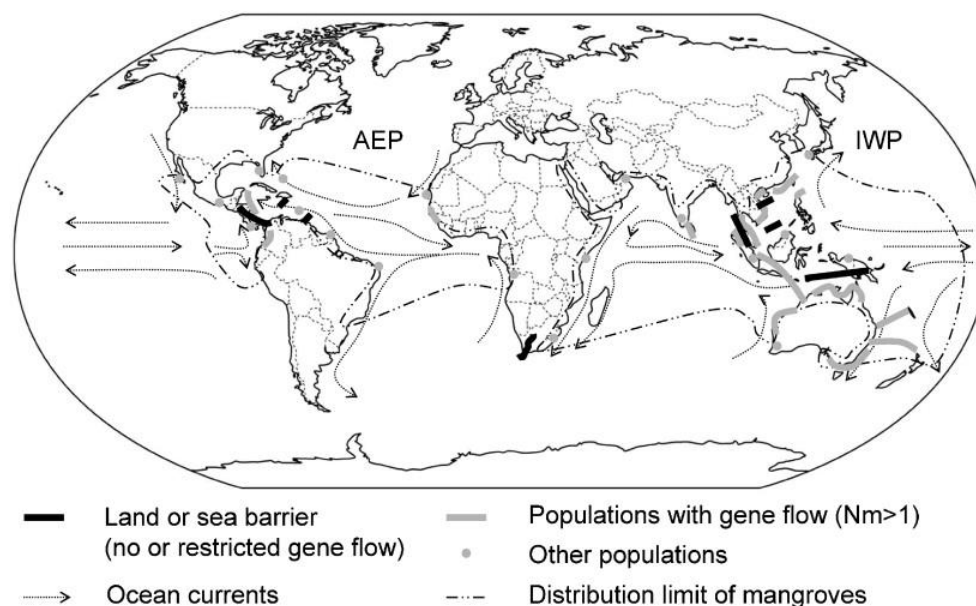

Figure 34 Conceptual overview of land and oceanic barriers and of coastal zones with high levels of gene flow within the Atlantic East Pacific region and the Indo West Pacific. Source: (Triest, 2008).

Studies on the genetic variability of *R. mangle* are still scarce, but so far little genetic variation is observed between red mangrove populations in the Caribbean region. For red mangrove populations on the Colombian (Arbeláez-Cortes et al., 2007), Costa Rican (Takayama et al., 2008), Brazilian (Pil et al., 2011) and Mexican coast (Sandoval-Castro et al., 2014), very low allelic diversity has been observed. Also for two red mangrove populations in Ecuador, little genetic variation between populations was found (Basyuni et al., 2017). Arbeláez-Cortis et al. (2007) found a low genetic differentiation along the Colombian coast, which could suggest high amount of gene flow, even over a distance of 400 km. Their results suggest a continuous genetic exchange between red mangrove forests at long distances, by means of floating propagules that can survive up to 12 months (Rabinowitz, 1978). Comparing six different mangrove species, Arbeláez-Cortis et al. (2007) found that *R. mangle* propagules had the greatest longevity (over a year) and showed the least genetic differentiation among populations. Only populations in the Atlantic and Pacific coast of Mexico are found to be genetically distinct, because of the geological phenomenon of the Panamanian Isthmus uplift about 3.5 million years ago, isolating plant and animal populations (Núñez-Farfán, 2002). A study from Canty et al. (2022), which conducted genetic analyses of mangrove forests across a range of spatial scales in Honduras, highlights that there is greater genetic structure at fine spatial scales. Their findings contradict the perception that genetic structure within mangroves mainly occurs along a coastline.

For the genetic population of mangroves on Bonaire specifically, no literature was found. However, regarding the literature on low genetic variation and high levels of gene flow across the Caribbean region, it would seem plausible that the populations of Colombia and Bonaire share at least some genetic structure. The only thing which should be considered is the geographical location of the island of Bonaire, which makes it a more distinct area than a continuous coastline on the mainland. As mentioned by Losos and Ricklefs (2009), this could increase the genetic differentiation of the Bonairian mangrove population.

- *Could red mangrove propagules from Bonaire be used for mangrove restoration in Colombia and what would be the consequences/risks involved in terms of mixing genetic populations?*

Genetic diversity plays an important role in the long-term survival of a species and its adaptation to environmental changes. Information about genetic diversity of mangroves is important for the planning of genetic resources conservation, afforestation and tree improvement programs (Hamrick et al., 1992). Previous studies on genetic variation of woody species and mangroves have shown that most variation is found among individuals within a population, but with little/no variation between populations (Basyuni et al., 2017; Hamrick et al., 1992). However, a high genetic diversity is important for the species to be less vulnerable to environmental change. To illustrate this, the study of Guo et al. (2018) showed that mangroves with less genetic diversity suffered much greater destruction from flooding events like sea level rise. For conservation and management of the species it would therefore be important to increase the number of populations (Núñez-Farfán, 2002) and thereby increasing the resilience of red mangroves to climate change. To support mangrove restoration and rehabilitation, Basyuni et al. (2017) also suggest to choose genetically superior and to introduce them into target sites to increase the genetic diversity.

Considering the literature reviewed in the current study, the import of mangrove propagules to a different geographic area for mangrove restoration purposes would solely have the advantage of increasing the genetic diversity and thereby improving the species' resilience for climate change. No disadvantages or risks of mixing the two different populations of Bonaire and Colombia have been found so far, although this very specific case has not been studied before and conclusions are based on previous studies available in literature.

Implications

Climate change (storms, sea level rise) and anthropogenic disturbance (e.g. shrimp farms, agriculture and cattle fields, salt extraction ponds and settlement areas) put pressure on mangrove ecosystems, with potential loss of habitat. Little genetic variation between mangrove populations may cause a higher vulnerability to environmental changes. This is noteworthy in planning future conservation. Suggestions to increase the number of populations (Basyuni et al., 2017; Núñez-Farfán, 2002) should be considered for mangrove restoration plans. The import of Bonairian red mangrove propagules for restoration in Colombia could therefore have positive effects in terms of genetic diversity and resilience of the forest. Further understanding of the geography of genetic variability of *R. mangle* can provide better insights for effective conservation strategies of the species and its environment.

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Water Quality Data Analysis 2021-2022

Background & purpose

Stichting Internos and Mangrove Maniacs conduct water quality (WQ) measurements in the mangrove forest of Lac Bay, Bonaire, as part of the EU project BEST2.0+. They use funding from this project for mangrove restoration on Bonaire and WQ data supports the first pillar of this restoration project: improving water circulation within the Lac Bay mangroves forest by way of maintaining and clearing existing channels. WQ data taken alongside the channel maintenance of the Mangrove Maniacs will show the effect of clearing channels and can help decide where new channels might be needed. This short analysis of WQ data from 2021-2022 is meant to check whether there are any noticeable changes in water quality over the last years or if there are great differences between the different sample locations.

Research question

- Are there any noticeable differences in WQ between the sample locations?
- Is there a trend in WQ change over time?

Method

Water quality was measured at 15 distinct locations in Lac Bay (Figure 1), using Hanna Instruments multiparameter HI98912. The following data was collected between 2021 and 2022: date, time, temperature, pH, conductivity, salinity, and dissolved oxygen (DO). Most locations were sampled every two weeks. However, some locations had less data points than others, because the measurements were stopped earlier or the location itself was added later. For the analysis, incorrect data points were taken out first. This was the case when '0' or a number close to 0 was measured because of an error in the equipment. This mainly happened for DO, which is why not all locations appear in those results. Data was analysed by making graphs in Excel and by adding trendlines. The link to this Excel file can be found below.
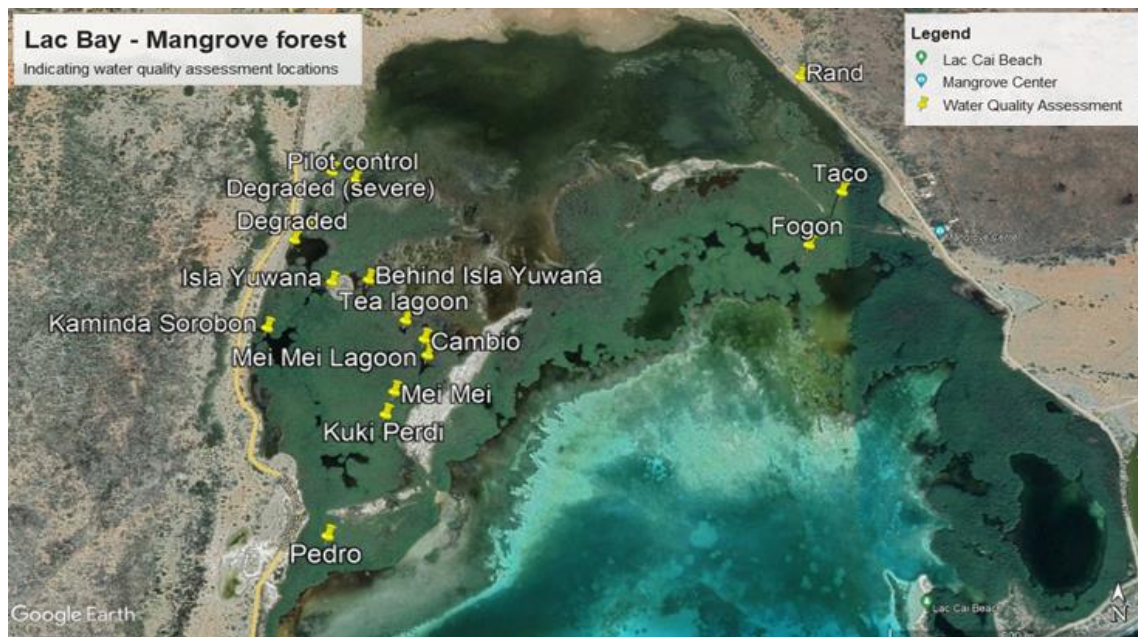
Figure 35 Map of Lac Bay with water quality assessment locations.

Result summary

Temperature has been decreasing at almost all locations between February 2021 and October 2022, except for locations Pilot, Behind Isla Yuwana, Cambio and Kuki Perdi (Figure 2). The highest increase in temperature has been measured at location Behind Isla Yuwana and the highest decrease in temperature was at Mdegraded (severe). The highest temperature measured was at Tea Lagoon in September 2021 (39.25 °C), but this temperature has stabilized around 30 °C since May 2022.

For changes in salinity there is a less clear pattern, some locations had a decrease in salinity over time, while other locations experienced an increase (Figure 3). However, the measurements of some locations stopped earlier or started later so this makes it more difficult to compare the various locations. Locations Tea Lagoon, Fogon, Taco and Pilot had a larger decrease in salinity compared to other locations. An increase in salinity was found for a couple of locations (M1 (degraded), Isla Yuwana, Mei Lagoon, Kuki Perdi, Rand), however, these trendlines were based on only a few data points.

Figure 4 shows that levels of dissolved oxygen (DO) have been higher for locations Mdegraded (severe), M1 (degraded), and Rand. For location Mdegraded (severe), DO levels stayed high during its whole measurement period (April to December 2021). An increase in DO was found for locations Mei Mei and Pedro, although Figure 4 shows a quick decrease in DO over time at Mei Mei Lagoon.

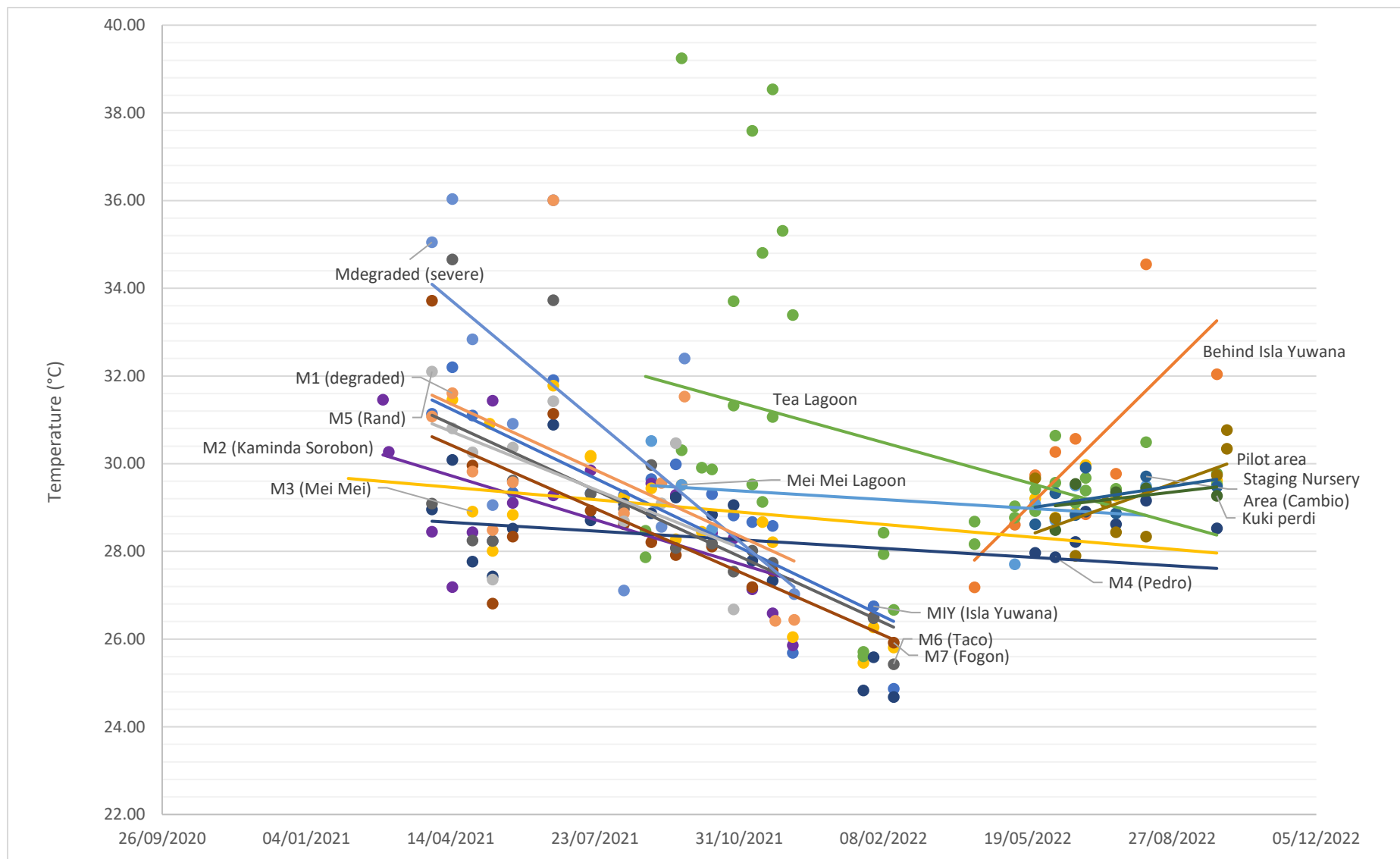More in detail graphs per location can be found in the Excel sheet (see link to data).

Figure 36 Change in temperature over time at water quality measurement locations in Lac Bay, Bonaire (2021-2022).
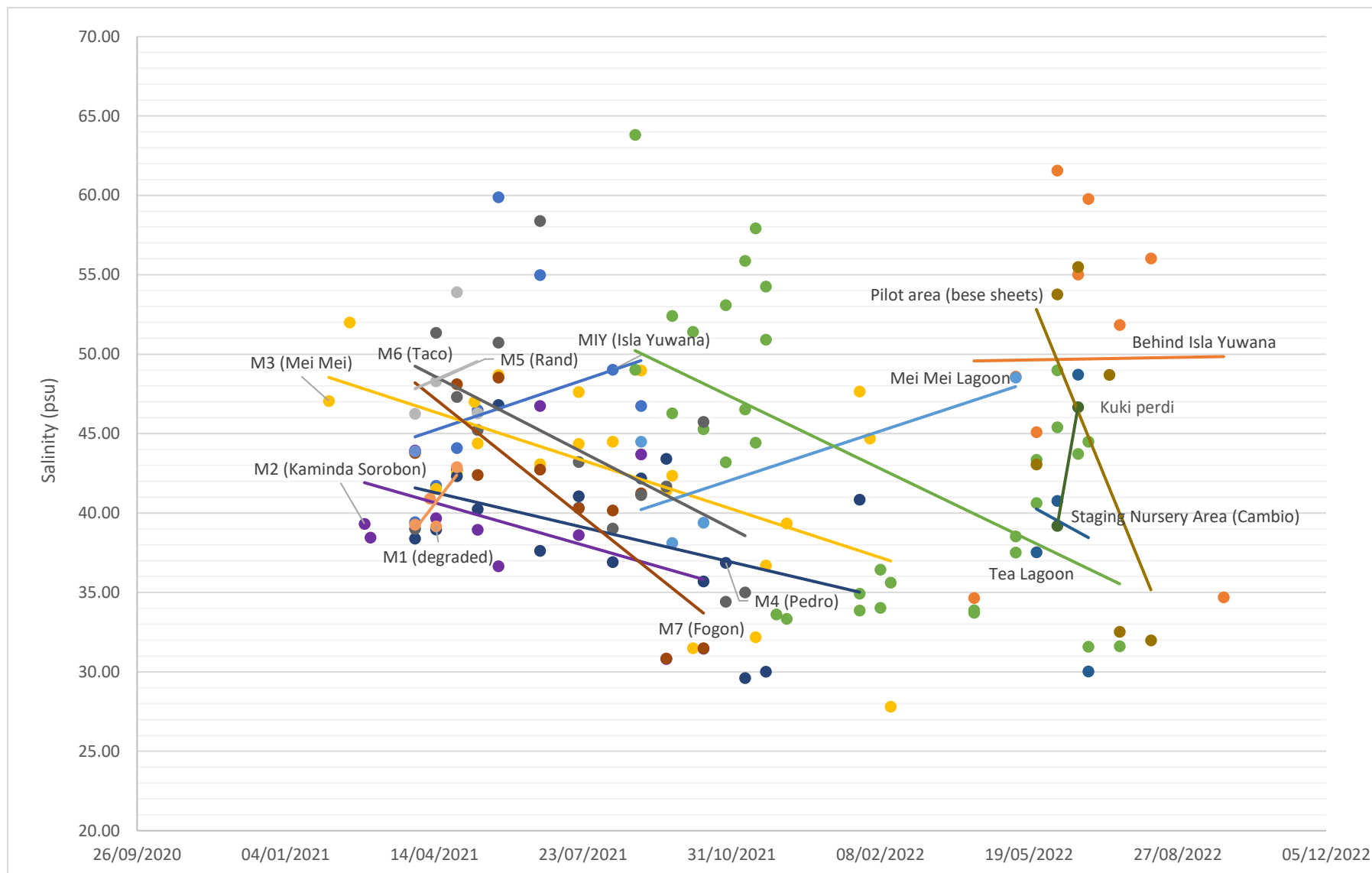
Figure 3 Change in salinity over time at water quality measurement locations in Lac Bay, Bonaire (2021-2022).
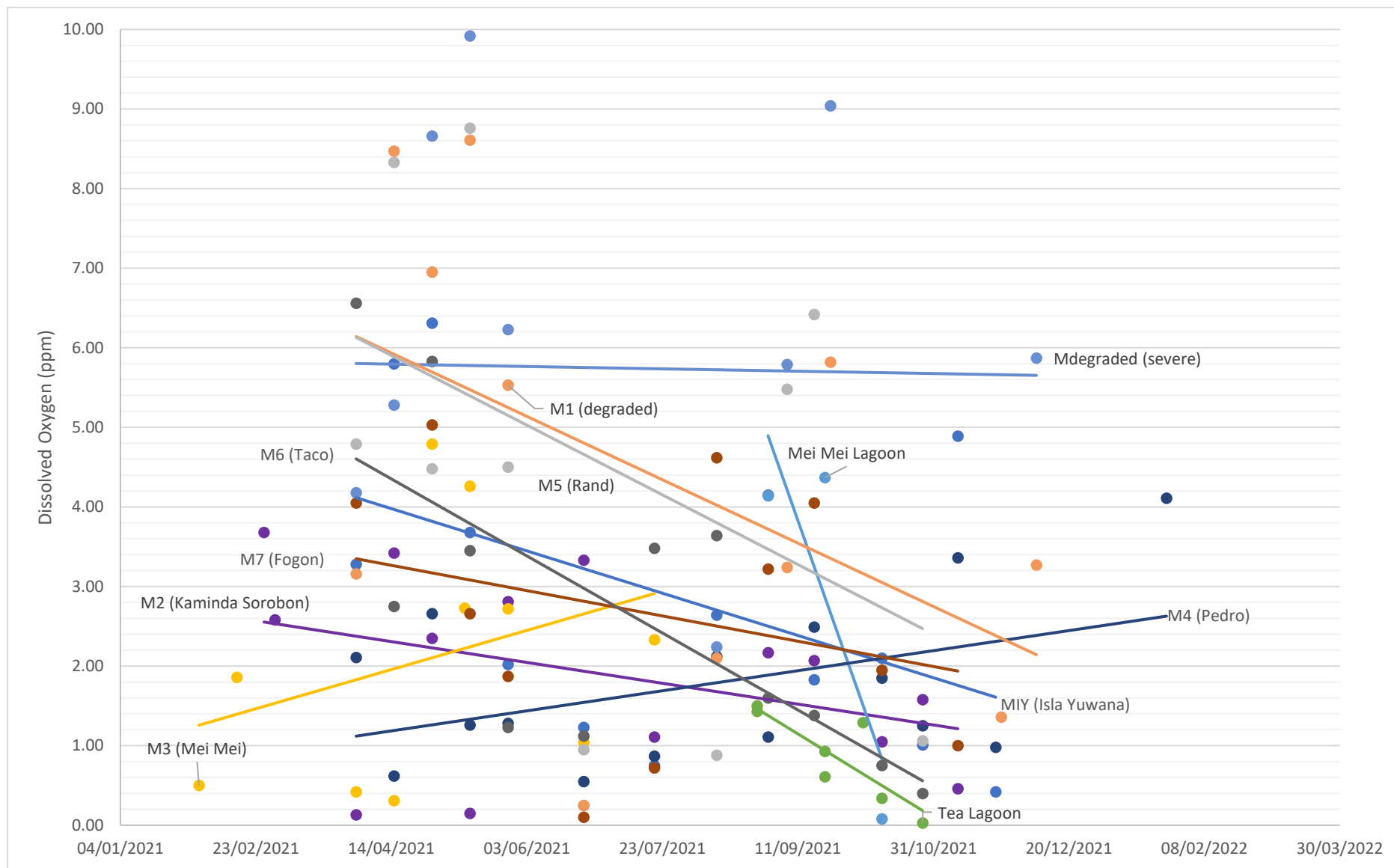
Figure 4 Change in dissolved oxygen (DO) over time at water quality measurement locations in Lac Bay, Bonaire (2021).

Implications

The decrease in temperature that was found at most locations could indicate that the tidal water fluctuation has indeed increased. With an increased water fluctuation, a decrease in salinity would also be expected (van Zee, 2022). This is because without refreshment, the water evaporates and salt stays behind, making the water more saline. With an in- and outgoing tide the water circulation improves, and salinity will drop. New channels or deepening and widening old ones (both activities of the Mangrove Maniacs) been shown to be efficient ways of improving the tidal exchange (van Zee, 2022).

Most locations in the 'front' of the forest (side of Lac Bay) did experience a decrease in salinity, although other locations in the 'back' of the forest (degraded area) had an increase in salinity which would mean that the tidal refreshment of the water did not reach this part. However, the increase at locations Mei Mei Lagoon and Kuki Perdi and the decrease at the Pilot do not align with this hypothesis. Therefore, measuring water depth with Hobo sensors at multiple locations ranging from the front to the back of the forest (alongside with rainwater data) could give more insights in this. Another recommendation would be to run statistical tests to check significance and thereby help determine future approaches of water quality assessments and mangrove restoration in Lac Bay, Bonaire. Lastly, the data collection of DO was not always accurate due to failure in the equipment (measuring '0'). Although these data were taken out, this could have affected the other data as well and should be considered. Nevertheless, this brief overview showed the general trends and could be a start for further exploration of WQ data.

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Key insights for mangrove restoration on Bonaire

Dutch Caribbean Nature Alliance (DCNA), Mangrove Maniacs

13-DEC-2022 - Since 2016 the Mangrove Maniacs of Bonaire have dedicated themselves to the restoration and conservation of mangroves on the island. Monitoring research has provided key insights into the conditions that favour growth and survival of these vital ecosystems and provide necessary information in support of management actions and planning.

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Lac Bay and its mangroves

When a mangrove forest experiences die-off, the important services it provides are lost: coastal protection, habitat for marine species, and carbon storage. This is currently the case with the northern part – also called Awa di Lodo – of the mangrove forest in Lac Bay. Unsustainable overgrazing by livestock has resulted in a depletion of ground cover vegetation. Wind, vehicle traffic and rainwater run-off therefore cause a high influx of sediment into Awa di Lodo. The sediment build-up clogs lagoons and creeks, reducing the hydrological connectivity between the front and back of the forest. This results in hypersaline conditions which cause the trees to die.

To fight this die-off, the Mangrove Maniacs dig channels to increase the tidal exchange and thereby improve the water quality conditions. They also plant mangrove propagules of two different species: red mangroves (*Rhizophora mangle*) and black mangroves (*Avicennia*

Outplant event on the southwest coast of Bonaire, 23 September, 2022 (Source: Josien Hendricksen)

germinans). These propagules are similar to a seed. They are grown in special 'nurseries' and are then planted in degraded areas or along the southwest coast to promote coastal protection. By monitoring propagule growth and survival as well as water quality parameters, we can increase our knowledge on the relationship between these factors and improve management plans for mangrove restoration and reforestation.

## Tale of two studies: mangrove growth and survival

A long-term monitoring study between 2016 and 2020 investigated red mangrove growth by comparing a healthy and a degrading area. The diameter at breast height (DBH; about 1.3 m above ground surface) and the growth of aerial roots was measured monthly. The results showed a clear difference in mean aerial root growth between the healthy and degraded locations. In general, it was seen that healthier sites had higher aerial root growth whereas the degrading areas had more DBH growth. Since the degrading area experiences a higher sun exposure due to a less dense canopy, these results would imply that shade promotes aerial root growth, while tree DBH keeps increasing in more sunny areas. In healthier areas, more energy is dedicated towards growing aerial roots, which could be the reason for the slower DBH growth.

Measuring the aerial root length of a red mangrove in Lac Bay (Source: Arno Verhoeven)

Another experiment with black and red mangrove propagules was carried out between 2020 and 2022. Here, the growth and survival of propagules in five different locations in Lac Bay was monitored: Pedro, Kaminda Sorobon, Isla Yuwana, Rand and Taco (see map) The salinity levels were also measured at these places. The monitoring took place along the regular hydrological restoration in the area, aiming at a better refreshment of water and improving conditions. During the propagule experiment the salinity levels have decreased over time at all locations, which is an expected result of the hydrological restoration efforts. Survivability rates of red mangrove propagules was found to be higher than that of black mangrove propagules due to inundation times. Further experiments where inundation changes are excluded are needed to assess the effects of salinity.
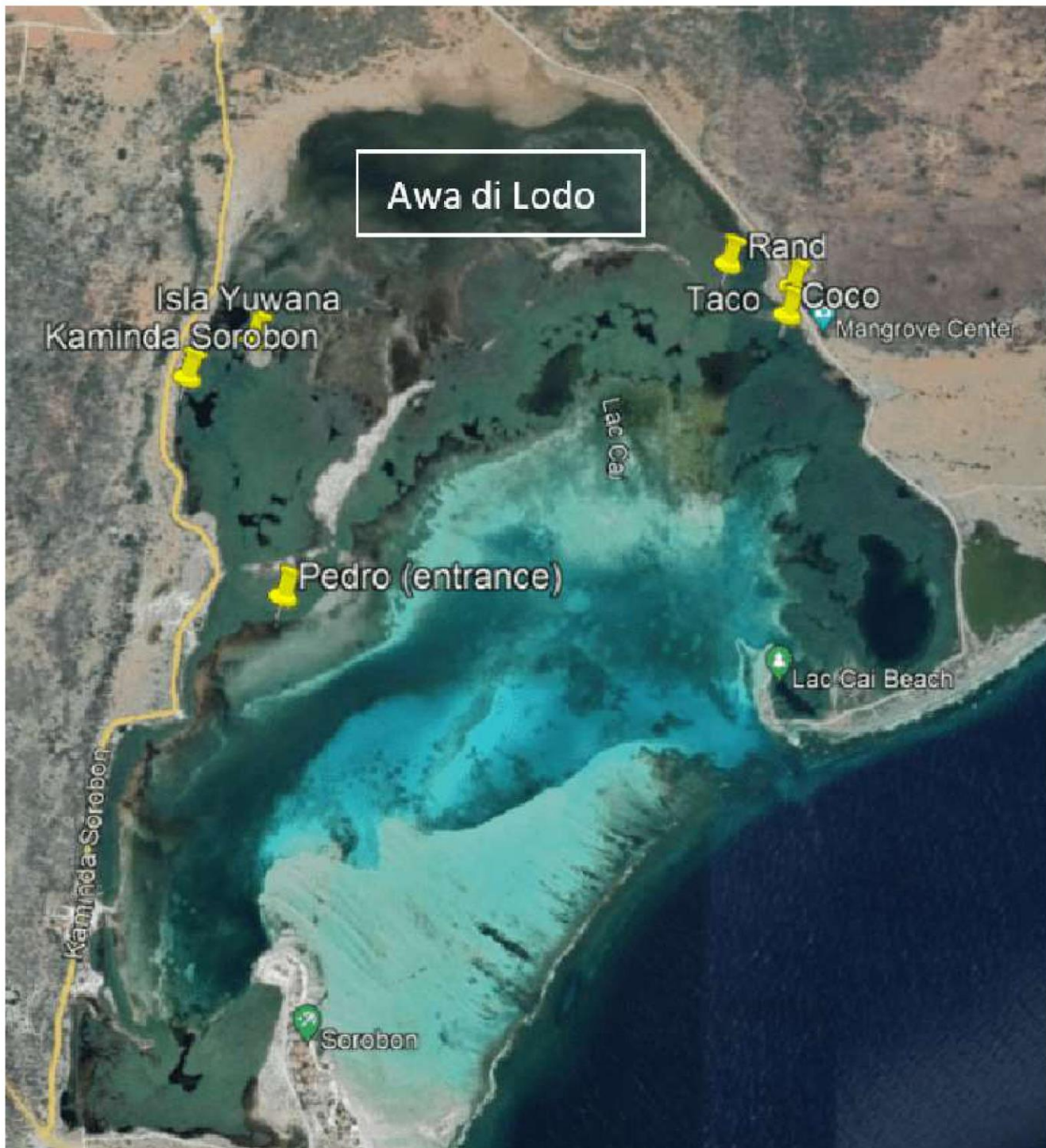
Monitoring locations of mangroves in Lac Bay, Bonaire (Source: Josien Hendricksen)

Future implications

The two studies clearly showed that salinity levels have decreased over the last years due to Mangrove Maniacs' restoration efforts, although the levels are still high. In general, more degraded areas had a higher salinity and also lower growth rates. Red mangrove propagules seem to have a higher resilience for changes in water level and salinity than black mangrove propagules. Their strategy of fast growth under a wide range of environmental conditions would be a reason to prefer red mangroves over other species for outplants in locations more susceptible to environmental change, like the southwest coast with sea level rise. The decrease in salinity over time shows the importance of channel maintenance in the mangrove forest of Lac Bay. To further improve water circulation and thus the health of the forest, new channels would be needed. This is already in the planning of the Mangrove Maniacs.

More information

- If you want to learn more, follow the Mangrove Maniacs on social media or come out to volunteer with them on Tuesday mornings at 8am in Lac Cai, boat space is limited so please sign up via Facebook.

Mangrove Maniacs at work (Source: Monique Grol)

Text: Josien Hendricksen
Photo's: Monique Grol; Josien Hendricksen; Arno Verhoeven

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