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The influence of herbivorous keystone fish species on the recruitment and growth of corals on artificial reefs

A study regarding the influence of Acanthuridae and Scaridae on coral recruitment and growth on three different types of artificial reefs: reef balls, layered cakes and natural rock reefs on Saba and St. Eustatius

AROSSTA
Artificial Reefs on Saba and St. Eustatius

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Before you lies the research report 'The influence of herbivorous keystone fish species on the recruitment and growth of corals on artificial reefs'. On behalf of the Artificial Reefs on Saba and St. Eustatius (AROSSTA) project, this research has been conducted for our 5-month Bachelor thesis assignment of Coastal and Marine Management at the University of Applied Sciences, Van Hall Larenstein in Leeuwarden. The research was conducted in the period from September 2018 till January 2019, of which two months in the Caribbean where we worked in collaboration with SCF, CNSI and STENAPA.

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We hope you will enjoy reading our research report.

Marijn van der Laan and Marit Pistor

Abstract

Coral reefs are one of the most important ecosystems in the world, in terms of both biological diversity and economy. These ecosystems are under a great amount of threats (e.g. climate change, pollution, coastal development and overfishing), which can lead to reef degradation and decrease of three-dimensional structure. In the worst-case scenario this can result in coral-algal phase shifts, this is in particular occurring when herbivorous fish are over exploited. The aim of this study was to investigate possible relations between herbivorous fish groups (Acanthuridae and Scaridae), coral recruitment and growth rates, on three different types artificial reefs on Saba and St. Eustatius. The reef types were [1] reef balls, [2] layered cakes and [3] natural rock reefs. Additionally, this research aimed to investigate the influence of unsustainable fishing practices and if present, how influences could be minimized. The data for this research was collected from three dive sites at a depth between 15 and 20 m. Two dive sites are in St. Eustatius and the third on Saba. On all three dive sites the three different kind of artificial reefs were monitored over a period of two months. A total of 30 herbivorous fish abundance surveys were conducted, 1080 minutes of herbivorous fish grazing footage was collected, and 15 surveys were executed to count the coral recruitment and to measure the coral growth. After analysing the data three results were found: 1) Similar patterns between artificial reef types of the highest abundance of the overall tested herbivorous fish, the individual abundance of Scaridae, the overall tested coral growth and the individual Porites growth were found. This suggests that the overall abundance of herbivorous fish enhances the overall coral growth and that Scaridae abundance enhances Porites growth. 2) A similar pattern between artificial reef types of the overall herbivorous fish grazing, both individual grazing groups and the growth of Agaricia was found additionally. Suggesting that the grazing of both Acanthuridae and Scaridae might enhance the growth of Agaricia. 3) The reef balls showed a significantly higher grazing impact from Acanthuridae compared to Scaridae, which corresponded with a significantly higher observed growth rate of Agaricia compared to Porites, which adds to the suggestion that grazing of Acanthuridae enhances the coral growth of Agaricia. However, since there is a great number of control variables that can influence the coral growth and recruitment, it is suggested to take these into account in further research. Based on the literature study, herbivorous fish have shown to be at risk of overexploitation through bycatch of unsustainable contemporary fishing pressure of fish and lobster traps on St. Eustatius. This could be prevented by some simple interventions, like escape vents and degradable fish trap panels.

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1 Introduction

Coral reefs are one of the most important ecosystems in the world, in terms of both biological diversity and economy, supporting shelter, home and food for nearly a quarter of all known marine species. Coral reefs provide ecosystem services that are crucial to human societies and industries through coastal protection, building materials, fisheries, new biochemical compounds, medical and pharmaceutical research and tourism (Cesar et al., 2003; Hoegh-Guldberg et al., 2007; Moberg & Folke, 1999). Yet these ecosystems are under a great amount of threats, such as increased pressure of climate change, pollution, coastal development and overfishing (Bryant et al., 1998; Gardner et al., 2003). The increase in environmental and anthropogenic stressors take their toll on the resilience of the coral reef (Meltvedt & Jadot, 2014). Climate change is causing severe rainstorms and flood events, which can lead to mass mortalities of corals, due to a decrease in salinity (Hoegh-Guldberg & Smith, 1989). Coastal development and deforestation cause increased turbidity through sediment rich runoff water, leading to a decrease in light availability for photosynthesis, resulting in coral bleaching (Chansang et al., 1981; Dahl, 1985; Hodgson & Dixon, 1988; Johannes, 1975; Rogers, 1985; Rogers, 1990). All of this together with overfishing constitutes to one of the biggest potential sources of reef degradation (Bellwood et al., 2003; Hughes, 1994; Jackson et al., 2001; Pandolfi et al., 2003). Overfishing does not only affect the size of harvestable stocks, it also alters the dynamics of the reef; it increases levels of diseases, and nutrients that normally would be taken in by those fishes can now impair the resilience of corals and their recovery after events like cyclones or bleaching (Gunderson & Pritchard, 2002; Hughes & Connell, 1999; Knowlton, 2001; Nyström et al., 2000).

When coral and fish conditions are poor, opportunities for the more dominant algae communities increase and in the worst case this can result in coral-algal phase shifts (Hughes, 1994). An excessive abundance of algae can lower the fecundity, survival and growth of established corals (Hughes et al., 2007; Jompa & McCook, 2002; Lewis, 1986; Tanner, 1995). Coral-algal phase shifts are in particular a problem for the Caribbean, where the amount of grazers on the reef have declined due to a massive *Diadema antillarum* die-off; one of the most important grazers (Bak et al., 1984). Herbivorous species can influence the recruitment, growth and survival of corals through grazing (Birkeland, 1977; Kaufman, 1977; Burkepile & Hay, 2010; Sammarco, 1982; Stephenson & Searles, 1960). The importance of herbivorous fishes differs per species. Certain species or families have different feeding behaviours, as they differ in what they feed on and how they impact the underlying substratum. This is why herbivorous fish species are divided in multiple functional grazing groups: scrapers/small excavators, large excavators/bioeroders, grazers/detritivores and browsers (Green & Bellwood, 2009). The two most important grazing groups in this research are grazers/detritivores (Acanthuridae) and scrapers/small excavators (Scaridae) (Choat, 1991). Grazers, detritivores, scrapers and small excavators (<35cm standard length) are intense grazers of epilithic algal turfs and play an important role in limiting establishment and growth of macroalgae. Acanthuridae are classified as grazers or detritivores and are specialized in cropping fast growing epithelial algae. Their impact is important for preventing dominant macro algae from overgrowing hard coral (Bak et al., 1984), and thereby enhances coral growth (Burkepile & Hay, 2010). Scaridae are classified as scrapers and small excavators and are known to provide clean substratum as they take non-excavating bites where they remove algae by scraping or closely cropping the reef surface, which can enhance coral recruitment (Green & Bellwood, 2009).

Commercial fishing within the Saba National Marine Park is prohibited, as there is only recreational fishing, meaning herbivorous fish are theoretically unaffected. The herbivorous fish biomass (based on the key herbivorous species Scaridae and Acanthuridae) has been increasing, from 1954 'fair' in 2015 to 'very good' in 2016. These indicators are based on values from the Reef Health Index, which is further explained in appendix 1: *Reef Health Index* (Hildebrand, 2017). Commercial fisheries in St.

Eustatius are mainly focussed on lobster and fish trap fisheries, which also entails high amounts of bycatch impacting the herbivorous fish densities. The herbivorous fish biomass (based on the key herbivorous species Scaridae and Acanthuridae) seems to be fluctuating but considered 'fair' in 2008 and 2014, while two large peaks were observed in 1999 and in 2015 A preliminary estimate about the status of overexploited fish stocks indicates three herbivorous key stone species to be at high risk of over exploitation in St. Eustatius: blue tang and doctorfish (Acanthuridae) and the princess parrotfish (Scaridae). Indicating that the current fishing effort is unsustainable through use of the current artisanal fishing methods (Kuijk et al., 2015). (Kuijk et al., 2015). Marine Protected Areas (MPA) with no take zones can stimulate coral and fish biomass, what can result in fish overspill, which then will enrich neighbouring fishing grounds (Lorenze Di el al., 2016). This means that setting fishing boundaries can increase the fish biomass, which results that corals will have a greater recruitment, growth and survival rate (Zgliczynski et al., 2013). Information on the relation between grazing and coral recruitment and growth can be applied on fisheries management to minimize the negative fishing impact on herbivorous fishes.

Debrot & Hylkema explain the previous issues through a double negative spiral, which is presented in *figure 1*. This spiral explains the decline of the three-dimensional structure (De Graaf et al., 2015). In the second negative spiral it is visible that the herbivorous keystone species are decreasing because of the degradation of coral coverage and so the loss in three-dimensional structure, which in terms provides shelter and nursing areas for (among others) these herbivorous keystone species. This decrease in grazers, stimulates algae to grow and to dominate coral reefs; since algae can then outcompete corals and bare hard substrates are taken over by algae before new coral recruits can settle. The first negative spiral works as the following: there is a decrease in the coral coverage, which follows with the loss of three-dimensional structure. Because of this loss, it leads to an increase in sedimentation, turbidity and erosion, resulting in a decline in coral coverage (Debrot & Hylkema, 2016).

The AROSSTA (Artificial Reefs on Saba and St. Eustatius) project aims to restore the natural reefs; by tackling the loss of the three dimensional structure by placing artificial reefs and so fighting against the double negative spiral (Debrot & Hylkema, 2016). Currently three different types of artificial reefs are investigated: reef balls, layered cakes and natural rock reefs (*figure 2*), at which fish attraction and coral recruitment are being studied. Recent results, from an unpublished thesis project of AROSSTA, have showed significant differences in both fish abundance as fish species richness across artificial reefs types. However, no significant differences in coral recruitment were found between artificial reefs within the first year after deployment (Heesink & Reid, 2018). The grazing of herbivorous fish species can benefit the coral reefs, since algae succession is limited by the grazing (Burkepile & Hay, 2010). Yet, not all grazers have a positive influence on the coral reef. Grazing of herbivorous fish can therefore be subdivided in categories of grazing impact, at which each category

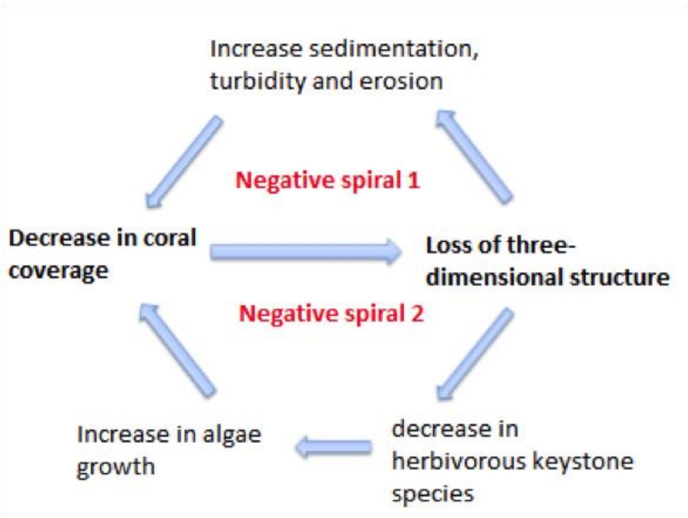

FIGURE 1 DOUBLE NEGATIVE SPIRAL (DEBROT & HYLKEMA, 2016)

FIGURE 2 THREE TYPES OF ARTIFICIAL REEFS: REEF BALLS, LAYERED CAKES AND NATURAL ROCK REEFS

is known to influence the benthic community differently (Green & Bellwood, 2009). Facilitating coral recruitment and maintaining a coral dominant ecosystem by removing macro algae is a pivotal function of these grazers (O'Leary, et al., 2013). It is therefore expected that the composition and the impact of differing grazers can provide important biotic influences of coral recruitment and growth on the artificial reefs (Lenihan et al., 2011).

It is known that on the artificial reefs of AROSSTA, the overall fish abundance differs per artificial reef type (Heesink & Reid, 2018), yet it remains unknown if there are significant differences in the herbivorous fish abundance between the reefs. Grazing on algae can stimulate coral recruitment and growth (Birkeland, 1977; Kaufman, 1977; Burkepile & Hay, 2010; Sammarco, 1982; Stephenson & Searles, 1960), but if this is the case for artificial reefs, is not proven yet. Differences in the status of herbivorous fishes are observed between Saba and St. Eustatius. Herbivorous fishes of St. Eustatius are considerably more pressured by unsustainable fisheries in comparison to Saba. The impact this might have on the coral reef ecosystem, and how possible solutions could be adapted in management is not yet clear.

1.1 Problem statement

There is a lack of knowledge about the influence of grazing of herbivorous fish on the coral recruitment and growth rates on three artificial reefs types provided by AROSSTA in the Dutch Caribbean and the impact of fisheries on the herbivorous fishes.

1.2 Research aim

For this thesis research the aim is to find out what the relation between herbivorous fish species and coral recruitment and growth rates are on artificial reefs in Saba and St. Eustatius. The second aim is to investigate how the effect of unsustainable fishing practices on herbivorous fish can be minimized using fisheries management.

1.3 Research questions

Main research question 1:
"What is the effect of grazing of herbivorous fishes on the coral recruitment and growth rates on artificial reefs around Saba and St. Eustatius?"

Sub-questions:

1. How does the abundance and bite impact of different functional grazing groups differ per artificial reef type?
2. What are the differences in the coral recruitment and growth rates per artificial reef type?
3. What is the relation between the herbivorous fish species abundance, the coral recruitment and the growth rates per artificial reef type?
4. What is the relation between the herbivorous fish grazing impact, the coral recruitment and the growth rates per artificial reef type?

Main research question 2:
"How can the effect of unsustainable fisheries on herbivorous fishes on Saba and St. Eustatius be minimized using fisheries management?"

Sub-questions:

1. What are the effects of unsustainable fisheries on herbivorous fishes?
2. How are fisheries currently managed on Saba and St. Eustatius, specified on herbivorous fishes?
3. How can fisheries management be adapted to minimize the impact of unsustainable fishing practices on herbivorous fishes?

2 About AROSSTA and its network

2.1 Stakeholders

There are multiple stakeholders involved in this project: Van Hall Larenstein (VHL), Saba Conservation Foundation (SCF), St. Eustatius National Park Foundation (STENAPA), Caribbean Netherlands Science Institute (CNSI), Wageningen Marine Research (WMR), Golden Rock Dive Centre (GRDC), fishermen and the researchers. The first six (VHL, SCF, STENAPA, CNSI, WMR and GRDC) have an active role within AROSSTA and are a part of the consortium. VHL, WMR and CNSI are research institutes that are involved in the inquiry of this project. STENAPA and SCF are the questionnaires and public partners of this project, and together with CNSI and GRDC they are located on the islands where research takes place. The stakeholders are further explained in the following paragraphs.

2.1.1 Marine park managers

The Saba Conservation Foundation (SCF) and St. Eustatius National Park Foundation (STENAPA) are the national park managers of Saba and St. Eustatius (SCF, n.d.-a; STENAPA, 2018a). They both share the same mission, which is managing and preserving the natural heritage of their islands, which includes preserving the coral reef ecosystems. As mentioned in the introduction the coral reefs are in a decreasing shape, therefore the project group of AROSSTA is studying an approach to tackle the loss of these ecosystems. The use of artificial reefs would counteract the loss in three-dimensional structure and thereby tackle the double negative spiral (*figure 1*). Both SCF as STENAPA are questioners and public partners of this project, they want to know which type of artificial reef type is most suitable, so that type can be used in the future for the restoration of coral reef ecosystems. In the course of the AROSSTA project, this study aims to provide results on the coral recruit recruitment and growth chances on the artificial reefs in relation to the herbivorous fish communities, which could impact the suitability per artificial reef type. In addition, the fishery management advice on herbivorous fish could add value to the preservation efforts of the coral reef ecosystem. Both organizations are committed to assist and advise during the monitoring period of this study, as both partners have a lot of experience and knowledge within the management of their marine parks. SCF will also offer logistic support by making their boats and cars available for the research (Debrot & Hylkema, 2016; SCF, n.d.-b; STENAPA, 2018a).

2.1.2 Research institutes

Van Hall Larenstein University of Applied Science (VHL) is the coordinator of the AROSSTA project and works on a lot of applied researches involving improvement, development and innovation of professional practice. The lectureship of Coastal and Marine Management therefore has a large network within the field of tropical ecology. The teacher-researchers from AROSSTA are from VHL and are experienced in the Caribbean and in the field of ecology and nature conservation and will guide the students through the research (Debrot & Hylkema, 2016).

Caribbean Netherlands Science Institute (CNSI) is a local science institute for research and education on St. Eustatius, that mainly focused on addressing issues and questions relevant to the sustainability of small tropical island economies (CNSI, n.d.). This indicates indirect interest in the artificial reef studies, where the importance lies in improving the natural coral reef ecosystem. CNSI plays an active role within the monitoring period of this research, as they facilitate and assist AROSSTA students on St. Eustatius. They also provide sampling and analysis equipment that can be used for ecological research (Debrot & Hylkema, 2016).

Wageningen Marine Research (WMR) is a Dutch research institute with the aim to gather knowledge and advice about sustainable management and use of sea and coastal areas. They play an active role in the consortium, supporting the project financially. At WMR, interventions for habitat restoration and building with nature are spearheads in tropical research (Debrot & Hylkema, 2016).

2.1.3 Local partners

Golden Rock Dive Centre is a local dive shop on St. Eustatius that has a direct interest with the placements of artificial reefs, as the artificial reefs function as small scale dive objects and directly enrich their offer to customers (Debrot & Hylkema, 2016; GRDC, n.d.). Golden Rock Dive Centre is a consortium partner from the business world and is experienced in artificial reef deployment, which made them very important in the first phases of AROSSTA and still supports AROSSTA with dive equipment in St. Eustatius (Debrot & Hylkema, 2016).

Fishermen are in favour of placing artificial reefs, as these enrich the fishing grounds (Bombace et al., 1994). On Saba there are roughly 10 fishing boats and about 30 active fishermen. On St. Eustatius there are about 15 fishing boats and 25 fishermen, of which only 5 are full-time fishermen (De Graaf et al., 2017). In the long term, the artificial reefs must enrich the coral reef ecosystems and thus also the fish stocks. However, based on results obtained in this study and a literature study on fisheries policy, a management recommendation on herbivores reef fish will be suggested, aiming to minimize fishing impact on herbivorous fish, this could have negative impacts in their field of work.

2.1.4 Client and researchers

The client wanted to know how the grazing of herbivorous fish effects the coral recruitment and growth. In this case the client was also one of the supervisors, therefore there has been consistent consultation. During the start of this study a lot of thoughts were put into the aim of this research. At this time a proposal was made, that included a number of survey techniques, which were thoroughly debated and tested in collaboration with the supervisors. During the monitoring period occasional consultation took place when methods had to be discussed or problems occurred. Upon finishing this study, the report has been submitted to the supervisors.

Our personal interest with the AROSSTA project concerns multiple aspects. Our main priority focuses on the learning process of writing a subsequent research in a professional manner. In addition to this it is the practical knowledge, acquaintance and cooperation with stakeholders of our future field of work that excites us, as the importance of marine conservation and in particular coral reef preservation has been a guiding theme through our study. Hereby, we are delighted that we can contribute to improving coral reefs of the Dutch Caribbean.

2.2 Relation with other studies

There are no projects directly involved with AROSSTA, but there are a lot of projects that work complementary to the AROSSTA project, a few examples are:

Coral Restoration Foundation Bonaire (CRF Bonaire) has the mission to develop affordable, effective strategies for protecting and restoring the shallow water population of *Acropora cervicornis* and *A. palmate* corals along the coastlines of Bonaire and Klein Bonaire. CRF is also building coral nurseries in a ladder-construction form (CFR Bonaire, 2013).

Sexual Coral Reproduction (SECORE) is a coral conservation project, using a multidisciplinary strategy combining research, active reef restoration, education and outreach to help coral reefs persist and thrive into an uncertain future. This is a worldwide organisation, but based and most invested in the Caribbean. They develop protocols based on other study subjects, so they can implement the findings in their field of work (SECORE Foundation, 2015).

The Coral Restoration Consortium (CRC) has the mission to work together to promote exchange technology as well as scientific and practical intelligence ingenuity to demonstrate that restoration can achieve meaningful results at scales relevant to reefs in their roles of protecting coastlines, supporting fisheries and serving as economic engines for coastal communities (RRN, 2018).

Restoration of Ecosystem Services and Coral Reef Quality (RESCQ) is a project in the Caribbean that aims to restore the coral reefs in the Caribbean. Saba Conservation Foundation (SCF), St. Eustatius National Parks (STENAPA), Nature foundations St. Maarten (NFSXM), Turks and Caicos Reef Fund (TCRF) and WMR work together on the RESCQ project (WUR, 2016). They are building coral nurseries in the form of ladder-constructions with coral fragments attached. Elkhorn (*Acropora palmata*) and Staghorn (*Acropora cervicornis*) are used since these are fast growing corals and their presence has been decreasing in the Caribbean. Eventually the corals will be transplanted upon restoration sites (Antilliaans Dagblad, 2016; Meesters, 2016; WUR, 2016). A colleague of one of the co-founders of AROSSTA coordinates RESCQ; information is shared when it is of use for the other project.

REEFolution is based in Kenya and is established to restore and stimulate more sustainable use of coral reefs. One way of restoring the ecosystem is by placing artificial reefs as coral nurseries and to add more shelter to enhance fish population (Osinga, 2015). This project is also supported by WUR and because of this mutual partner the founders have met and now share information on the efficiency of the artificial reefs.

The Diadema Restoration Project mainly focuses on repopulating the reefs around Puerto Rico with sea urchins (specifically *Diadema antillarum*) since this is a keystone species and a very effective herbivore. With a high Diadema population on a reef with a lot of algae, herbivory will be increased and will increase available space for corals (Williams et al., 2010).

All these projects, together with AROSSTA, aim for a healthier coral reef ecosystem within the Caribbean. Where other projects actively restore coral species, AROSSTA researches the natural restoration and the influences of the surroundings. After contact with the Diadema Restoration Project, the founders of AROSSTA are now also setting up a *Diadema antillarum* project in Saba and St. Eustatius complementary to the AROSSTA project to increase the effectiveness of restoring a healthy coral reef ecosystem. This is why it is important to publish research reports so projects and studies can learn from each other and together the mutual interest can be accomplished: to enrich and restore the coral reef ecosystems, and in this case of the Caribbean.

2.3 Sustainability

The AROSSTA project is committed to research the potentials of different types of artificial reefs with the aim to counter the loss in three-dimensional structure and thereby stimulate coral reef ecosystem recovery. Therefore, this research primarily concerns the ecological interest. However, there are many parties with interest in the coral reefs like the fisheries and tourism sectors. The recreational value of reefs, as indicated by income from tourism, is potentially enormous (Moberg & Folke, 1999). For example, estimated reef recreation value in the Caribbean is approximately US$ 1.654 per hectare per year, this indicates the potential economic interest (Chong et al., 2003). The ecological research conducted by AROSSTA can be applied to recognize trends or patterns in the health status of coral reef ecosystems of Saba and St. Eustatius. When negative trends are linked to anthropogenic influences of stakeholders (e.g. unsustainable fisheries), a management recommendation can be written to adjust fishing techniques, limiting fishing effort or fishing grounds. Ecological research is necessary to support and create management decisions, through which sustainable use of coral reef ecosystems can be realized. AROSSTA provides the opportunity for students to get involved in a project in Saba or St. Eustatius, to research the efficiency of artificial reefs in the Caribbean. Because of AROSSTA, multiple parties come together to talk about the possibilities on how to improve the current state of the coral reef ecosystems.

2.4 Project and policy

DCNA published the Nature Policy Plan of the Caribbean Netherlands for the years 2013 till 2017, it includes the plans of the national parks: The areas that should be protected are decided by the government of the islands themselves. The islands both have a National Marine Park around the island. Saba also has four marine reserves and St. Eustatius has two marine reserves, marine parks and reserves are presented in *figure 3 & 4* (DCNA, 2013, 2014a, 2014b). In the Legislation Handbook for the National Marine Parks of St. Eustatius (2008) the regulations for permit holders are described. There are regulations on turtles, mammals, lobster sizes, fishing materials, but no forbidden fish species to fish on (Blijden et al., 2008). These rules are from 2008, no other rules can be found on this specific subject. Usually that would mean that there are no new rules, but it cannot be said with certainty. Personal experience showed that indeed no certain fish species are excluded from the catch of fishermen, but most reef fishing techniques used by the local fishermen are not focused on herbivorous fish species.

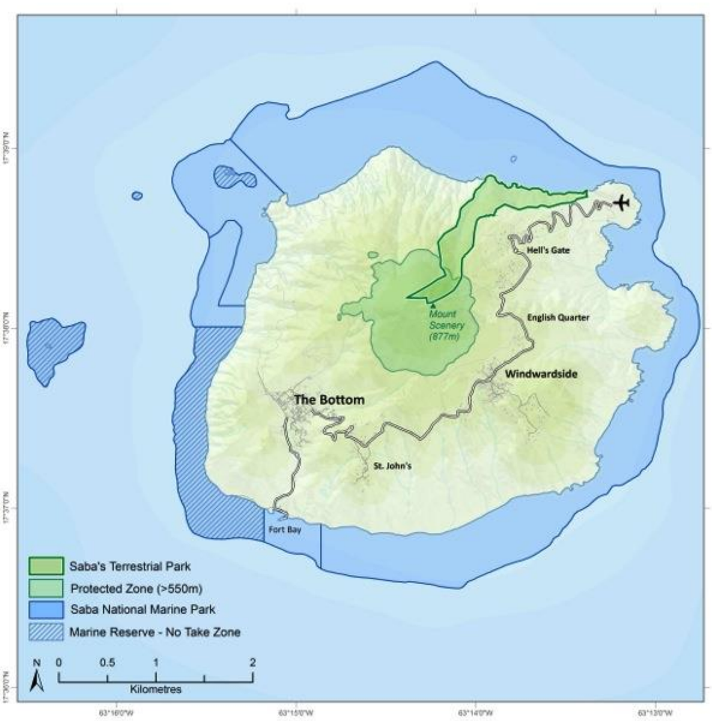

FIGURE 3 SABA NATIONAL PARKS (DCNA, 2014 A)

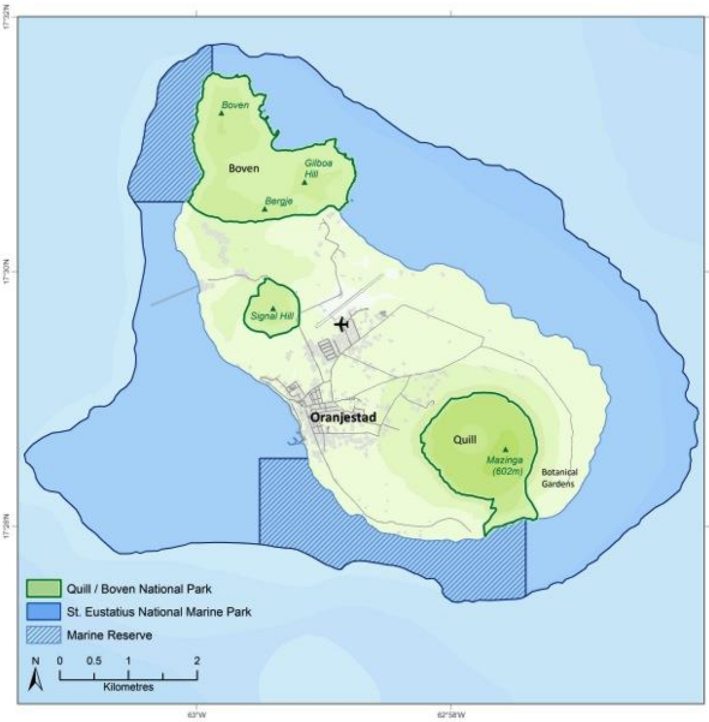

FIGURE 4 ST. EUSTATIUS NATIONAL PARKS (DCNA, 2014 B)

3 Methods and materials

3.1 Study site

The data for this research has been collected at three dive sites, of which two in St. Eustatius: Twin Sisters (coordinates: N: 17.51715, W: -063.00337) and Crooks Castle (coordinates: N: 17.47220, W: -062.98911). The artificial reefs on Saba were deployed in May 2017 and on St Eustatius in June 2017. Currently in Saba there is only one dive site left; Big Rock Market (coordinates: N: 17.36772, W: 063.14264). Ladder Bay was located in the West of Saba but because of a large swell in February 2018, the artificial reefs have completely sunk into the sea bottom. The dive sites are also shown in *figure 5*. The dive sites have a depth between 15 and 20 m each. On all three dive sites there are three artificial reef plots that consist: 3 layered cakes, 3 reef balls or a natural rock reef, the natural rock reefs measure 120x160x65 cm and are based on the average size the layered cake and reef ball plots. On the Big Rock Market there is a second natural rock reef, which is used for the coral growth, this will be further explained in *chapter 3.2.4 Coral growth survey*. The observations have taken place from the 22nd of October until the 24th of December, since this was when the researchers were on the islands.

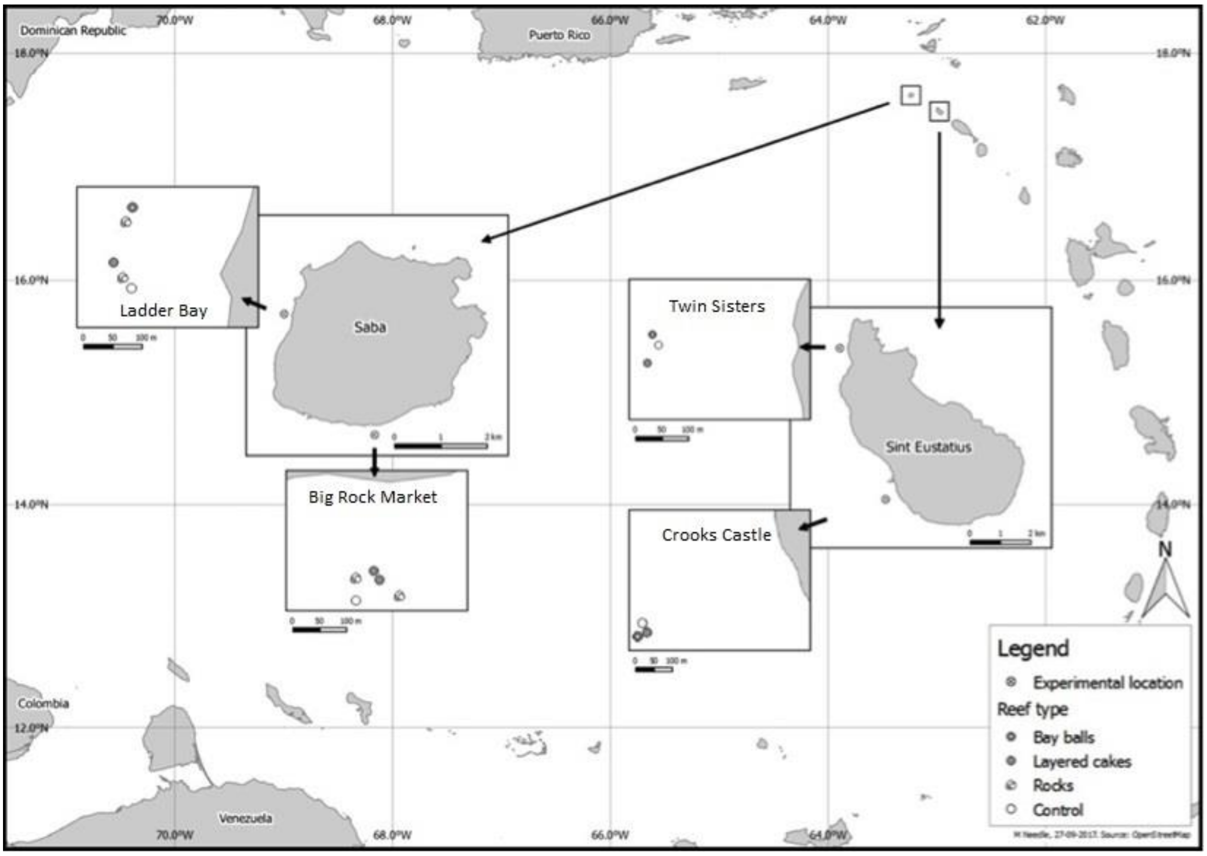

FIGURE 5 MAP OF THE LOCATION FROM THE STUDY SITES

3.2 Data collection

3.2.1 Herbivorous fish abundance survey

A total of 339 herbivorous fish were counted, of which 84 on the reef balls, 145 on the layered cakes and 110 on the natural rock reefs. Ten fish surveys per dive site were conducted to monitor the fish species that were on the different types of artificial reefs; one diver recorded the sizes and amount of fish species per reef type by writing it on a slate. The second diver recorded the fish with a GoPro for future reference and for identification of unknown species. The exact fish survey protocol can be found in appendix 2: *Fish survey protocol*. All the recorded fishes have been analysed, by writing down the information e.g. species, size category, location and artificial reef type.

3.2.2 Herbivorous fish grazing survey

In addition to the fish survey, a grazing survey was conducted to determine not only what fishes were present around the artificial reefs, but also to see if they were grazing on the artificial reefs. In total six hours of data was collected per artificial reef type per dive site. These surveys were conducted by hanging a GoPro on a floating PVC construction above the artificial reefs. During a survey, each individual artificial reef plot had one of these camera constructions recording herbivorous fish grazing behaviour for a time period of a maximum of an hour simultaneously per day. Usually the grazing survey was combined with a fish count, where the cameras were hung after a fish monitoring and picked up either later that dive or in a second dive. The exact protocol of this survey is presented in appendix 3: *Herbivorous fish grazing protocol*.

After the recording, the footage was played to record the species present and the number of bites taken by individual fish. A bite was only recorded when grazing behaviour was recognized. This is the case when either the fish applied its jaw to the algae and closes its mouth or when the body movement of the grazing pattern was recognized. Rapid bites in quick succession that cannot be separated were counted as a single bite, as other studies have done like (Korzen et al., 2011). A total count of 27,742 bites was recorded, 14,417 of these bites were observed on the reef balls, 5,297 on the layered cakes and 8,028 on the natural rock reefs.

Occasionally grazing footage was influenced by current or a misplaced angle of view of the camera. By calculating the missed estimated percentage of non-recorded artificial reef, the bite impact could be compensated. An irregular scope due to current presence was compensated by dividing the missing surface area in ½ and when the camera was misplaced the entire missing surface area was compensated. The exact protocol on this can be found in appendix 4: *Estimating non-recorded grazing impact protocol*.

After processing the data, the body mass (weight in gram) per size classes of the herbivorous species was calculated by using the following formula: log weight (g) = log a + b x log Fork Length (mm) (Bohnsack & Harper, 1988; Paddack et al., 2006). With this weight, the total number of bites was then converted to a standardized bite impact (total bites * body mass fish in kilograms) (Bohnsack & Harper, 1988; Kulbicki et al., 2005; Odat, 2003). All logs a and b values for the herbivorous fish species were available. All log a and b values were obtained from Bohnsack & Harper (1988) and are presented in the table in appendix 5: *More information on herbivorous fish species*. With these calculations, an overview of the grazing impact of herbivorous fish, per size class per artificial reef was formed. These methods were based on multiple researches (Fox & Bellwood, 2008; Korzen et al., 2011; Mantyka & Bellwood, 2007). By sorting the previous calculated bite impact per functional grazing groups a biomass bite impact per functional grazing group has been formed (Green & Bellwood, 2009).

3.2.3 Coral recruit survey

In November 2018, during late afternoons one or two coral surveys per dive site were conducted to identify the coral recruitment per artificial reef type. The artificial reefs were monitored with use of an Ultraviolet light, providing a reliable monitoring technique, which makes locating hard corals easier, as they reflect the UV light. The total number of recruits was counted per artificial reef. In total 628 coral recruits have been counted during this research, of which 228 on the reef balls, 273 on the layered cakes and 127 on the natural rock reef. It was decided only to count the corals instead of mapping, taking photos and identifying the corals, because of the high amount of corals found and the limited amount of time. The exact protocol can be found in Appendix 6: *Coral count survey protocol*.

3.2.4 Coral growth survey

In November 2018, a total of 15 coral surveys have been conducted to relocate, monitor and photograph the coral recruits that were found during the previous study April 2018. Again with the use of the UV lights and an overview of the mapped corals, they were relocated. When found, a picture was taken of the coral with an size indicator and the number of the coral, the detailed protocol of this survey can be found in appendix 7: *Coral growth survey protocol*. This picture was used to measure the surface area and the perimeter of the coral with the use of ImageJ. It was decided that the coral recruits found in the first survey had to have a surface area between 10 mm^2 and 30 mm^2, so the initial values were equal. A total of 98 corals recruits were relocated, of which 49 were fit (>10 mm^2 - <30 mm^2) for the analysis, 29 were too small (<10 mm^2) and 20 coral recruits were too large (>30 mm^2). Of these 49 remaining corals (39 *Porites astreoides* and 10 *Agaricia agaricites*. These species are further referenced as Porites and Agaricia, unless noted otherwise), 21 were located on the reef balls, 25 on the layered cakes and 3 on the natural rock reefs. The measured coral areas from the previous and this study were compared. By dividing the second coral area by the first coral area, the growth rates were calculated. The exact protocol of the coral growth measurement is presented in appendix 8: *Coral growth measurement protocol*. Because there were only 4 corals in total relocated on the natural rock reef (without taking the ones that were too small and too big into account), the relocated corals on the second natural rock reef at Big Rock Market were also taken into account to increase the N value. These natural rock reef counts were combined as they belonged to the same dive site, were located only 50 meters apart and therefor experienced the same circumstances. The lack of corals found back on the natural rock reefs can be explained through the damage of hurricane Irma, which resulted in a reconstruction of the natural rock reef plots.

3.2.5 Fisheries management

To find information on the effect of unsustainable fisheries on herbivorous fishes and how the effects can be minimized on Saba and St. Eustatius, a literature study has been conducted to gather more information about the fisheries rules and regulations that are present on the islands, directed at herbivorous fish species. In addition there will be looked into the current health status and trends of macroalgae and coral coverage as well as the herbivorous fish densities to further investigate the fisheries impact. Terms that were used to search for this literature are for instance ”fisheries management Saba”, “fisheries management St. Eustatius”, “regulations fishing Caribbean”, “policy plan Saba”, “legislation St. Eustatius”, “status coral reef ecosystem Dutch Caribbean”, “effects of fisheries”, “fishing on herbivorous fishes”, “selective fishing effects” or “minimizing unsustainable fishing effects”. Next to a literature study, some of the stakeholders; the Saba Conservation Foundation (SCF), St. Eustatius National Parks (STENAPA), Caribbean Netherlands Science Institute (CNSI) and the Harbour Master from Saba, have been contacted to gather more information on data and about the actual situation. STENAPA is contacted through mail, the Harbour Master has been personally contacted but shared information through mail and SCF has been contacted personally only.

3.3 Statistical analyses

The difference in mean herbivorous fish abundance between the artificial reefs was tested. Levene’s test was used to check the dataset on homogeneity, the dataset turned out to be homogeneous ($p= 0.934$). The normal distribution has been tested on the two herbivorous fish grazing groups abundance per artificial reef, this has been done with the use of the Shapiro-Wilk test. The reef balls were normally distributed ($p= 0.090$), but the layered cakes ($p= 0.009$) and natural rocks reefs ($p= 0.017$) were not normally distributed. Both Acanthuridae ($p= 0.290$) and Scaridae ($p= 0.150$) were normally distributed. Because some artificial reefs were not normally distributed, the Mann-Whitney test was used to test the two herbivorous fish groups abundance on the different artificial reefs.

The difference in mean herbivorous fish grazing bite impact between the artificial reefs was tested. Levene’s test has been used to check the homogeneity of the herbivorous fish grazing dataset. The dataset is not homogeneous ($p = 0.001$). The Shapiro-Wilk test has been used to test the normal distribution on the two herbivorous fish groups bite impact per artificial reef. None of the artificial reef types were normally distributed (reef balls and natural rock reef $p < 0.001$; layered cakes $p = 0.001$), also the two grazing groups were not normally distributed ($p < 0.001$). Because the dataset is not homogeneous and not normally distributed, the Kruskal-Wallis test has been used to test the herbivorous fish grazing impact on the different types of artificial reef. To test the two herbivorous fish grazing groups bite impact on the different artificial reef types, the Mann-Whitney test has been conducted per artificial reef type because the dataset was not normally distributed.

The Shapiro-Wilk test has also been used to test if the coral recruitment dataset was normally distributed; the layered cakes ($p = 0.669$), the reef balls ($p = 0.220$) and the natural rock reef ($p = 0.517$) are normally distributed. With the use of Levene's test it was concluded that the dataset is homogeneous ($p = 0.304$). Since the dataset is both homogeneous and normally distributed, the One-way ANOVA was conducted to compare the effect of the three artificial reef types on the coral growth. The coral recruitment dataset was also tested to see if there were differences in the dive sites, this also was conducted through a One-way ANOVA.

The Shapiro-Wilk test has been conducted to find out if the coral growth dataset was normally distributed. The layered cakes ($p < 0.001$) and the reef balls ($p = 0.020$) resulted to be not normally distributed, but the natural rock reef ($p = 0.477$) was normally distributed. With the use of Levene's test it was concluded that the dataset was not homogeneous ($p = 0.044$). The ANOVA test is most sensitive to homogeneity, so the Kruskal-Wallis was used to test the difference between artificial reef types in coral growth. The coral growth data set was also tested between the species per artificial reef, the Mann-Whitney for the reef balls and layered cakes, but the natural rock reef could not be tested, because there was only one Agaricia species found back on which the growth could be measured on that reef. To test between the two species growth rates per dive site, the Kruskal-Wallis test was conducted. The Mann-Whitney test was also used to test differences in mean growth between the species.

4 Results

4.1 Herbivorous fish abundance

The highest mean biomass (± SE) in herbivorous fish abundance was observed at the layered cakes (465.30 ± 182.09 g), followed by the natural rock reefs (418.87 ± 147.52 g) and the lowest abundance was observed at the reef balls (416.54 ± 187.57 g) see *figure 6*. The analysis of variance showed that the effect of artificial reef types on herbivorous fish biomass was not significant ($F(2, 19)= 0.025$, $p= 0.975$).

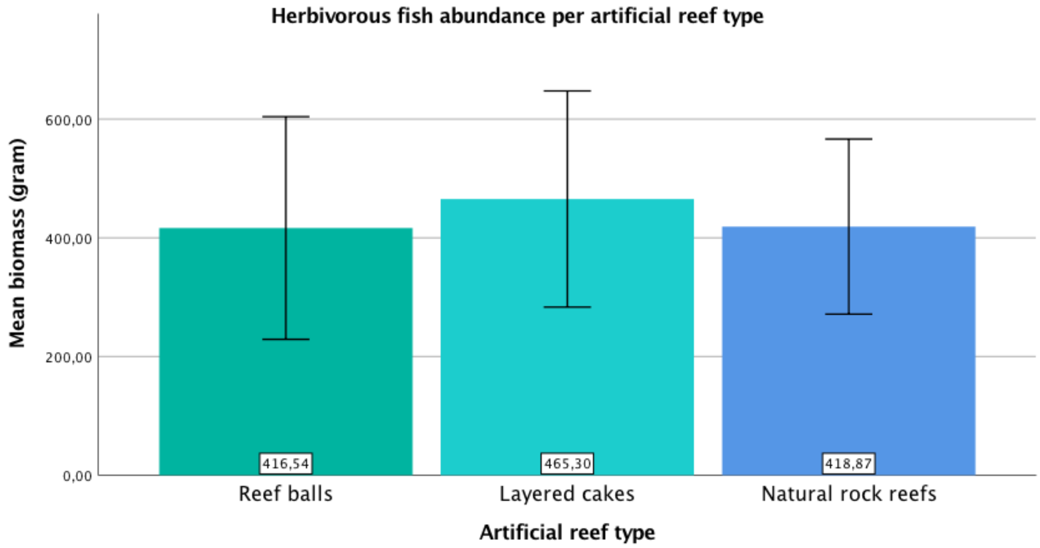

FIGURE 6 MEAN BIOMASS IN GRAM (± SE) HERBIVOROUS FISH ABUNDANCE PER ARTIFICIAL REEF TYPE

The difference between artificial reefs of the abundance of the two grazing groups was tested with the Mann-Whitney U test and showed no significant differences: the layered cakes had the highest mean biomass (± SE) ($U= 6$, $p= 0.175$), followed by the natural rock reefs ($U= 1$, $p= 0.165$) and the lowest abundance was observed at the reef balls ($U= 4$, $p> 0.999$). Overall, Scaridae showed to be the grazing group with the highest biomass (in gram) in the dataset, see *figure 7*.

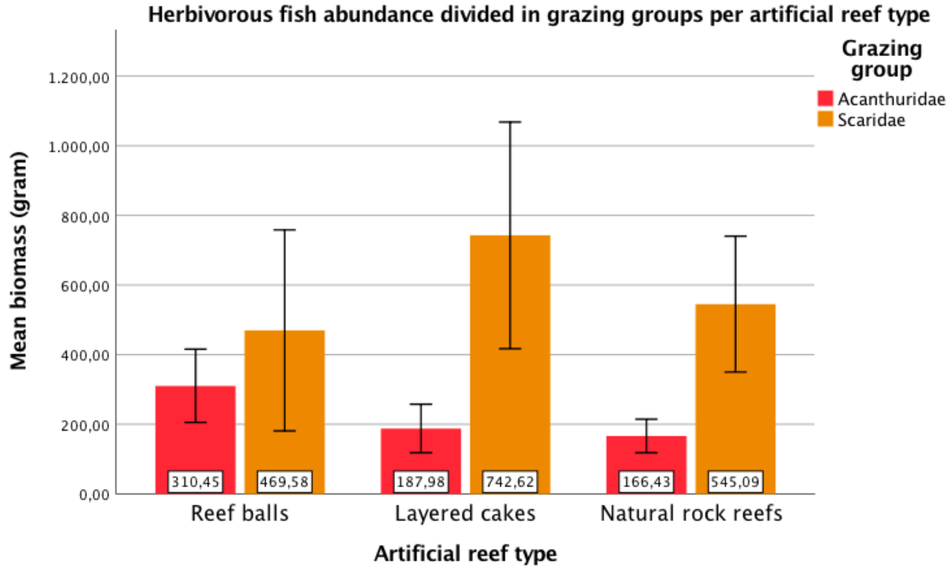

FIGURE 7 MEAN HERBIVOROUS FISH BIOMASS IN GRAM (± SE) DIVIDED IN GRAZING GROUPS PER ARTIFICIAL REEF TYPE

4.2 Herbivorous fish grazing

The reef balls experienced the highest mean bite impact (± SE) (22.32 ± 9.17 kg/h), followed by the natural rock reefs (10.81 ± 4.57 kg/h) and the lowest bite impact was observed on the layered cakes (6.27 ± 2.51 kg/h), see *figure 8*. The Kruskal-Wallis test showed no significant difference between the mean bite impact of herbivorous fish per artificial reef type (H(2)= 1.039, p= 0.595).

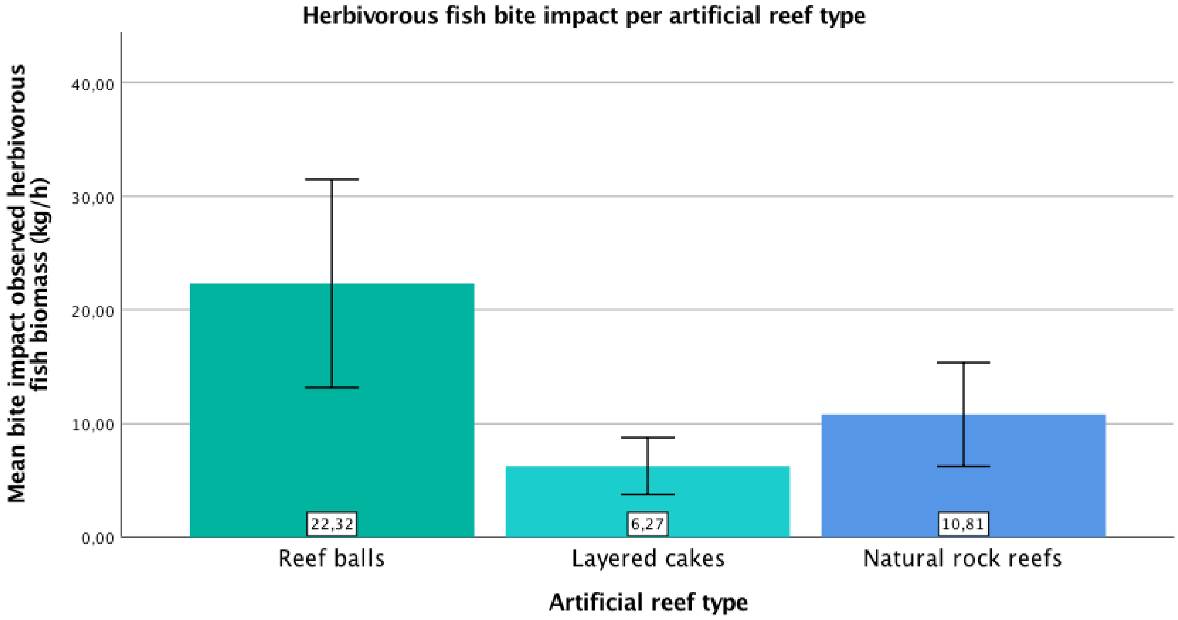

FIGURE 8 MEAN HERBIVOROUS FISH BIOMASS IN KG/H (± SE), BITE IMPACT OBSERVED PER ARTIFICIAL REEF TYPE

The grazing group that showed the highest overall bite impact (kg/h) was Acanthuridae in this dataset. The reef balls experienced the highest bite impact, see *figure 9*. The Mann-Whitney U test showed a significant difference in bite rates between the two grazing groups on the reef balls (U= 9, p= 0.028), but no significant difference on the layered cakes (U= 15, p= 0.391) and the natural rock reefs (U= 18, p= 0.247).

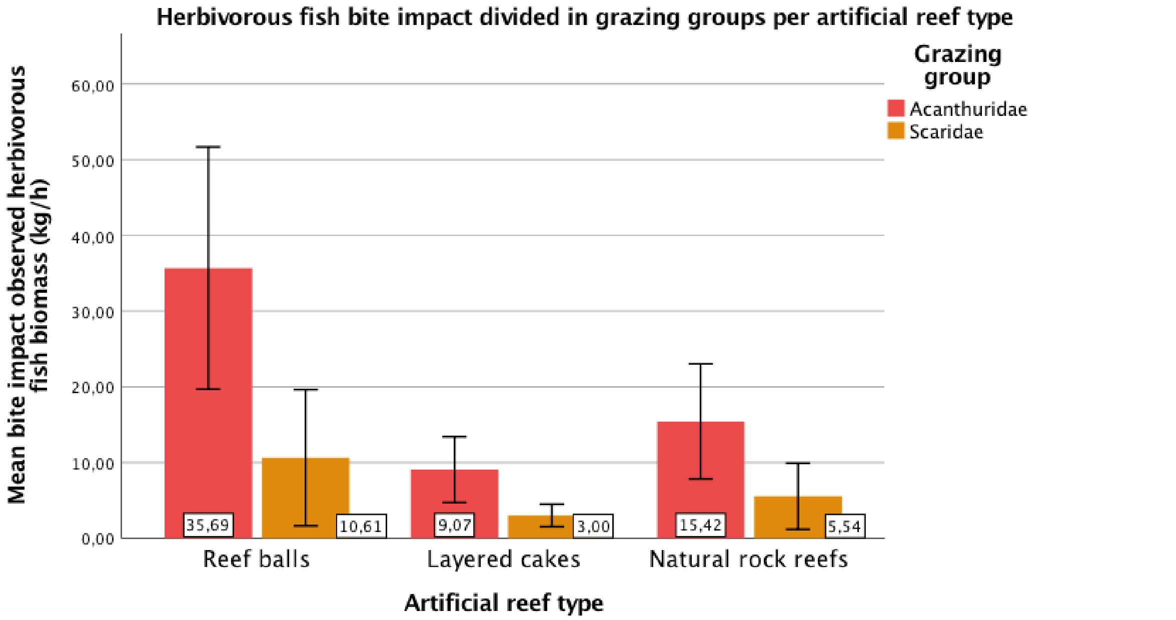

FIGURE 9 MEAN BITE IMPACT OF OBSERVED HERBIVOROUS FISH BIOMASS IN KG/H (± SE) DIVIDED IN GRAZING GROUPS PER ARTIFICIAL REEF TYPE

4.3 Coral recruitment

The highest mean number of coral recruits (± SE) was found on the layered cakes (91.00 ± 26.08), followed by the reef balls (76.00 ± 42.78) and the lowest number of coral recruits was observed at the natural rock reefs (42.33 ± 22.66), see *figure 10*. The analysis of variance showed that the effect of different artificial reef types on coral recruitment was not significant ($F(2, 6)= 0.616$, $p= 0.571$).

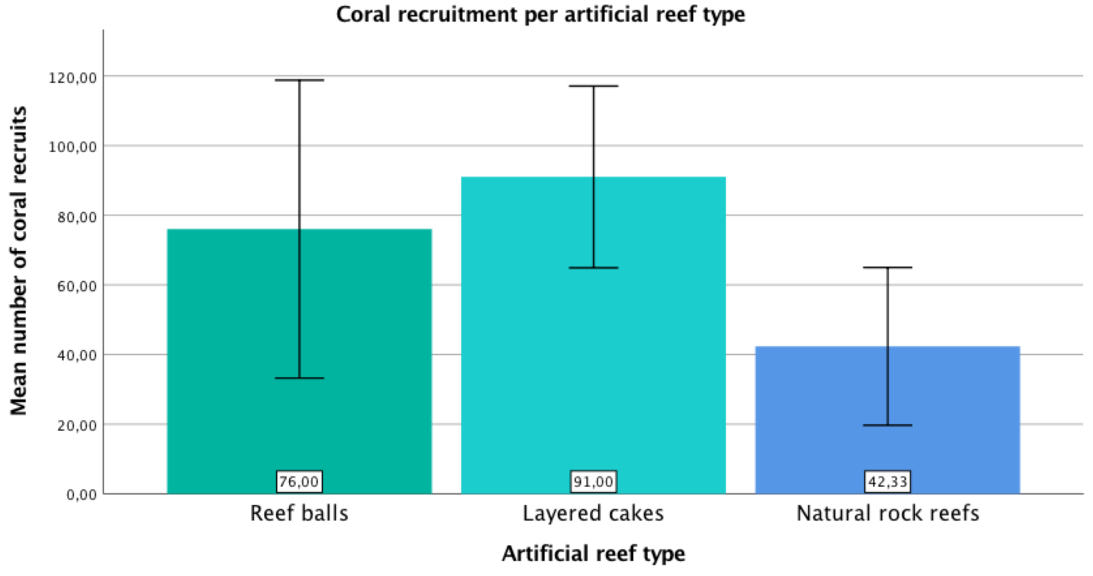

FIGURE 10 MEAN NUMBER OF CORAL RECRUITS (± SE) PER ARTIFICIAL REEF TYPE

The highest mean number of recruits (± SE) was found at the Big Rock Market (129 ± 38.69), followed by Crooks Castle (51.67 ± 26.84) and Twins Sisters (28.67 ± 20.75), see *figure 11*. The analysis of variance showed that the effect of different dive sites on coral recruitment was significant, $F(2, 6)= 9.391$, $p= 0.014$. Post hoc comparisons using the Bonferroni correction indicated that the mean difference between Big Rock Market and Twin Sisters ($M= 100.33$, $SE= 24.26$, $p= 0.018$) was significant. Big Rock Market and Crooks Castle ($M= 77.33$, $SE= 24.26$, $p= 0.057$) was not significantly different and Crooks Castle and Twin Sisters ($M= 23.00$, $SE= 24.26$, $p> 0.999$) was also found to be not significantly different.

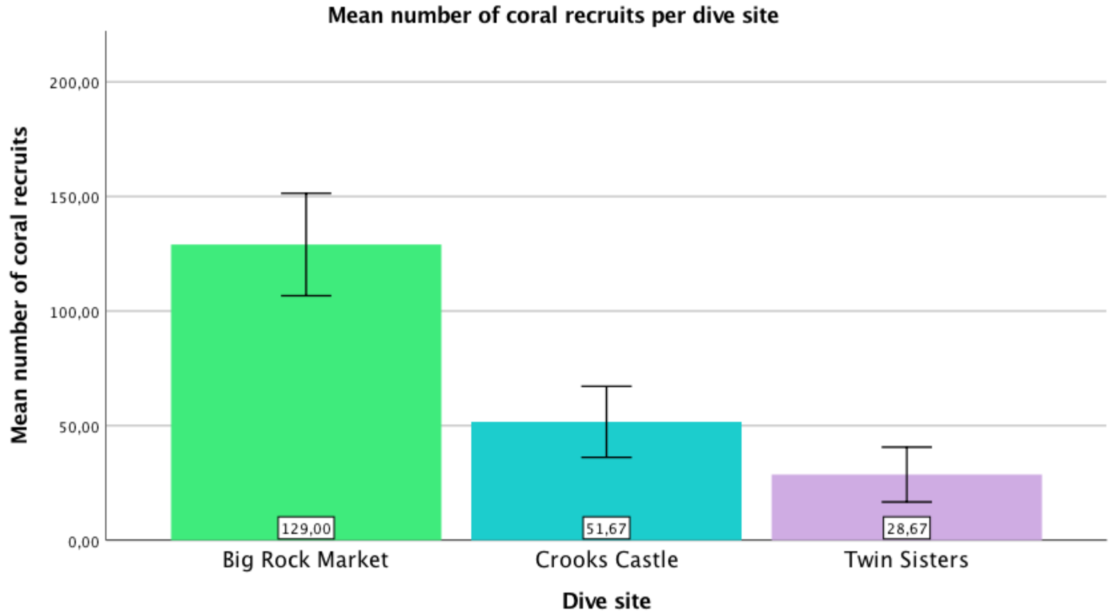

FIGURE 11 MEAN NUMBER OF CORAL RECRUITS (± SE) PER DIVE SITE

4.4 Coral growth

The highest mean relative growth measured as surface area per year (± SE) were observed on the layered cakes (5.26 ± 1.54), followed by the natural rock reef (4.23 ± 1.54) and the lowest growth rates were observed on the reef balls (3.62 ± 0.37), see *figure 12*. The Kruskal-Wallis test showed no statistically significant difference between the coral growth per type of artificial reef (H(2)= 1.212, p= 0.546).

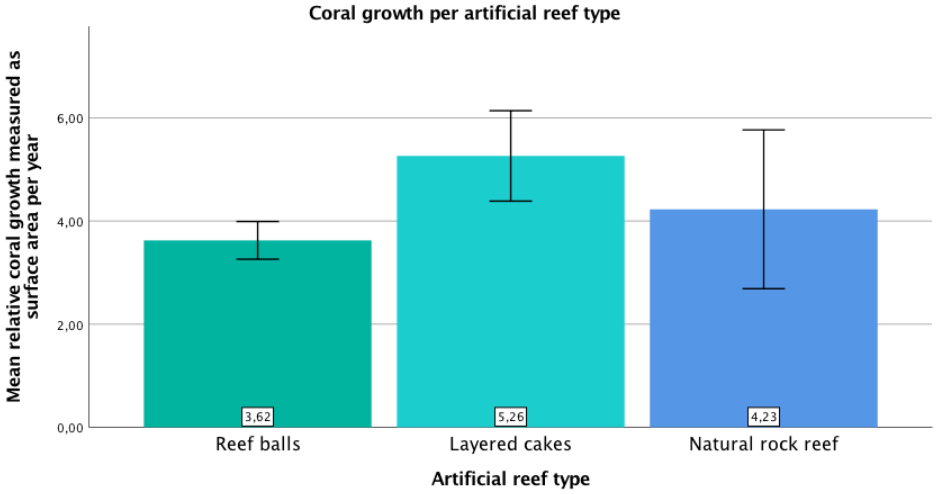

FIGURE 12 MEAN CORAL GROWTH (± SE) PER ARTIFICIAL REEF TYPE

A significant difference was found on the reef balls between Porites and Agaricia growth (Mann-Whitney: p= 0.007), but no significant difference was found between the two species on the layered cakes (Mann-Whitney: U= 130, p= 0.739). In *figure 13* the mean coral growth is presented per species.

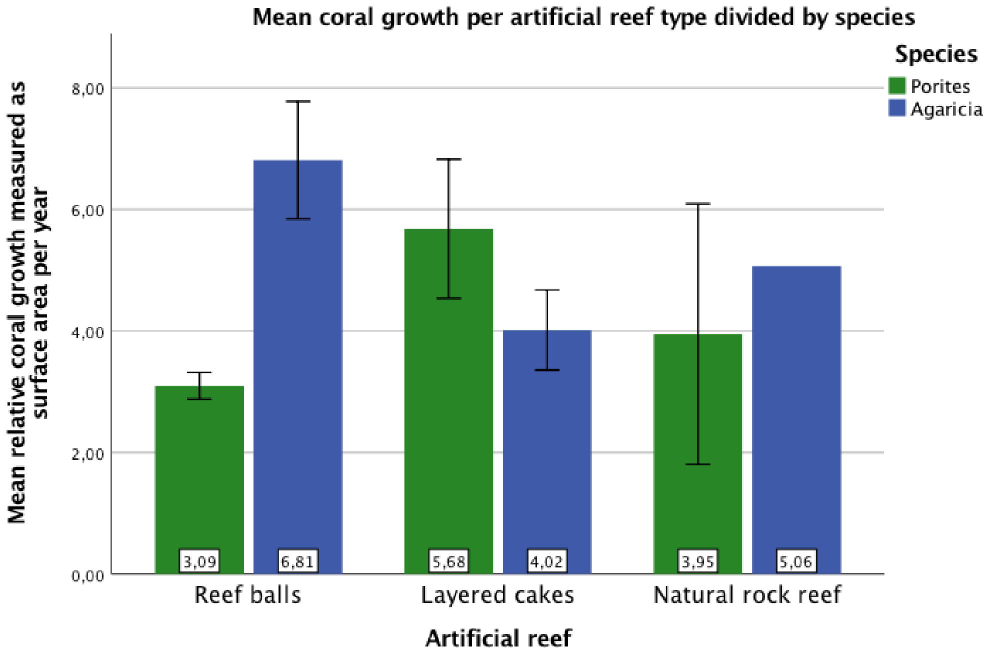

FIGURE 13 MEAN CORAL GROWTH (± SE) PER ARTIFICIAL REEF TYPE DIVIDED BY SPECIES. ON THE NATURAL ROCK REEF ONLY ONE AGARICIA WAS FOUND, WHICH HAD A RELATIVE GROWTH MEASURED AS SURFACE AREA OF 5.06 PER YEAR

The Kruskal-Wallis test showed that there was no significant difference in the growth between the dive sites (p= 0.219) and the Mann-Whitney U test showed that there was no significant difference in the growth between Porites (mean relative growth measured as surface area per year ± SE) (4.96 ± 0.62) and Agaricia (4.35 ± 0.58) (p= 0.107).

4.5 Ecosystem health analysis of Saba & St. Eustatius

Saba

Current macroalgae and coral coverage

Coral cover has shown a lot of variation over the past decades (*figure 14*). Indicating an increase in coral cover in the early 90's which then plummeted between 1999 and 2015 to an current coral cover of 5.5% which is considered 'poor' by Reef Health Index standards (which is explained in Appendix 1: *Reef Health Index*). A slight increase of 1.2% was observed in 2016 resulting in a current known coral cover of 6.6%, which is still considered 'poor'. Increased macro algae cover has been observed over the last 40 years in the entire Caribbean indicating a 30% average macro algae cover since 2005, which is considered 'critical' (*figure 15*). The macro algae cover around Saba has been observed to be much lower compared to the entire Caribbean but did show an increase from 15.6% to 20.6% between 2015 and 2016 and is considered 'poor' (Hildebrand, 2017).

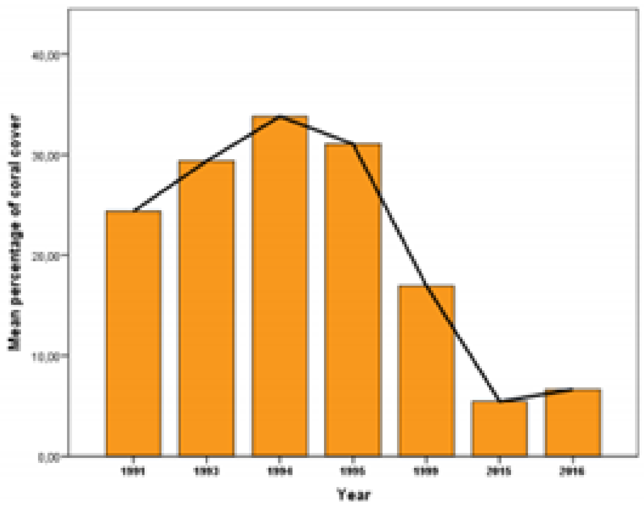

FIGURE 14 CORAL COVER IN THE SNMP OVER THE LAST 25 YEARS (HILDEBRAND, 2017)

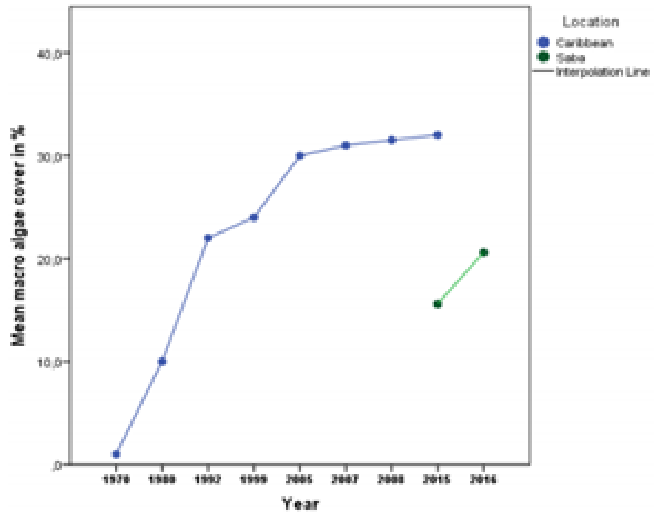

FIGURE 15 MEAN MACRO ALGAE COVER OF SABA AND THE WHOLE CARIBBEAN (HILDEBRAND, 2017)

Current status of herbivorous fish

The herbivorous fish biomass (Scaridae and Acanthuridae) indicates improvement from 2015 as the Reef Health Indicator indicates a 'fair' herbivorous biomass at 1954 g/100 m² in 2016 and a 'very good' biomass in 2016 at 3741 g/100 m². In both years higher herbivorous fish biomass was observed in zones that allowed fishing (*figure 16*) (Hildebrand, 2017; Menger, 2017).

Key Herbivorous Fish (g/100 m^2)			
Total 2016	RHI	Total 2015	RHI
3741	5	1954	3
Fished sites	RHI	Fished sites	RHI
4480	5	2251	3
Unfished sites	RHI	Unfished Sites	RHI
3002	4	1656	2

Key Commercial Fish (g/100 m^2)			
Total 2016	RHI	Total 2015	RHI
1242	3	1319	4
Fished sites	RHI	Fished sites	RHI
845	3	488	2
Unfished sites	RHI	Unfished sites	RHI
1640	4	2150	5

FIGURE 16 HERBIVOROUS FISH BIOMASS SABA (HILDEBRAND, 2017)

Current fishing status

Unfortunately no data on this subject is available in Saba. Mostly because the fishing in the Marine Park is only performed by recreational fishermen and no data is obtained on their catch or fishing pressure.

St. Eustatius

Current macroalgae and coral coverage

Between 1999 and 2007 coral coverage has been shifting between 23% and 27%, which was considered good for Reef Health Index standards (see appendix 1: *Reef Health Index*). This number plummeted in 2008 to a 'poor' coverage of 6.5%. In 2015 the coral coverage was approximately 5%, which is considered 'poor' and was remarkably low compared to the average coral cover reported for the Caribbean.

The macro algal cover was measured at its highest peak in 2005 at 43%, which is considered 'critical'. The macro algae coverage then rapidly declined to a 'poor' 14%-18% coverage between 2007-2008. In 2015 the latest measurement indicated a 'critical' 25.2%, which is similar to the average in the Caribbean (De Graaf et al., 2015). Even though the coral coverage is low, nearly 12 coral recruits were observed per m^2. In Bonaire this was between 10-20 recruits per m^2 (Steneck et al., 2014) and in the Wider Caribbean Region an average of ~4 coral recruits were observed per m^2 (Kramer, 2003).

Current status of herbivorous fish

The herbivorous fish biomass (based on the key herbivorous species Scaridae and Acanthuridae) seems to be fluctuating, shifting between 2100 g/100m² and 2514 g/100m² between 2008 and 2014 which is considered 'fair', while two large peaks were observed in 1999 (4977 g/100m²) and in 2015 (9411 g/100 m²) which are considered 'very good', as shown in in *figure 17* (Kuijk et al., 2015).

***=CARIPES).**

REEF HEALTH INDEX (RHI)									
Reef Health Index Indicators	**1999**	**2004**	**2005**	**2007**	**2008**	**2014**		**2015**	
Coral Cover (%)	23	ND	27	26	6.5	ND		***5***	***5***
Fleshy Macroalgae Cover (%)	ND	ND	43	18	14	ND		***25.2***	***25.2***
Key Herbivorous Fish (g/100m²) ***(only parrotfish and surgeonfish)***	4977	ND	ND	ND	2100	2514		***2400****	***9411***
Key Commercial Fish (g/100m²) ***(only snapper and grouper)***	921	1132	ND	ND	2261	1144		***1670****	***2035***
RHI Score	ND	ND	ND	ND	3	ND		2.5	3.5

FIGURE 17 OVERVIEW OF THE REEF HEALTH INDEX SCORES FOR ST. EUSTATIUS (DE GRAAF ET AL., 2015)

Current fishing status

In the period 2012-2015 between 200 and 500 kg of mixed reef fish was landed monthly in St. Eustatius, resulting in an average annual catch of just under 4 tonnes on St. Eustatius. Within the fish trap fisheries, the main target species consist of all grouper (Serranidae) and snapper *(*Lutjanidae*)* species while other reef fish (*figure 18)* are landed as bycatch. The most commonly landed herbivorous species in number were the blue tang (25%) and doctor fish (9%), and in weight the blue tang (15%) (De Graaf et al., 2017). The blue tang and doctorfish (Acanthuridae) appear to be at high risk, as for these species the stock biomass indicator was estimated to be low while the fishing pressure is high. The princess parrotfish, stoplight parrotfish (Scaridae) and ocean surgeonfish (Acanthuridae) were estimated to be in a decent shape with stoplight parrotfish and ocean surgeonfish being close to pristine state. Even though the estimated size of the stock was in good shape, the princess parrotfish (Scaridae) is possibly being overfished. In 1908 only 5% of the catch consisted of surgeonfishes (Acanthuridae) while in 2012-2015 this and boxfishes (Ostraciidae) almost made up 50% of the catch (De Graaf et al., 2017; Zaneveld, 1961). The high percentages of bycatch indicate that current fish traps methods are unsustainable fishing practices subsequent to the contemporary fishing pressure. In addition, these fish pods form a danger as ghost fishing traps as they maintain functioning up to 2 years and on average 0.6 fish traps are lost per fishing trip, which are 300 traps estimated annually (De Graaf et al., 2017, 2015).

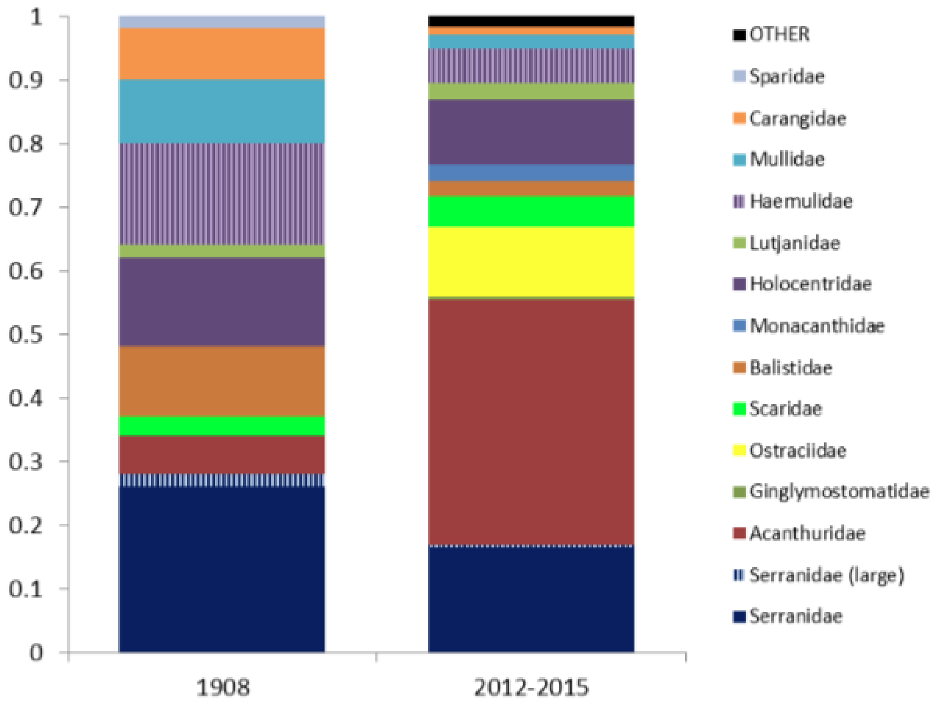

FIGURE 18 SPECIES COMPOSITION (IN NR) OF MIXED REEF FISH IN ST. EUSTATIUS (ZANEVELD, 1961; DE GRAAF ET AL., 2015)

4.6 Effect of unsustainable fisheries on herbivorous fish in coral reef ecosystems

Sustainable use of biological resources in coral reef ecosystems is a difficult principal, this especially due to the complexity of interactions between the large numbers of diverse species (Gunderson & Pritchard, 2002). Coral reefs and other marine ecosystems are increasingly impacted by overfishing, resulting in distorted food webs (Hughes et al., 2003) By fishing selectively certain individuals and species are removed faster than others. Large predatory fishes, that are known for their late maturity and slow reproduction rate; like sharks, groupers and snappers, usually disappear first (Pandolfi et al., 2003). The broader effects of overfishing and their impacts on ecosystems and food webs are just beginning to be understood. However, there is a clear link between unsustainable fisheries and the joint degradation of the benthic composition in coral reef ecosystems. The loss of herbivores, for example, is closely linked to an increase in macroalgae, which could lead to phase shifts from coral to algal dominance on tropical reefs (Mumby, 2006). These system-wide phase shifts are usually composed of multiple anthropogenic stressors or disturbances occurring locally and on a global scale. Locally overfishing of herbivorous fishes can drastically alter benthic competitive dynamics to favour algal growth over reef building organisms, but this is also influenced by diseases or adverse water quality changes (Edwards et al., 2014). Globally anthropogenic carbon emissions have led to ocean acidification and warming which profoundly affects the health and growth of stony corals (Anthony et al, 2008). Coral degradations will generally result in a reduction or loss of key ecosystem services including; coastal protection, fisheries productivity and economic revenue associated with tourism (Bellwood et al., 2012). There still is a lack in knowledge in the comprehensive patterning of individual disturbances in coral reef ecosystems. But, what is clear is that herbivorous fish exclusion will quickly and consistently lead to algal dominance on coral reef ecosystems (Burkepile & Hay, 2006).

4.7 Current fisheries management

Saba National Marine Park and fisheries management

The National Marine Park of Saba (*figure 3*) was established by the Saba Conservation Foundation in 1987 and includes all the surrounding waters of Saba to a depth of 60 meters at high water, creating a total area of approximately 1300 ha (SCF, n.d.-b). The Marine Park is divided into 4 different zones, a no-take zone that covers 33% of the Marine Park. Within this area fishing is prohibited and no anchoring and mooring is allowed by larger recreational vessels (>15 m). The only recreational activities allowed within this area are SCUBA diving with one of the dive operations (SCF, n.d.-b). Within the other 3 zones recreational fisheries are allowed when the person is in possession of a recreational fishing license but is limited to trawling with rod and reel or handline or by use of spear gun only when freediving (The Island Council of the Island Territory of Saba, 1987). Commercial fisheries on Saba are focused on the Saba Bank, which is why there is only recreational fishing on the Saba National Marine Park zoning system (SCF, n.d.-b; personal communication Saba Harbour Master: Johnson, 29-10-2018; personal communication Saba Bank Officer: Kuramae-Izioka, 26-11-2018).

St. Eustatius National Marine Park and fisheries management

In 1996 the St. Eustatius Marine Park has been established by STENAPA, who actively manages the area of approximately 2750 ha around the island till a depth of 30 metres (STENAPA, 2018b). Within the Marine Park there are two Marine Reserves (*figure 4*). Spearfishing is not allowed anywhere in the St. Eustatius Marine Park or Marine Reserves when use of SCUBA or Hookah is made. It is also forbidden to fish in the areas using poison, poisoned bait and/or other materials as well as chemicals and explosives. Also setting lobster traps in the park reserves and catching more than 20 conchs per fishermen per year are prohibited (Dilrosun, 2004).

Lobster- and fish traps, hand line, conch diving, trolling and seine nets are fishing methods that are allowed in the Marine Park (DCNA, 2013; Dilrosun, 2004; Esteban & MacRae, 2007; personal communication STENAPA Marine Park Manager: Berkel, 24-10-2018). There are about 25 fishermen, who mainly catch their fish and lobsters with the use of fish traps; also conch diving is popular (De Graaf et al., 2015).

4.8 Adapting fisheries management to minimize unsustainable fishing practices on herbivorous fish

With the current fishing pressure the lobster and fish trap (artisanal) fisheries on St. Eustatius are considered unsustainable and influence herbivorous fish stocks quite drastically, especially blue tang and doctorfish (*Acanthidurea)* form a large part of the bycatch of these traps, to a point of over exploitation (De Graaf et al., 2015). Also princess parrotfishes showed signs of being overfished. To stimulate a healthier herbivorous or general fish population, multiple interventions can be made. Adjustments to the original fish trap like introducing escape vents, could lead to a lower bycatch rate of unwanted or under sized species without reducing the harvest of target species (snappers and groupers) (De Graaf et al., 2015). Another adjustment that could benefit the fish stocks and fishermen on the long run, would be introducing degradable fish trap panels, hereby lost or abandoned fish traps could be prevented from future ghost fishing (Toller & Lundvall, 2008).

Ideally it would be desirable to stimulate fishermen on St. Eustatius to put more fishing effort in short lived, fast growing, large pelagic species like dolphin fish (*Coryphaena hippurus)* and wahoo (*Acanthocybium solandri)*, as this fisheries section is currently undeveloped with less than <50 pelagic fishing trips conducted annually. By spreading the fishing pressure over a larger environment and by enhancing the number of targetable fish species, reef fish will experience reduced fishing pressure and will thereby be more sustainable (De Graaf et al., 2015).

To conclude if the (herbivorous) fish stocks of Saba and St. Eustatius are well managed and thriving, it is important to continuously monitor the reef health status and fisheries landings. The Wider Caribbean GCRMN (Regional Global Coral Reef Monitoring Network) provides methods to monitor status of the coral reef health, based on 6 elements; 1) abundance and biomass of key reef fish taxa, 2) coral coverage of reef building organisms, 3) coral reef health assessments, 4) recruitment of reef-building corals, 5) invertebrate abundance, and 6) water quality (GCRMN, n.d.). By regularly resampling these 6 elements, a valuable dataset on the status of the coral reef health can be obtained, as current available data is minimal to compose a statement on current trends of the (herbivorous) fish densities, especially on Saba. Fisheries landings on St. Eustatius and for the Saba Bank are well monitored, but as for the recreational fisheries within the Saba National Marine Park no data is available. When analysing the impact on the Reef Health Index, clear differences between fished and no take zones can be observed, see *figure 3* (De Graaf et al., 2015), which suggests landings within the Saba National Marine Park could provide valuable information as fish status health indicator.

5 Discussion

Grazing

It was noted that some species of herbivorous grazing fish, among others, showed territorial behaviour during the grazing surveys. Predominantly it was the ocean surgeonfish that chased other herbivorous fishes away, they were also observed being chased by blue tangs and striped parrotfishes. Apart from these herbivorous species also other species were chasing herbivorous species away; the bicolour damselfish (*Stegastes partitus*), blackbar soldierfish (*Myripristis jacobus*), sergeant majors (*Abudefduf saxatilis*) and squirrelfish (*Holocentrus adscensionis*) were observed. In one occasion predatory behaviour of a great barracuda (*Sphyraena barracuda*) on a redband parrotfish (*Sparisoma aurofrenatum)* was observed. Territorial behaviour on herbivorous fish species can influence the grazing impact, which could influence the coral recruitment and growth (Hay, 1981; Hourigan, 1986; Lobel, 1980; Low, 1971; Mahoney, 1981; Ogden & Lobel, 1978; Vine, 1974). In a study of Hixon & Brostoff (1996) it was noted that when algae settling plates were moved from damsel territories to outside the damsel territory, within a day the plates were covered with numerous fish bite marks, as evident that there was grazed upon (Hixon & Brostoff, 1996). Rogers, et al., (1984) said "Territorial behaviour of damselfishes limits grazing and scraping by other herbivorous fishes (Brawley & Adey, 1977; Vine, 1974) and inhibits successful coral settlement, as corals cannot settle and survive on substrate heavily covers by non-coralline algae." (Rogers et al., 1984)

Fish abundance and grazing impact

On the artificial reef the overall herbivorous fish abundance (biomass in gram) was highest on the layered cakes, where the grazing impact (bite impact of observed herbivorous fish biomass in kg/h) was lowest. Vice versa for where the grazing impacts were highest (reef balls), the herbivorous fish abundance was lowest. This would suggest that there is no connection between the abundance and grazing impact of herbivorous fish. No other articles were found that suggest that high herbivorous fish abundance would also lead to a higher herbivorous fish grazing impact. Although, it does sound logical that were the herbivorous fish abundance is high, there is a greater grazing impact by herbivorous fishes, compared to where the herbivorous fish abundance is low.

Coral recruitment

Because a significant difference in coral recruitment between dive sites was found it was not recommended to lump the data. However, since the dataset on coral recruitment was limited to counts per reef plot per dive site, it was unfit to apply a General Linear Model or a Mixed Model, which is why it was still decided to lump the data. Differences between dive sites could be associated with factors like the health of the natural surrounding coral reef and diversity of coral species (Richmond, 1997), competing benthic organisms (Vermeij, 2006), sedimentation (Risk, 2014) or the differences in current (Elmer et al., 2016).

The number of coral recruits found in this study was remarkably high (mean number of recruits ± SE: layered cakes 91.00 ± 26.08, reef balls 76.00 ± 42.78, natural rock reefs 42.33 ± 22.66) compared to a similar study by Vermeij (2006) in Curacao, which had a total number of 33 coral recruits within two years (23 *Madracis pharensis*, 5 *Rhizosmilia maculata* and 4 *Agaricia solitaria*). After four years *P. astreoides* and *A. agaricites* settled on the artificial reefs from Vermeij, while in this study these are the only two identified coral species within 18 months after deployment of the artificial reefs. The artificial reef substrate of Vermeij (2006) was made of egg crates and Formica and covered a surface of 300x105x80 cm, which covers over double the size of the artificial reef plots used in this study (120x160x65 cm). An explanation for the variety in the number and type of species of coral recruits between these studies besides the geographic diversity between Curacao, Saba and St. Eustatius, could be associated with the difference in artificial reef material, as coral planulae are known to preferably settle on rough textured substrates (Burt et al., 2009). The egg crates and Formica artificial reefs of Vermeij (2006) seemed to obtain much smoother surfaces, compared to the concrete and natural rock artificial reef structures used in this study. Other explaining factors could involve: the coral species richness and health of surrounding natural reefs (the amount of larval supply) (Ayre & Hughes, 2004; Birrell et al., 2008; Hughes & Tanner, 2000; Ledlie et al., 2007; Pearson, 1981; Richmond, 1997; Roberts, 1997), sedimentation (Bak & Engel, 1979; Birkeland, Rowley, & Randall, 1981; Birkeland, 1977; Green & Bellwood, 2009; Risk, 2014; Rogers et al., 1984), water quality differences (Al-Horani & Khalaf, 2013; Fabricius, 2005; Wittenberg & Hunte, 1992), or other competing benthic organisms such as: sponges, bivalves, macroalgae and tunicates (Birrell et al., 2008; Vermeij, 2006).

The number of recruits on the natural rock reefs are lower (not significantly) than the reef balls and the layered cakes. This makes sense, considering that the impact of Hurricane Irma dismantled the natural rock reefs and thereby also caused a reset in coral recruitment as natural rock reefs had to be rebuilt.

Coral growth

In this study Agaricia had an overall higher mean relative growth, measured as surface area per year, than Porites. Huston (1985) found that *A. agaricites* had a lower mean growth rate (0.9-1.1 mm) than *P. astreoides* (2.5-3.1 mm) per year on a depth range of 16-25 m. Huston concluded that *P. astreoides* grew faster, while this study found that *A. agaricites* grew faster (Huston, 1985). Coral growth can be altered by a great amount of environmental conditions and it is not always clear what triggers specific growth responses in corals (Barnes & Crossland, 1982; Dodge & Brass, 1984; Gladfeiter, 1982; Gladfelter, 1983; Rogers, 1990). Growth can vary in similar environmental conditions between colonies of the same species or even within a single colony (Brown & Howard, 1985; Rogers, 1979). Thus, from this study it cannot be determined what might have caused Agaricia to grow faster than Porites.

Fish abundance and coral recruitment

No similar patterns of artificial reefs were found in the herbivorous fish abundance (biomass in gram) and the coral recruitment. It was expected that Scaridae would enhance the coral recruitment (Green & Bellwood, 2009), when assuming that herbivorous fish abundance is linked to grazing. The layered cakes have the highest overall herbivorous fish, and Scaridae abundance as well as the highest number of coral recruits. The second highest number of recruits was found on the reef balls and the second highest overall herbivorous fish, and Scaridae abundance were found on the natural rock reefs. No similar patterns were found between fish abundance and coral recruitment. When considering the consequences of Hurricane Irma, similarity between the mean abundance of herbivorous fish and the high number of coral recruits on the layered cakes and reef balls were observed.

Fish abundance and coral growth

Similar patterns of artificial reef types were found in the highest mean herbivorous fish abundance and the highest mean coral growth. This was expected since high abundance of herbivorous fish would most likely result in herbivorous fish grazing, which can enhance coral recruitment and growth (Burkepile & Hay, 2010; Green & Bellwood, 2009). When looking into the species, it seems that the similar artificial reef type pattern is established between Scaridae abundance and Porites growth. In other studies it was found that Scaridae would not necessarily enhance coral growth, but would enhance coral recruitment, as they scrape off algae and leave a bare substrate (Green & Bellwood, 2009). One can assume that the bare substrate provided by grazing of Scaridae could create space for a coral recruits to settle, but could also be suitable for a corals to grow.

Grazing impact on coral recruitment

No similar artificial reef patterns were found between the coral recruitment and the grazing impact of herbivorous fish. It was expected that coral recruitment rates would be enhanced by the grazing impact of Scaridae (Green & Bellwood, 2009). No studies were found that could explain why Scaridae grazing impact and coral recruitment did not have similar patterns. Several parameters that were mentioned before are expected to have a stronger impact on the coral recruitment than the observed grazing impact of Scaridae on the artificial reefs.

Grazing impact on coral growth

On the reef balls the highest mean bite impact of herbivorous fish (biomass in kg/h) from both fish species and the highest mean growth of Agaricia was observed, followed by the natural rock reefs and the lowest mean bite impact and mean growth were observed on the layered cakes. Porites had the highest mean coral growth on the layered cakes, then the natural rock reefs and the lowest mean coral growth was found on the reef balls. It seems likely that the grazing of both herbivorous fish species enhance the coral growth of Agaricia. It is peculiar that the artificial reefs with the lowest Porites growth in this study have the same pattern as the artificial reefs with the highest grazing rate of Scaridae. The bite impact of Acanthuridae and the growth of Porites were expected to have a similar pattern in highest results on the artificial reefs, since Burkepile & Hay (2010) concluded that grazing of surgeonfishes (Acanthuridae) enhances the growth of *Porites porites* and *P. astreoides*. In the study of Burkepile & Hay they enclosed ocean surgeonfishes in 4 m^2 cages at a depth of 17 m in the Florida Keys, to study the effect of herbivory on algae and how that would (indirectly) influence coral. *A. agaricites* was not taken into account in this study, only *Porites porites* and *P. astreoides*. Surgeonfishes crop algae surrounding corals (Burkepile & Hay, 2010), resulting in a lower algae cover on reefs, which grants coral the opportunity to grow (Hughes et al., 2007; Jompa & McCook, 2002; Lewis, 1986; Tanner, 1995). In the case of Burkepile & Hay (2010) the coral with the opportunity to grow was Porites, since these were the species that were involved in the study. It is unsure if the same had happened with Agaricia if this species was included in the study, however it would be expected that other corals, like Agaricia, would grow as well. No similar artificial reef patterns were expected to be found in grazing of Scaridae and growth of either of the coral species, since the study of Burkepile & Hay (2010) found no grazing effects of parrotfishes on growth of either *P. porites* or *P. astreoides* and because some parrotfishes are corallivorous (Miller & Hay, 1998; Rotjan & Lewis, 2008). The species observed within this study that are considered corallivorous are the stoplight parrotfish (*Sparisoma viride*) (Bruggemann et al., 1994; Rotjan & Lewis, 2006) and the redband parrotfish (*Sparisoma aurofrenatum*) (Rotjan & Lewis, 2006). In the studies of Rotjan & Lewis (2006) they investigated selective grazing by parrotfish on coral species. Their results showed that the parrotfishes grazed on 3.77% from the 212 investigated colonies of *A. agaricites* and 1.93% from the 931 colonies of *P. astreoides*. Burkepile & hay (2010) resulted that there was no effect of parrotfishes on either Porites species; also no grazing scars were detected on the corals. It is especially exceptional that in this study the growth of Agaricia seems to be enhanced by the grazing impact of Scaridae and the growth of Porites seems to be reduced by the grazing impact of Scaridae, because Rotjan & Lewis (2006) suggested that Scaridae had an even higher corallivorous impact on *A. agaricites* than on *P. astreoides*. The coral growth rate does not clarify the results of this study either; *A. agaricites* has a lower mean growth rate per year of 0.9 - 1.1 mm and *P. astreoides* grows 2.5 - 3.1 mm per year on a depth range from 16-25m (Huston, 1985). Nor does the recovery rate: 64% of *P. astreoides* tissue lesions and 48% of tissue and skeleton lesions were completely regenerated after 140 days, while *A. agaricites* only regenerated 8% of tissue lesions and 4% of tissue and skeleton lesions. This was concluded in the study of Bak and van Es (1980) where they investigated the regeneration of artificial lesions by stimulating damage by predators and physical factors (Bak & Es, 1980). It could be that there are other reasons why the growth of Agaricia is enhanced and of Porites is reduced by the grazing impact of Scaridae, because Porites and Agaricia are not preferred by corallivory parrotfishes (Rotjan & Lewis, 2006). Coral growth can be altered by multiple environmental conditions as stated before.

6 Conclusions

Sub-question 1.1: "How does the abundance and bite impact of different functional grazing groups differ per artificial reef type?"

No significant differences were found in the abundance (biomass in gram) between the two grazing groups per artificial reef type. Overall, a higher abundance of Scaridae was observed compared to Acanthuridae. There were also no significant differences in the observed mean grazing impact of herbivorous fish (biomass kg/h) per type of artificial reef were found. A significantly greater bite impact of Acanthuridae was observed over Scaridae on the reef balls. On the artificial reef the herbivorous fish abundance was the highest, were the grazing impact was the lowest. And vice versa: where the herbivorous fish grazing impact was the highest, the herbivorous fish abundance was the lowest. From this dataset it seems that there is no connection between the two variables. No studies were found confirming or disproving this hypothesis.

Sub-question 1.2: "What are the differences in coral recruitment and growth rates per artificial reef type?"

There were no significant differences in coral recruitment or growth per artificial reef type were found. A pattern of the highest coral recruitment and growth rates were observed on the layered cakes, coral recruitment followed with the second highest number on the reef balls and the lowest recruitment was found at the natural rock reefs, this was vice versa for growth. On the reef balls Agaricia had a significant greater growth rate than Porites.

Sub-question 1.3: "What is the relation between the herbivorous fish species abundance, the coral recruitment and the growth rates per artificial reef type?"

Because of the wide spread in numbers of coral recruits and fish abundance (biomass in gram) between the types of artificial reef there appears to be no pattern. However, this could be explained by the impact of Hurricane Irma.

Similar patterns between the artificial reef types were found for highest mean herbivorous fish abundance and highest mean coral growth. Looking into the species, there appears to be a pattern between Scaridae and Porites. As Scaridae provides bare substrate, which enhances the coral recruitment, but it can be assumed that it also enhances coral growth.

Sub-question 1.4: "What is the relation between herbivorous fish grazing impact, coral recruitment and the growth rates per artificial reef type?"

Although it was expected that Scaridae would enhance the coral recruitment, no similar artificial reef patterns were found between the coral recruitment and the grazing impact of herbivorous fish. It seems that the coral recruitment is impacted by other parameters than herbivorous fish grazing.

Between the artificial reef types similar patterns were observed for the highest grazing impact of both Acanthuridae and Scaridae with the growth of Agaricia. Acanthuridae crops the algae, while Scaridae scrapes the algae. Although other studies found that cropping would only stimulate the coral growth and scraping would only stimulate coral recruitment, one could assume that both make place for coral to either settle or grow.

On the artificial reefs where Acanthuridae and Scaridae had the highest grazing impact, Porites had the lowest growth rates and vice versa. Certain Scaridae can be corallivorous, which can affect coral growth, but other studies show that there is a higher corallivorous impact on Agaricia compared to Porites. It is unsure why Porites growth had an opposite pattern in artificial reefs compared to the Acanthuridae grazing impact, since other studies showed that Porites was enhanced by Acanthuridae grazing. For both, the only viable explanation could be clarified by other environmental conditions.

According to other studies; territorial behaviour, especially from damselfishes, has been found to influence grazing of herbivorous fishes, which can influence the coral recruitment and growth and most likely has been an influence in this study.

Main research question 1: "What is the effect of grazing of herbivorous fishes on the coral recruitment and growth rates on artificial reefs around Saba and St. Eustatius?"

The effect of grazing of herbivorous fishes on coral recruitment and growth on artificial reefs in Saba and St. Eustatius cannot be concluded from this study because there are many more environmental parameters that have to be taken into account before statements like these can be made. However, a similar pattern between artificial reef types and the highest abundance of the overall tested herbivorous fish, the individual abundance of Scaridae, the overall tested coral growth and the individual Porites growth was found. This suggests that a high overall herbivorous fish abundance would enhance an overall coral growth and that the Scaridae abundance would enhance the Porites growth. The overall herbivorous fish grazing impact, both the individual herbivorous fish grazing groups grazing impact and the growth of Agaricia showed a similar pattern between the pattern between the artificial reef types. Suggesting that the grazing of both Acanthuridae and Scaridae might enhance the growth of Agaricia. Acanthuridae had a significantly higher grazing impact compared to Scaridae on the reef balls, Agaricia also showed a significantly higher growth rate than Porites on the reef balls, which adds to the suggestion that the bite impact of Acanthuridae enhances the coral growth of Agaricia.

Sub-question 2.1: "What are the effects of unsustainable fisheries on herbivorous fishes?"

Fishing selectively can greatly impact the food webs by removing species and individuals; usually this starts with large predatory fishes disappearing first. There is a clear link between unsustainable fishing and the joint degradation of the benthic composition in coral ecosystems. With the loss of herbivorous fishes, there will be an increase in macroalgae, which could lead to a phase shift from a coral to an algae dominant ecosystem. On a local scale unsustainable fisheries can contribute to these phase shifts by overfishing herbivorous fishes. This however often goes hand in hand with global anthropogenic stressors like ocean acidification and warming, which affects the health and growth of stony corals. Eventually these phase shifts will result in the reduction or loss of key ecosystem services.

Sub-question 2.2: "How are fisheries currently managed on Saba and St. Eustatius, specified on herbivorous fishes?"

In Saba all the professional fishermen only fish on the Saba Bank. Theoretically only recreational fishermen with licences are taking fish from the Saba National Marine Park, by use of trawling with hand line or rod and reel or spearfishing when free diving. 33% of the Saba National Marine Park is a no-take zone; within this area fishing is prohibited.

Around St. Eustatius spearfishing is only allowed whilst free diving. Fishing with the use of poison, poisoned bait and/or other materials as well as chemicals and explosives are prohibited. Within the Park Reserves lobster traps and catching more than 20 conchs per fishermen per year are forbidden. Outside of the Marine Reserves lobster- and fish traps, hand line, conch diving, trolling and seine nets are allowed.

Sub-question 2.3: "How can fisheries management be adapted to minimize the impact of unsustainable fishing practices on herbivorous fishes?"

By introducing a variety of adjustments to the unsustainable lobster/fish trap fisheries on St. Eustatius, fishing pressure on herbivorous fishes can be decreased. By implementing escape vents, landings of unwanted bycatch species and undersized fishes can be reduced. Through use of degradable fish trap panels, future ghost fishing can be prevented. And by stimulating fishing effort on short living, fast growing, large pelagic species, fishing pressure can be reduced within the coral reef ecosystem.

To conclude if the fish stocks and coral reef ecosystem of St Eustatius and Saba is healthy, it is recommended to continuously monitor the reef ecosystem health status through e.g. GCRMN surveys, especially for the Saba National Marine Park as there is minimal information available.

Main research question 2: "How can the effect of unsustainable fisheries on herbivorous fishes on Saba and St. Eustatius be minimized using fisheries management?"

Unsustainable fisheries can greatly influence the entire health of a coral reef ecosystem especially when overfishing of herbivorous fish takes place. In worst-case scenarios overfishing of herbivorous fish can lead to coral- algal phase shifts. Within the Saba National Marine Park there is no commercial fisheries as only recreational fisheries is allowed. In St. Eustatius the herbivorous fish densities are mainly influenced by unsustainable lobster and fish trap fisheries. The blue tang and doctorfish (Acanthuridae) appear to be at high risk of over exploitation, this also applies for the princess parrotfish (Scaridae). To stimulate healthier herbivorous fish densities on St. Eustatius and more sustainable fisheries, adjustments to the fish traps like introducing escape vents and biodegradable fish trap panels have to be made. Another improvement could be realised by stimulating fishing effort for short lived, fast growing, large pelagic species.

7 Recommendations

For further research it is recommended to research the control variables: influence of sedimentation, light, temperature, algae distribution and larval supply (by investigating coral species located on natural surrounding reefs), so the relation of fish and coral productivity, the differences between artificial reefs or the differences per dive site, can be tested. It was also noted that there were species that showed predatorial or territorial behaviour, it is suggested to research this in further studies since this can impact the grazing behaviour, especially the damselfishes since they may affect the coral growth. There are some parrotfish species that feed directly on corals, researching the corallivory by looking for grazing scars on the corals would be interesting to see if this might affect the coral survival and growth rates.

On St. Eustatius in 2008 and 2014 the key herbivorous fishes were considered to be 'fair' according to the Reef Health Index, but showed to be 'very good' In 2015. However during the same year the status of blue tangs, doctor fish and princess parrotfish appear to be at high risk of overexploitation based on landings. These fishes make up for a large part of the bycatch of fish and lobster traps, as the target fish consists of groupers and snappers which makes the on-going fishing effort combined with current fishing methods unsustainable. On Saba commercial fisheries in prohibited within the Saba National Marine Park and only recreational fisheries in conducted under allowance of a recreational fishing permit. The last recorded status of herbivorous key species was 'fair' in 2015 and 'very good' in 2016 according to the Reef Health Index. Both the RHI of Saba and St. Eustatius went from 'fair' to 'very good', which indicates high fluctuations in herbivorous fish key species.

There are no direct relations found between herbivorous fish grazing and coral recruitment or growth, but there is a possibility that grazing of Acanthuridae could enhance the growth of Agaricia. The necessity of adjusting fisheries management cannot be concluded based on results found in this this study. However, based on previous studies, the loss of herbivorous key stone species in coral reef ecosystems can alter the reef dynamics and resort to coral-algal phase shifts. This implies that recommendations for more sustainable use of the marine resources can still be beneficial to the health of the coral reef ecosystem of St. Eustatius. Therefore, it is recommended to introduce the following two adjustments to the currently used fish/lobster traps:

- **Escape vents:** Can be used to minimize the amount of bycatch, especially of undersized fish, without losing the marketable target species
- **Degradable fish trap panels:** Can be used to prevent ghost fishing. Numerous fish/lobster traps are lost or abandoned and will continue ghost fishing to a maximum on 2 years after being lost

In addition, it is recommended to stimulate fishing effort on short lived, fast growing, large pelagic species, as this fishery is currently under developed on St. Eustatius, by spreading the fishing pressure over a larger environment, reef fish can experience reduced fishing pressure.

For both Saba and St. Eustatius, it is recommended to continue conducting (at least annual) reef health monitoring surveys, following GCRMN standards. This is important especially for Saba, as minimal data is available. By maintaining annual overviews status and trends of the coral reef ecosystem can be observed and controlled.

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Appendix 1: Reef Health Index

The Reef Health Index was developed by the Healthy Reef Initiative (Kramer, 2003; McField & Kramer, 2007) and the description of the four key reef health indicators is given by Kramer et al. (2015).

The Reef Health Index (RHI) is based on four key coral reef health indicators:

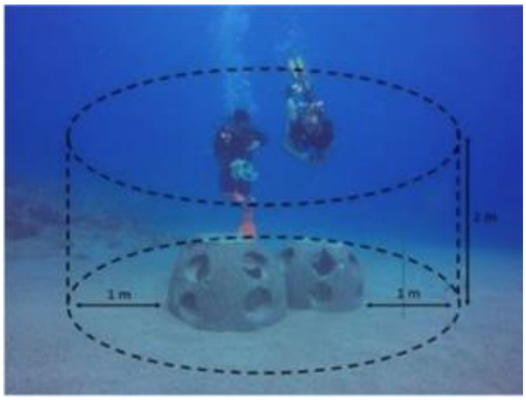
- Coral cover - the proportion of benthic surface covered by live stony corals, contributors to the three-dimensional framework
- Fleshy macroalgae cover - the proportion of benthic surface cover by fleshy macroalgae, and increase in macroalgae limits stony coral recruitment and recovery
- Herbivorous fish - a measure of biomass of herbivorous reef fish (e.g. parrotfish and surgeonfish), these grazing species play a major role in controlling (macro) algae that could overgrow coral reefs
- Commercial fish - a measure of biomass of reef fish (e.g. groupers and snappers) with commercial importance to people

The mean values of the indicators are compared to the criteria listed in the table underneath. The indicators are given a grade from one ('critical') to five ('very good'). The four grades are combined and equally weighted to obtain a RHI score. An overall score of 1-1.8 is "critical", >1.8-2.6 is "poor", >2.6-3.4 is "fair", >3.4-4.2 is "good" and >4.2-5 is "very good"

REEF HEALTH INDEX (RHI)					
Reef Health Index Indicators	Very good (5)	Good (4)	Fair (3)	Poor (2)	Critical (1)
Coral Cover (%)	≥40	20.0-39.9	10.0-19.9	5.0-9.9	<5
Fleshy Macroalgae Cover (%)	0-0.9	1.0-5.0	5.1-12.0	12.1-25	>25
Key Herbivorous Fish (g/100m^2) ***(only parrotfish and surgeonfish)***	≥3480	2880-3479	1920-2879	960-1919	<960
Key Commercial Fish (g/100m^2) ***(only snapper and grouper)***	≥1680	1260-16.79	840-1259	420-839	<420

Overview of the criteria for the four key coral reef health indicators (Kramer et al., 2015)

Appendix 2: Fish survey protocol



(Heesink & Reid, 2018)

Fish survey protocol v1.2 February 2018

<u>Materials</u>

1. Dive computer
2. Secchi disk
3. Go pro + under water light
4. Slates, pencils, and sheets printed on underwater survey paper

<u>Method</u>

Divers will start with the outer experimental plot of an experimental block. This plot will be surveyed using the described method. After finishing the first survey, divers continue to the adjacent experimental plot, survey this plot, and continue to the next experimental plot, etc.

1. Check if all the equipment is present and working and go to the right location
2. Fill in the names of the observers and the date, time and location
3. Measure Horizontal Secchi Disk Depth (HSDD) with 10 cm precision. The Secchi disk should face the sun. HSDD should be at least 5 meter to proceed with the survey.
4. Start survey dives on alternating outer experimental plots (*e.g.* start first survey at north side, second at south side, third at north, etc.)
5. Descend at least 10 m away from the experimental plot
6. While slowly swimming towards the survey area horizontally, diver 1 will record the fish, while diver 2 is filming the survey for future reference and for identification of unknown sp.. As diver 2 is not to disturb the fish before the counting, he will swim slightly behind/next to diver 1.

All the fish within a virtual cylinder (1 meter sideways of the plot and 2 meters upward from the bottom) around the experimental plot are included in the survey; the virtual cylinder is shown in the figure above. Fish in the cylinder are identified up to species level, counted and classified in size categories 0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-40, 40-50, 50-60, etc., cm TL (from the tip of the snout to the tip of the longer lobe of the caudal fin).

1. Starts with filming the survey sheet, so date, time, location, HSDD are visible on film.
2. Start recording **fleeing fish** at 5 meters distance of the artificial reef.
3. At 2 meters stop swimming and start stationary count for **3 minutes (use the go pro to monitor the time)**.
4. During the stationary count, **all** fish in the cylinder, also fish entering during the survey, are included in the survey. Of course you count a fish only once, even if it repeatedly swims in and out the cylinder.
5. First record all schools, then record the other fish.
6. After 3 minutes, the artificial reefs will be thoroughly searched to record all the hiding fish. New fish entering the cylinder will not be included in the survey. Use a torch if necessary.
7. Unknown fish will be described as detailed as possible (e.g. Large blackish striped grouper) and can be identified later using video footage.
8. Count all lobster and estimate their carapace length
9. **Note anything striking on the artificial reefs** (eg. Under water visibility only 4 meters, or: Sergeant majors laying eggs on layered cakes)
10. Determine temperature and bottom depth of the experimental plot.
11. When all fish are counted move towards the next experimental plot and repeat step 6 to 16.
12. If 50 bar is reached, ascend slowly to 5 meters to make a safety stop for 3 minutes, then ascend slowly. Fill in your data as soon as possible, always on the same day! Always make a picture of the original survey sheets.

Appendix 3: Herbivorous fish grazing protocol

Grazing protocol v1.1. November 2018

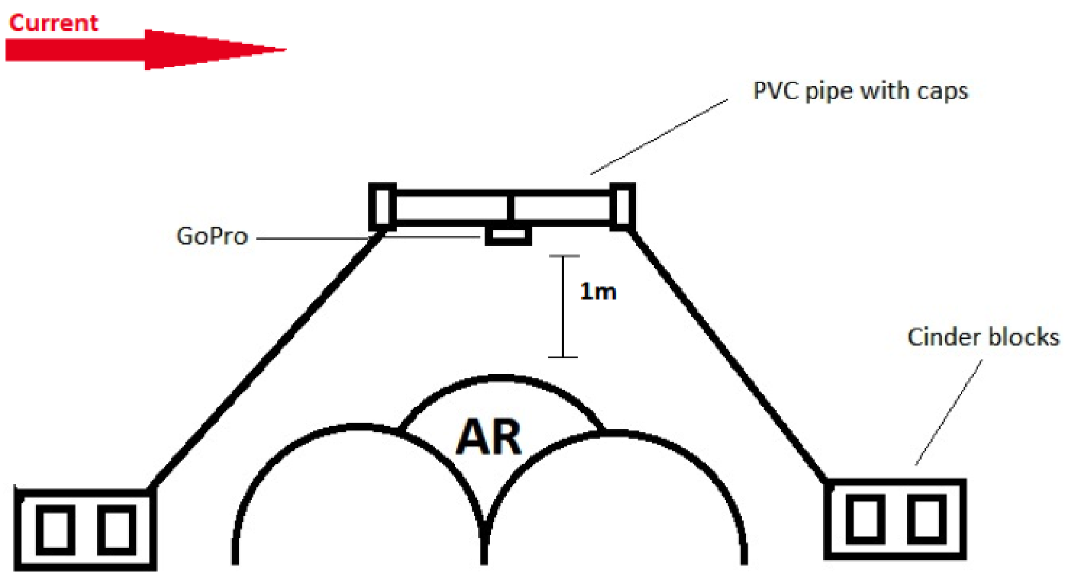
<u>Materials</u>

1. 50cm PVC pipe p/setup
2. 2 PVC caps p/setup
3. PVC cement
4. 2 4m ropes p/setup
5. 2 cinder blocks p/setup
6. GoPro p/setup
7. Reusable tie-wraps

<u>Setup</u>

Setups will be placed on all artificial reefs (reef balls, layered cakes and natural rock reefs)

1. Make floatable PVC pipes by attaching PVC caps on both ends of the PVC pipe securing it with PVC cement. Make sure to let the PVC cement dry for an extended period of time (at least 24hours) before using them in the setup.
2. Take all necessary equipment to the required location and drop cinder blocks on a sandy patch near the artificial reefs. Use a snorkeler to find a suitable location.
3. Take the PVC pipes and the rope with you on your dive.
4. When descended place cinder blocks on either side of the artificial reefs and attach the PVC pipe to the blocks with a rope.
5. The PVC pipe has to float approximately 1 m above the artificial reef. The figure underneath shows an overview of how the setup should be.
6. When the setup is ready use a GoPro to make sure the whole reef is captured in the GoPro frame. Try to place the setup **alongside the current** to minimize unwanted movement during the survey
7. After finishing setup remove the GoPro and ascend according to PADI standards.



Survey

At the start of every survey the setup has to be reviewed and adjusted to the current. Make sure all GoPro's are fully charged on the day of surveying.

1. Attached the camera's to the setup at the beginning of the dive, this is done with a reusable tie-wrap. Check if the whole artificial reef is in the frame and start filming.
2. The cameras can be picked up at the end of the dive after finishing other activities or when low on air. The recording time should be as long as possible and interruption during the recording should be avoided.

Data input

The collected recordings should be reviewed and data is to be filled in on the grazing survey sheet. **Only count bites when you can see the fish's mouth touching the artificial reef surface or when the fish has a very apparent charge when grazing!**

1. Open data sheet and save a new version of this sheet **before** entering data.
2. Count fish bites taken on the artificial reefs only and fill data in on the sheet. **Do not count the first and last 2 minutes of the recording.** A maximum of 1 hour is allowed per day of a certain artificial reef.
3. Make a screenshot of the recording on a moment that best represents the average frame coverage of the artificial reef. (This to determine the percentage of the artificial reef shown in the frame)
4. Name the grazing video with the island, dive site, treatment, date and number of video out of the total amount. So when a video is taken in Saba at Big Rock Market on the Reef Balls on the first of October and it is the first video out of seven it will be the following: Grazing_Saba_BRM_RB_01-10-18_1-7.
5. Write down information that can influence the data, like for instance when blackbar soldierfish are aggressive to other fishes and scaring them away.
6. Write down the length of the footage used per day (an hour maximum), and the total amount of time that is collected per treatment per dive site. An example is given in figure underneath

Island:					Saba	Saba	Saba
Location (eg TS3):					BRM	BRM	BRM
Treatment: reef ball (RB), layered cake (LC), rock (RO), Control (CO), Patch (PA):					LC	RO	RB
Observer (invoer):					Marijn	Marit	Marijn
Date:					19-11-18	19-11-18	19-11-18
Time:					14:23	14:30	14:35
Temperature:					28	28	28
Time of video in minutes					60	60	60
Total time per artificial reef in minutes					60	60	60
Footage used from - till					from 1-5 02:00 till 4-5 8:18	from 1-8 2:00 till 6-8 2:00	From 1-7 2:00 till 6-8 2:00
Remarks (be as specific as possible, for instance "agressive behaviour blackbar							
Common name	Genus	species	size category	Date added	Bites taken		
Banded Butterflyfish	Chaetodon	Striatus	5-10	19-11-18	1		4
Bar Jack	Caranx	ruber	20-25	19-11-18		3	1
Bicolor Damselfish	Stegastes	partitus	0-5	01-10-18			
Bicolor Damselfish	Stegastes	partitus	5-10	01-10-18			
Black durgon	Melichthys	niger	20-25	01-10-18			
Black durgon	Melichthys	niger	25-30	01-10-18			
Black durgon	Melichthys	niger	30-35	01-10-18			
Bluehead wrasse	Thalassoma	bifasciatum	0-5	01-10-18			
Bluehead wrasse	Thalassoma	bifasciatum	5-10	01-10-18			
Bluehead wrasse	Thalassoma	bifasciatum	10-15	01-10-18			
Bluehead wrasse	Thalassoma	bifasciatum	15-20	01-10-18			
Bluetang	Acunthurus	coeruleus	0-5	01-10-18			
Bluetang	Acunthurus	coeruleus	5-10	01-10-18			
Bluetang	Acunthurus	coeruleus	10-15	01-10-18			
Bluetang	Acunthurus	coeruleus	15-20	01-10-18	101	36	101
Bluetang	Acunthurus	coeruleus	20-25	01-10-18		15	

Appendix 4: Estimating non-recorded grazing impact protocol

Sometimes a part of the artificial reef is outside of the frame or a part of the reef is invisible because of the angle of the camera. It is important to calculate those parts of the reef so it can be corrected during the calculations of the grazing pressure. Two methods are described that apply to the video conditions. “A” is used when a part of the reef is outside of the frame; “B” is used when a part of the reef is invisible because of the angle of the camera. With both of the methods the part of the reef that **is visible** is calculated. Both are supposed to be filled in Excel for further calculations to correct the complete grazing pressure.

A. Part of the reef not in the frame

Occasionally grazing footage is recorded during presence of current. This could lead to a irregular scope of the artificial reef plot. As the camera fluctuates back and forth parts of the reef will be variously visible or invisible. To calculate the percentage of non-recorded artificial reef plot: take a screenshot of the average situation and follow the next steps.

Part of the reef ball or layered cake is invisible:

1. Estimate the missing surface of artificial reef by comparing it with a picture of a fully visible artificial reef.
2. Divide missing surface per reef ball/layered cake by the total surface area and calculate the fraction of the reef ball/layered cake that is visible.
3. Calculate the total fraction. There are 3 RB/LC, a single RB/LC counts for 0.3333. An entire visible reef concludes 0.3333 + 0.3333 + 0.3333= 1. When parts of the RB/LC are variously visible the following formula is used 0.3333 + 0.3333 + (0.3333*visible fraction calculated at step 2.)= Fraction total RB/LC visible. For instance: RB 1 is entirely visible, RB 2 is 95% visible, and RB 3 is 50% visible.
   0.3333 + (0.3333*0.95) + (0.3333*0.5) = 0.816585

Irregular scope of natural rock reef plot is invisible due to current fluctuations:

1. The natural rock reef is placed on top of a grid of rebar, dividing the reef in columns. This makes it easy to calculate the percentage: the amount of columns visible/amount of columns in total.
2. If it is not possible to calculate the columns, make an estimate with the sizes of the grid.
3. Surface visible*0.5/ total surface = fraction visible

B. Part of the reef invisible because of camera angle

When herbivorous fishes are “disappearing” next to a reef ball or layered cake, it could be that it has been eating without it being recorded.

Part of the reef ball or layered cake is invisible:

1. Determine the surface area of the artificial reef
2. Determine the surface area of the part of the artificial reef that is not visible
3. Calculate the visible part of the reef by step 2. / Step 1.
4. Calculate the total visible part. There are 3 reef balls/layered cakes, so each visible one counts for 0.3333. If a part of the reef is invisible use: 0.3333 + 0.3333 + (0.3333 * part that is invisible (calculated in step 4)). Example: reef ball 1 & 2 are visible but 3 is 1/5th part (=0.2) only visible for half (=0.5): 0.3333 + 0.3333 + (0.3333 * 0.2)= 0,73326 visible

Part of the natural rock reef is invisible:

1. The natural rock reef is placed on top of a grid of rebar, dividing the reef in columns. This makes it easy to calculate the percentage: the amount of columns visible/amount of columns in total.
2. If it is not possible to calculate the columns, make an estimate with the sizes of the grid.
3. Surface visible / total surface = fraction visible

Appendix 5: More information on herbivorous fish species

Within the grazers/detritivores and scrapers/small excavators there are multiple herbivorous fish reef families, the two most important families in these survey are Acanthuridae (surgeonfishes) and Scaridae (parrotfishes) (Choat, 1991). The herbivorous species that are included in this research are presented in table underneath.

Common name	**Genus**	**Species**	**Family**	**Grazing group**	**Log a**	**b**	**Source fish info**	**Source logs**
Blue tang	*Acanthurus*	*coeruleus*	Acanthuridae / Surgeonfish	Grazer / Detrivore	-4,2165	2,8346	Green & Bellwood, 2009	Bohnsack & Harper, 1988
Doctorfish	*Acanthurus*	*chirurgus*	Acanthuridae / Surgeonfish	Grazer / Detrivore	-5,9255	3,5328	Green & Bellwood, 2009	Bohnsack & Harper, 1988
Ocean surgeonfish	*Acanthurus*	*tractus*	Acanthuridae / Surgeonfish	Grazer / Detrivore	-4,6005	2,9752	Green & Bellwood, 2009	Bohnsack & Harper, 1988
Princess parrotfish	*Scarus*	*taeniopterus*	Scaridae / Parrofish	Scraper	-4,1836	2,7086	Green & Bellwood, 2009	Bohnsack & Harper, 1988
Queen parrotfish	*Scarus*	*vetula*	Scaridae / Parrofish	Scraper	-	-	Green & Bellwood, 2009	-
Redband parrotfish	*Sparisoma*	*aurofrenatum*	Scaridae / Parrofish	Scraper	-5,7587	3,4291	Green & Bellwood, 2009	Bohnsack & Harper, 1988
Redtail parrotfish	*Sparisoma*	*chrysopterum*	Scaridae / Parrofish	Scraper	-5,1754	3,1708	Green & Bellwood, 2009	Bohnsack & Harper, 1988
Stoplight parrotfish	*Sparisoma*	*viride*	Scaridae / Parrofish	Small excavator	-4,5223	2,9214	Green & Bellwood, 2009	Bohnsack & Harper, 1988
Striped parrotfish	*Scarus*	*iseri*	Scaridae / Parrofish	Scraper	-4,8887	3,0548	Green & Bellwood, 2009	Bohnsack & Harper, 1988

(Bohnsack & Harper, 1988; Green & Bellwood, 2009)

Appendix 6: Coral count survey protocol

Coral and mobile benthos survey v1.2 November 2018

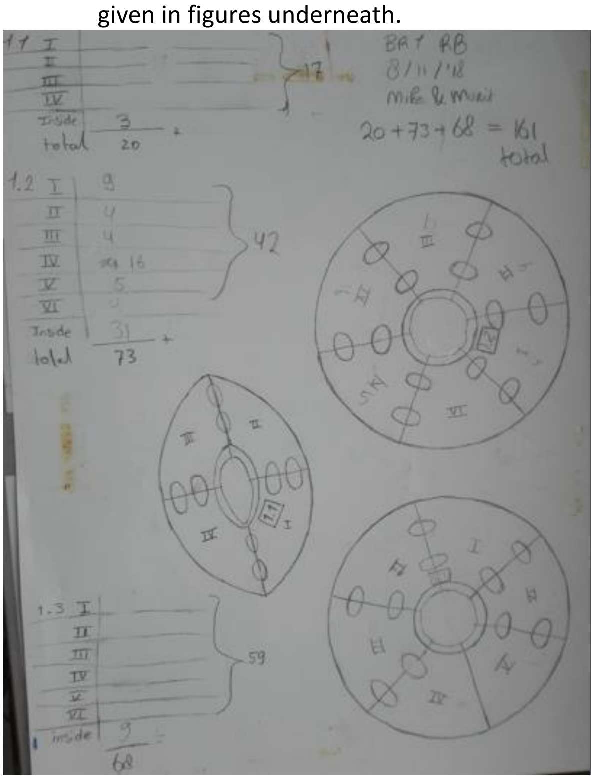
Materials

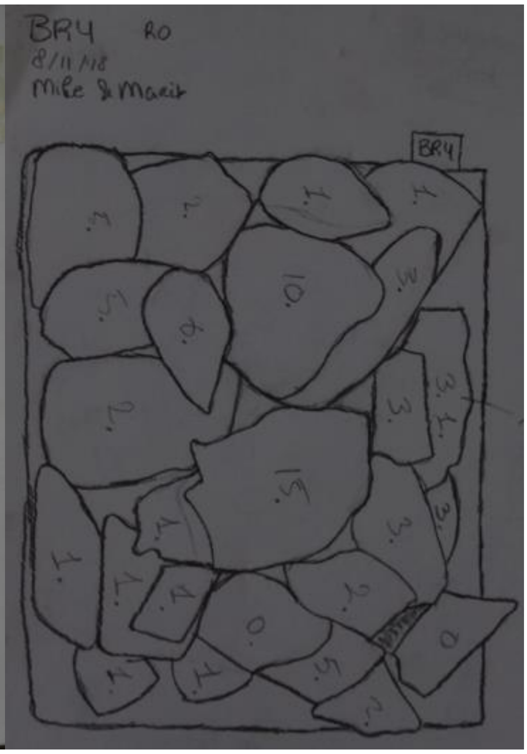
1. Dive computer
2. Slates, pencils, and location sketch of the artificial reef from above
3. Lights
4. UV light
5. Fluorescence masks
6. Papers with overview maps
7. Underwater camera with flash and focus light

Counting of coral recruits

The artificial reefs are surveyed once every survey period. Mapping of coral recruits starts just before sunset (start dive at 17:30 in November).

1. Before the dive, put the UV light in **permanent mode**
2. Fill in the names of the observers and the date, time and location
3. Use the UV light and the fluorescence masks to systematically search the reef for stony corals. Brush away algae, etc. Also look inside the shelters.
4. The artificial reefs are divided in zones, one of the observers will show the second observer which zone has to be searched first. The second observer counts all the corals within this zone and the first observer will write it in the sketch. The first observer will point out the second zone and so on. After the artificial reef is completed, in case of a reef ball the inside will be checked as well. In case of the natural reef rocks, an overview is sketched where all the rocks are drawn separately. Here the first observer will point out which rock the second researcher has to be searched
5. In the end the corals can be added up per artificial reef type in total per dive site, two examples are given in figures underneath.





Appendix 7: Coral growth survey protocol

Coral growth rate survey v1.1 November 2018

Materials

1. Dive computer
2. Slates, pencils, and location sketch of the artificial reef from above
3. Lights
4. UV light
5. Fluorescence masks
6. Papers with numbers 1-30 and scale
7. Underwater camera with flash and focus light

Search for coral recruits

The artificial reefs have been surveyed in a previous period. The previous found coral recruits have been mapped in a location sketch from the artificial reefs; to ease the process, write the species with the numbers of the corals so you know what to look for.

1. Before the dive, put the UV light in **flash mode** when the dive is during the day
2. Fill in the names of the observers and the date, time and location
3. Use the UV light to search for the corals mapped on the sketch
4. When a coral is found and it matches with the location and species of a mapped coral, take a picture of the coral with the same number and mark on the sketch that the coral is found

General guidelines

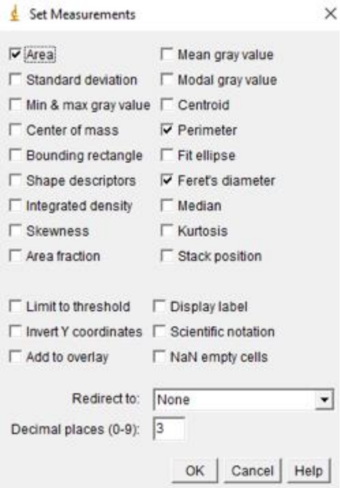
1. If 50 bar is reached, ascend slowly to 5 meters to make a safety stop for 3 minutes.
2. After safety stop ascend slowly to the surface and signal the boat.
3. **Fill in your data as soon as possible, always on the same day! Always make a picture of the original survey sheets.**

Appendix 8: Coral growth measurement protocol

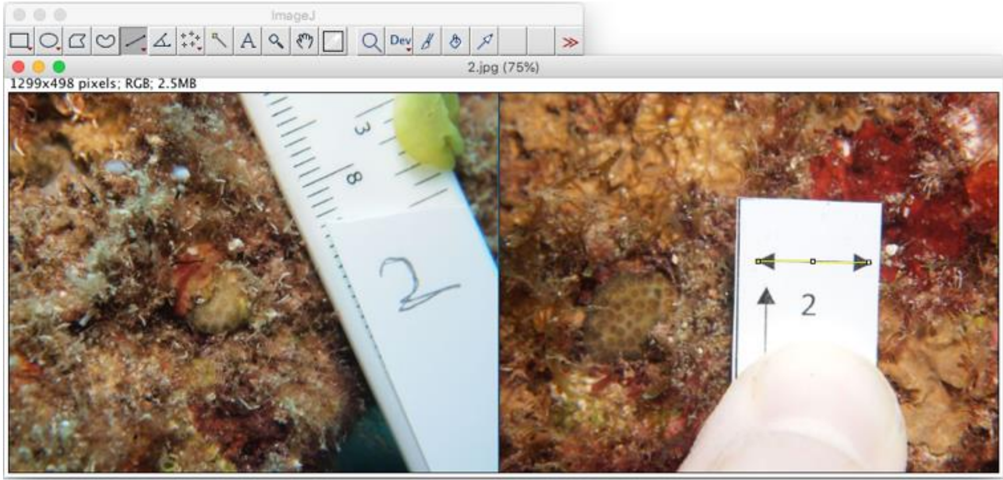
Protocol coral growth measurement v1.1 November 2018

This protocol describes the procedure to measure coral recruits with ImageJ. ImageJ is a freeware program, made to process and analyse images. ImageJ can be downloaded via this link: https://imagej.nih.gov/ij/download.html

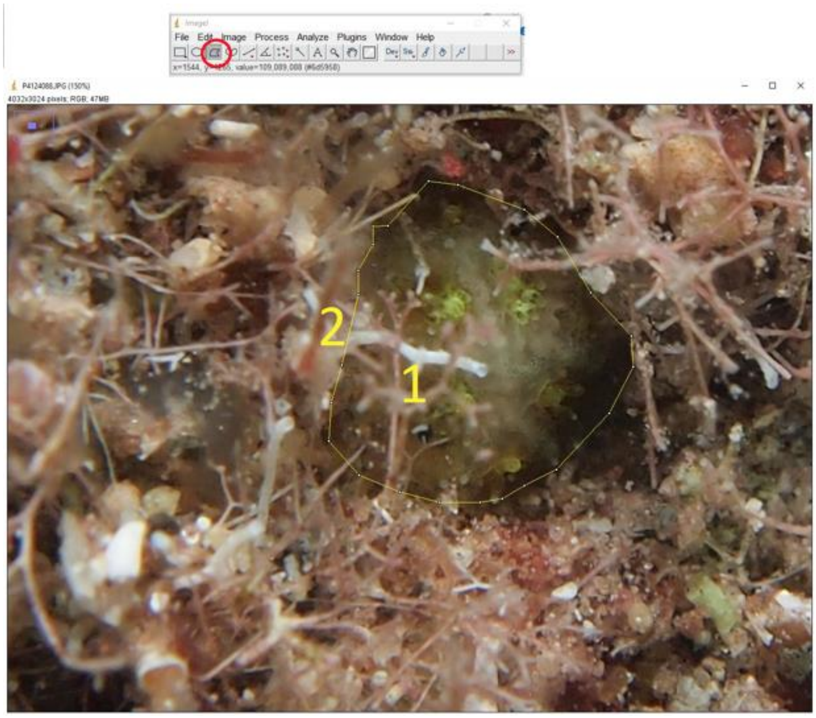
1. Merge the two pictures of the same coral (old and new) into one picture
2. Open ImageJ and open the merged picture (File à Open (CTRL + O))
3. To set the desired variables go to: Analyse -> set measurements…. Here, select Area, Perimeter, and Feret's diameter. Click on OK



4. Select the line *Straight*, and measure mm-scale on the callipers. Try to measure *at least* 10 stripes, covering 1 cm. To set the scale, go to: Analyse -> set scale…. Fill 'Known distance:' accordingly to the amount of stripes covered by the straight line. 10 stripes is 1 (1 cm), 11 stripes is 1,1 (1,1cm), 20 stripes is 2 (2 cm), etc. Click on 'OK'. If there is an arrow instead of the mm-scale select the arrow and fill 'Known distance' as 1.28cm



5. Select 'Polygon selections'. Draw a polygon around the coral. If algae covers the coral yet the shape remains clear, draw the line through the algae (1). If the shape of the coral is unclear follow the algal line (2)



6. To complete the measurement go to Analyse à Measure (CTRL + M) and write down the area and perimeter
7. Repeat step 4 till 6 for the second coral, do this for all the corals that were found. A similar table as underneath should be the result

Coral measurement				Old coral		New coral		Info
Location	**AR Type**	**AR Number**	**Coral nr**	**Area**	**Perimeter**	**Area**	**Perimeter**	**Species**
Big Rock Market	RB	BR1.1	1	0.258	1.899	0.374	2.466	PO
Big Rock Market	RB	BR1.1	2	0.094	1.164	0.381	2.390	PO
Big Rock Market	RB	BR1.2	1	0.186	1.737	0.433	2.882	PO
Big Rock Market	RB	BR1.2	2	0.217	1.923	0.801	3.744	PO
Big Rock Market	RB	BR1.2	3	0.225	1.858	0.526	3.018	PO
Big Rock Market	RB	BR1.2	4	0.135	1.389	0.566	2.954	PO
Big Rock Market	RB	BR1.2	6	0.065	0.978	0.251	1.883	PO

8. To measure the coral growth, the new coral area is divided by the old coral area, which results in the growth factor. So for instance take coral number 1 on BR1.2: 0.374/0.258= 1.450. So coral 1 on BR1.1 has grown 1.450 times between the first and second survey.