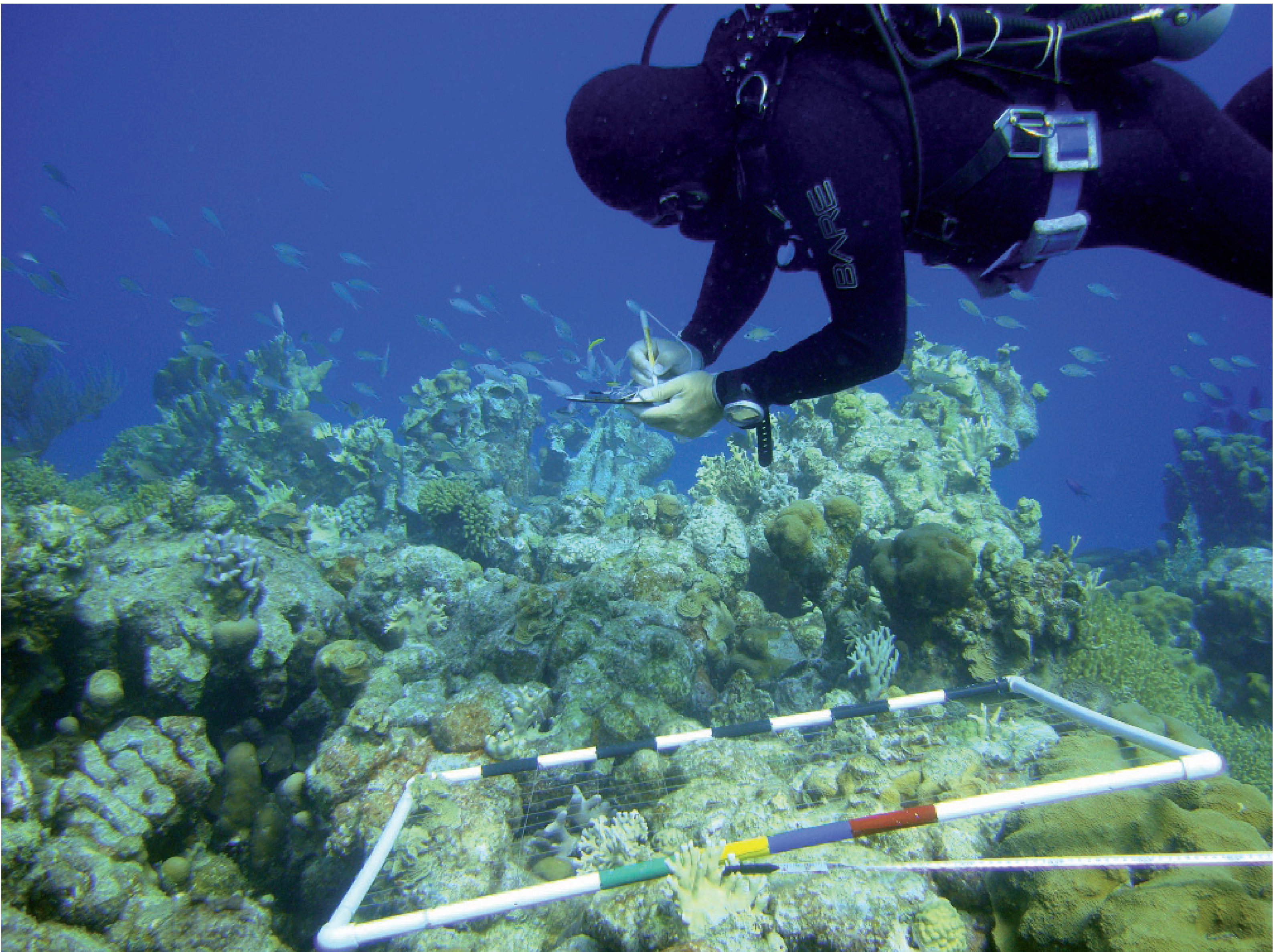
Coral Reef Resilience Assessment of the Bonaire National Marine Park, Netherlands Antilles

Surveys from 31 May to 7 June, 2009



IUCN Climate Change and Coral Reefs Working Group

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Acknowledgements

This survey was conducted as part of the IUCN Climate Change and Coral Reefs Working Group global coral reef resilience assessments, and was made possible by the generous support of the National Fish and Wildlife Foundation, the Stichting Nationale Parken Bonaire and the Bonaire National Marine Park manager, Ramon de Leon. Partners included The Nature Conservancy (TNC), Caribbean Research and Management of Biodiversity (CARMABI), the University of Maine and Yale University.

Cover Photography

Front cover: 'Bonaire National Marine Park manager Ramon de Leon surveying coral reefs'. Credit: Gabriel Grimsditch, IUCN

Back cover: 'The salt pier in Bonaire, Netherlands Antilles, at sunset' Credit: Gerick Bergsma 2009/Marine Photobank.

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Coral Reef Resilience Assessment of the Bonaire National Marine Park, Netherlands Antilles

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About the IUCN Climate Change and Coral Reefs Marine Working Group

The IUCN Climate Change and Coral Reefs Marine Working Group (formerly the IUCN Resilience Science Working Group), focused on coral bleaching, resilience, and climate change, was established in 2006 by the Global Marine and Polar Programme of IUCN on a 3-year grant from the John D. and Catherine T. MacArthur Foundation. The goal of the working group is to draw on leading practitioners in coral reef science and management to streamline the identification and testing of management interventions to mitigate the impacts of climate change on coral reefs. The working group consults and engages with experts in three key areas: climate change and coral bleaching research to incorporate the latest knowledge; management to identify key needs and capabilities on the ground; and ecological resilience to promote and develop the framework provided by resilience theory as a bridge between bleaching research and management implementation.

One of the outputs of this group was the setting up of a website that provides links to projects, events, partners and publications.

For more information, see http://www.iucn.org/cccr/index.cfm

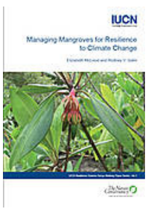
This publication is part of a series of publications on management tools to promote resilience in marine ecosystems. Selected titles, also available from IUCN's Global Marine and Polar Programme, are listed below:

Coral Reef Resilience and Resistance to Bleaching

IUCN Resilience Science Group Working Paper Series – No 1
Gabriel D. Grimsditch and Rodney V. Salm
© IUCN/TNC, October 2006

Resilience Assessment of Coral Reefs: Rapid assessment protocol for coral reefs, focusing on coral bleaching and thermal stress

IUCN Resilience Science Group Working Paper Series – No 5
David Obura and Gabriel Grimsditch
© IUCN / TNC, April 2009



Managing Mangroves for Resilience to Climate Change

IUCN Resilience Science Group Working Paper Series – No 2
Elizabeth Mcleod and Rodney V. Salm
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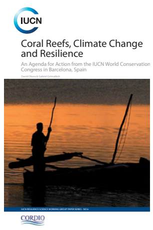

Coral Reefs, Climate Change and Resilience An Agenda for Action from the IUCN World Conservation Congress in Barcelona, Spain

IUCN Resilience Science Group Working Paper Series – No 6
David Obura & Gabriel Grimsditch
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Managing Seagrasses for Resilience to Climate Change

IUCN Resilience Science Group Working Paper Series – No 3
Mats Björk, Fred Short, Elizabeth Mcleod and Sven Beer
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A Framework for Social Adaptation to Climate Change - Sustaining Tropical Coastal Communities & Industries

NA Marshall, PA Marshall, J Tamelander, D Obura, D Malleret-King and JE Cinner
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Executive Summary

Although Bonaire's coral reefs remain among the healthiest and most resilient in the Caribbean, this IUCN report based on the IUCN Resilience Assessment of Coral Reefs highlights some of the threats that exist to Bonaire's coral reefs, and which could have serious implications for resilience to future climate change and other threats. The report identified recommendations for addressing the current threats, as well as high and low resilience sites.

The threats and recommendations identified include:

Coastal development and artificial beaches.Recommendation: All coastal construction on Bonaire should be strictly regulated and follow the construction guidelines. The guidelines should become law in order to be enforced appropriately.

Leaching from septic tanks. Recommendation: It is strongly recommended that Bonaire invest in appropriate sewage treatment facilities to improve water quality and increase the resilience of its valuable coral reefs. It is also recommended that a water quality monitoring program be set up and sustained.

Increasing damselfish populations. Recommendation: It is recommended that the fishing of predatory fish species on Bonaire's coral reefs be controlled and managed to a sustainable level to prevent population explosions of prey fish capable of modifying the reef habitat.

***Trididemnum* and *Lobophora*.** Recommendation: It is recommended that the populations of Tridemnum and Lobophora are closely monitored and the factors contributing to the unnatural abundance of these coral-overgrowing organisms should be studied and then eliminated.

Due to a variety of factors affecting resilience which were assessed using the IUCN methodology, sites were also ranked according to their overall resilience:

Resilience rating	Sites	Management
High	Marine Reserve North	NDA
High	Playa Frans	NDA
High	Karpata	MPA
High	Margate Bay	MPA
High	Vista Blue	MPA
High	South Bay	MPA
Medium	Playa Funchi	MPA
Medium	Wayaka II	MPA
Medium	Oil Slick Leap	MPA
Medium	Cliff	FPA

Resilience rating	Sites	Management
Medium	Bari	FPA
Medium	Something Special	FPA
Medium	18th Palm	FPA
Medium	Bachelor’s Beach	MPA
Medium	Angel City	MPA
Medium	Salt City	MPA
Medium	Tori’s Reef	MPA
Medium	Carl’s Hill	MPA
Medium	Mi Dushi	MPA
Medium	Keepsake	MPA
Low	Chachacha	FPA

It is noteworthy that sites with lowest resilience ratings (e.g. Chachacha) are those most impacted by coastal development, while sites with highest resilience ratings (e.g. Marine Reserve North, Playa Frans, Karpata, Margate Bay, Vista Blue and South Bay) are those furthest away and least impacted by coastal development.

1. Introduction

1.1 The Study

This survey was conducted as part of the IUCN Climate Change and Coral Reefs Working Group global coral reef resilience assessments, and was made possible by the generous support of the National Fish and Wildlife Foundation, the Stichting Nationale Parken Bonaire and the Bonaire National Marine Park manager, Ramon de Leon. Partners included The Nature Conservancy (TNC), Caribbean Research and Management of Biodiversity (CARMABI), the University of Maine and Yale University. This document aims to provide information on how to incorporate resilience information and climate change responses into Marine Protected Area design and management. Specifically, the study objectives are:

1. **To design and implement a rapid assessment protocol to monitor and quantify bleaching and reef resilience tailored to the needs the Bonaire Marine Park;**
2. **To survey the resistance and resilience of coral reefs in Bonaire to coral bleaching and climate change;**
3. **To train regional Marine Protected Area managers and other partners in implementation of the aforementioned surveys; and**
4. **To make recommendations on management of coral reefs within the Marine Protected Area based on the survey findings.**

This report contains information on objectives 2 and 4, while objective 3 was met through a training workshop organised on Bonaire in conjunction with The Nature Conservancy and the National Oceanic and Atmospheric Administration. Members of the survey team incorporated staff from the following partner organisations:

Table 1

Name	Organisation	Data collected
Suzanne Arnold	The University of Maine	Coral recruits, algae
Henry de Bey	Yale University	Predatory fish
Jeanne Brown	The Nature Conservancy	Herbivorous fish
Sabine Engel	Stichting Nationale Parken Bonaire	Coral size class
Gabriel Grimsditch	IUCN	Benthic cover
Ramon de Leon	Stichting Nationale Parken Bonaire	Coral recruits, algae
Mark Vermeij	Caribbean Research and Management of Biodiversity	Coral size class

1.2 Reef resilience

Reef health is largely determined by a reef's "resilience", i.e. its ability to resist threats and to recover to its former state after a disturbance has occurred.

The natural resilience of reefs is being undermined by stresses associated with human activities. These local pressures reduce the resilience of the system by undermining its ability to cope with additional stresses, such as those associated with climate change. Increasingly, policy-makers, conservationists, scientists and the broader community are calling for management actions to restore and maintain the resilience of the coral reefs in order to minimize the negative impacts of climate change.

The approach used in this study was developed by the IUCN Climate Change and Coral Reefs working group (http://cms.iucn.org/cccr), led by CORDIO East Africa, which has outlined a series of protocols that include basic resistance and resilience indicators in coral reef assessments. These methods are designed to assist management authorities in focusing management effort to priority areas.

1.3 Bonaire

Bonaire lies in the Southern Caribbean approximately 100km (60 miles) north of Venezuela and 12' north of the equator, separated from the South American mainland by a deep water trench. Bonaire is part of the Kingdom of the Netherlands and is regarded by the European Union as an Overseas Territory.

The reefs around Bonaire and Klein Bonaire form a narrow fringing reef, which starts at the shoreline and extends to a maximum of 300 meters offshore. The entire reef system is protected as part of the Bonaire National Marine Park (BNMP).

The reefs considered in this study were on the leeward western shore of the island. In general, such reefs consist of a shallow terrace extending from the shore to a drop-off at a depth of approximately 10-15 meters, On the windward eastern shore of Bonaire, the terrace generally extends 100-200 meters offshore to a depth of 12 meters and is covered primarily with crustose coralline algae and *Sargassum* or gorgonians. The shallow terrace on the leeward shore was characterized by coral communities dominated by Acropora *palmata* and A. *cervicornis* mixed with *Montastrea annularis* and gorgonians. Unfortunately, Hurricane Lenny which passed through in November 1999 and Hurricane Omar in October 2008 caused significant damage to these communities and wiped out nearly all Acropora colonies, leaving a rubble terrace. From the drop-off the fore reef slopes with an inclination of between 30° and 60° to a sediment-covered platform at a depth of around 50-80 meters. About 65 species of scleractinian coral are found on Bonaire's coral reefs.

The Bonaire National Marine Park (BNMP) was created in 1979, and has had consistent management since 1991. It includes all the waters surrounding Bonaire and Klein Bonaire (since 2001), from the high-tide mark to 60 meters of depth. It comprises 2,700 hectares of coral reef, seagrass and mangrove ecosystems and provides habitat for a diverse range of marine species including about 65 species of stony coral and more than 450 species of reef fish. Furthermore, there are five internationally-recognized Ramsar sites on the islands – Lac, Klein Bonaire, Saliña Slagbaai, Gotomeer and Pekelmeer.

The park is managed by a local nongovernmental, not for profit organization, STINAPA Bonaire which has a co-management structure with stakeholders, conservationists and local interest groups represented on the Board. The day to day management is carried out under the supervision of a Director by the Marine Park manager, Chief Ranger and Rangers which are all employed by STINAPA Bonaire.

The mission of the BNMP is ‘protect and manage the island’s natural, cultural and historical resources, while allowing ecologically sustainable use, for the benefit of future generations’. It hosts approximately 60,000 visitors a year of which 38,000 are SCUBA divers. One of the primary challenges of managing the BNMP is dealing with the various stakeholders who use the park and enabling sustainable use of natural resources. Stakeholders are varied and include the government, tour operators, hotel owners, schools, building and zoning departments, environment and nature management department, legal department, harbor office, agricultural department, dive operators and other water sport activity providers, non-governmental organizations, law enforcement, maintenance, research and monitoring, education, advisory and volunteer groups among others. Some of the main challenges to management include over-fishing, nutrient enrichment, land-use change, poaching, heavy recreational use, sedimentation, terrestrial run-off, illegal sand mining, artificial beach creation, invasive lionfish. All these threats could be compounded in the near future by climate change-related threats such as coral bleaching or ocean acidification.

Despite the many threats, the successful management of BNMP means that Bonaire’s coral reefs remain among the healthiest in the Caribbean. The islands lie outside the path of most hurricanes (Hurricanes Omar and Lenny were exceptions). They are also subject to the strong Caribbean Current which constantly flushes the reefs with fresh oceanic waters. Therefore, coral mortality seems to have been delayed compared to most other Caribbean sites.

However, a study by Steneck et al. (2007) shows some disturbing trends that are affecting the health and resilience of Bonaire’s coral reefs. They identified increasing macroalgae, declining herbivory from parrotfish, increases in damselfish populations and loss of large-bodied predators such as groupers and barracudas as current and growing threats to the reefs. Increasing macroalgal cover means that corals are being outcompeted for space and light, with a subsequent loss of diversity and habitat as well as a decrease in reef accretion and growth. Increased macroalgae can also reflect loss of herbivores or poorer water quality. Declining herbivory by parrotfish and other reef herbivores causes increased macroagal cover, as herbivores (e.g., parrotfish, surgeonfish, sea urchins) are a crucial functional group in maintaining the competitive advantage of hard corals over macroalgae on a reef. They scrape algae off the reef substrate to prepare it for coral recruitment and are therefore a crucial driver of coral reef resilience. Declining herbivore populations can be caused by increased fishing efforts. In addition the number of damselfish has increased as these small fish increase in numbers now that their predators (e.g. groupers or barracudas) have been reduced due to overfishing. Damselfish cause additional coral mortality by ‘cultivating’ territorial turf algal patches, off which they feed, on large coral colonies. They maintain and defend these turf algae, which then overgrow the coral leading to mortality and reduced reproduction.

As well as declining herbivory, overfishing and increasing damselfish, the effects of climate change are also a possible major threat to Bonaire’s reefs. Sustained above-average water temperature can lead to ‘coral bleaching’, a phenomenon where the symbiotic relationship between the coral host and the unicellular micro-algae that live in its tissue is disrupted. The micro-algae living in the coral tissue photosynthesize and are thus crucial for the coral’s energy needs, as well as providing the coral with pigments. However, with sustained above-average temperatures and high UV-radiation from the sun, the symbiosis between the coral and the micro-algae is damaged and the micro-algae are expelled from the coral. This leaves the coral weak and in a vulnerable state to overgrowth by seaweed, infection by disease or mortality. The phenomenon is called 'bleaching' because as the coral loses its pigments, the calcium carbonate (aragonite) skeleton becomes visible and the corals appear white. With increasing sea surface temperatures around the world due to climate change, bleaching events are becoming more frequent and more intense. In 1998-1999 a global bleaching event caused an estimated 16% mortality of corals worldwide (Willkinson, 2002). More recently in 2005, a mass bleaching event in the Caribbean caused mortality from 0-27% in different Caribbean countries. Bleaching events are predicted to increase in frequency and intensity as seawater warms up and the climate changes. Bonaire is also at risk from the bleaching threat, and it is thus important for the management of the park to take this into account in management schemes.

1.4 Purpose of the study

Different coral reefs react differently to bleaching events and other threats because of various factors that influence their resilience to disturbances. Because of their various biological compositions and physical conditions (see Overview of Methods) we can expect different coral reefs, even on the same island, to follow different trajectories with rising sea temperatures and increased bleaching events. Therefore it is important for a manager to understand which resilience factors are characteristic of the coral reefs in their management zone. This study aims to assess the various resilience characteristics of the coral reefs in the Bonaire National Marine Park, therefore giving the manager a better understanding of the potential responses of the reefs to future climate change and bleaching events.

Map of Bonaire and survey sites

Table 2 - Sites surveyed in Bonaire in June 2009. Geographic coordinates, management regime and depth of sampling are shown.

Date 2009	Site	Depth (m)	Lat (N)	Long (W)	Management
31 May	Playa Funchi	10	12°16’56.18”	68°24’54.48”	MPA
31 May	Wayaka II	10	12°16’9.34”	68°24’53.53”	MPA
4 June	Playa Frans	10	12°14’45.08”	68°24’53.62”	NDA
4 June	Marine Reserve North	10	12°13’12.60”	68°22’26.76”	NDA
31 May	Karpata	10	12°13’8.21”	68°21’7.83”	MPA
3 June	Oil Slick Leap	10	12°11’59.69”	68°18’31.86”	MPA
3 June	Cliff	10	12°10’25.23”	68°17’25.72”	FPA
2 June	Bari	10	12°10’3.37”	68°17’16.54”	FPA
1 June	Something Special	10	12°9’43.61”	68°17’7.22”	FPA
30 May	18th Palm	10	12°8’16.30”	68°16’37.79”	FPA
5 June	Chachacha Beach	10	12°8’44.82”	68°16’37.84”	FPA
4 June	Bachelor’s Beach	10	12° 7’32.31”	68°17’17.54”	MPA
4 June	Angel City	10	12° 6’3.64”	68°17’14.43”	MPA
5 June	Salt City	10	12°4’48.51”	68°16’56.76”	MPA
5 June	Tori’s Reef	10	12°4’17.41”	68°16’55.16”	MPA
1 June	Margate Bay	10	12°2’50.93”	68°16’18.02”	MPA
1 June	Vista Blue	10	12°1’57.39”	68°15’55.06”	MPA
2 June	Carl’s Hill	10	12°9’51.79”	68°19’23.01”	MPA
7 June	Mi Dushi	10	12°9’32.99”	68°19’34.32”	MPA
2 June	South Bay	10	12°8’59.04”	68°19’21.56”	MPA
7 June	Keepsake	10	12°8’57.19”	68°17’45.80”	MPA

MPA = Marine Protected Area; NDA = No Diving Area; FPA = Fish Protected Area

1.5 Overview of methods

The methods applied in this study were developed by the IUCN working group on Climate Change and Coral Reefs, specifically to examine the resilience of coral reefs to climate change (i.e., future increases in seawater temperature). Several components of the reef ecosystem were measured at varying levels of detail, as follows:

1) **Benthic cover** – provides the main overall indicators of reef state, and particularly the balance between corals and algae. Benthic photographs were used to assess benthic cover. Photos were taken from about 1 meter above the substrate and were later analyzed using Coral Point Count software.

2) **Fleshy algae** – provides information on the main competitors to corals on degrading reefs. Fleshy algae cover (%) and height (cm) was estimated in 1m^2 quadrats.

3) **Coral size class distribution** – provides detailed information on the demography and sizes of coral colonies, and can show indications of past impacts by the presence or not of large colonies. It includes sampling of recruitment and small corals in 1 m^2 quadrats, and larger corals in 25x1 m belt transects.

4) **Fish herbivores and other functional groups** – fish exert primary control on the reef community, and on algae through herbivory, thus controlling competition between algae and corals. The numbers of fish in different functional groups, including herbivore functional groups, was measured in 50x5 m belt transects.

5) **Resilience indicators** – these are factors that affect the resistance of corals to bleaching and the resilience or recovery potential of the reef community. A broad range of indicators in different classes is measured, including those overviewed in 1-6 above and some at qualitative levels. The main classes of indicators are listed below:

One of the surveyors enjoying the fish counts on Bonaire's reefs.

Table 3

Indicator	Type	Description
Benthic Cover	Cover	Primary indicators of reef health, particularly of coral and algal dominance and competition.
Coral community	Current	Indicators of the current condition of the coral community, including recruitment, aspects of size class structure, condition, etc.
	Historic	Indicators of the historic condition of the coral community, including past impacts and recovery to date.
Ecological – reef community	Positive	Abundance of organisms that are positive indicators of coral health – e.g. sea urchins, predatory fishes.
	Negative	Abundance of organisms that are negative indicators of coral health – e.g. boring organisms, encrusting sponges, damselfish etc.
	Herbivory	Health of the fish herbivore community.
Physical	Substrate	Substrate health, critical for settlement and survival of young corals.
	Cooling & flushing	Factors that cause mixing and cooling of water, which can reduce the high temperatures experienced by a reef.
	Shading & screening	Factors that reduce light penetration in the water, thus reducing synergistic stress to corals from temperature and light.
	Acclimatization	Factors that cause high variability in environmental conditions, that promote acclimatization of corals to stress, for example exposure of corals at low tide or ponding and pooling of water leading to high temperature variability.
Anthropogenic	Water	Human impacts to water quality, that reduce the recovery ability of reefs and increase stress to corals.
	Substrate	Human impacts to the reef substrate, that reduce the recovery ability of reefs and increase stress to corals.
	Fishing	Degree of fishing and its impact on recovery ability of reefs.

2. Major findings

This section summarizes the main findings from the Detailed results (section 4), which can be consulted for additional details and background information of the findings overviewed here.

2.1 Overview

The resilience data (section 4.1) highlights that certain sites on Bonaire are expected to have higher overall resilience to stressors, including climate change. It also indicates sites that are predicted to be more susceptible to future stress. Table 4 below shows the classification of sites according to their resilience category (high, medium and low) based on data in graphs 4.1.1 and 4.1.2. These graphs clearly identify 3 distinct groups of which those characterized by “high resilience” can be considered to have greater reef “health” of all sites surveyed:

High resilience sites: Playa Frans, Marine Reserve North, Karpata, Margate Bay, Vista Blue and South Bay.

Medium resilience sites: Playa Funchi, Wayaka II, Oil Slick Leap, Cliff, Bari, Something Special, 18th Palm, Bachelor’s Beach, Angel City, Salt City, Tori’s Reef, Carl’s Hill, Mi Dushi and Keepsake.

Low resilience site: Chachacha.

Unsurprisingly, the highly resilient sites are located away from Kralendijk, the main urban centre and where the main coastal development impacts are. Playa Frans, Karpata and Marine Reserve North are away to the north; furthermore Playa Frans and Marine Reserve North are No Diving Areas, meaning that there is even less human impact. Margate Bay and Vista Blue are to the southern end of the island. South Bay is on Klein Bonaire but on the opposite side of the island away from Kralendijk.

Playa Frans, South Bay, Karpata and Marine Reserve North stand out for their healthy, resilient coral populations (graph 4.1.5). They have the highest live coral cover of all sites surveyed with covers between 26-40% (graphs 4.2.2 and 4.2.4), and low macroalgal cover. It appears that these sites have recovered best from the devastation caused by Hurricanes Omar and Lenny. Furthermore, these sites, as well as Margate Bay in the south, provide suitable habitat conditions favoring bleaching-susceptible coral species (for the purpose of this study defined as *Acropora palmata, Acropora cervicornis, Eusmilia fastigata, Meandrina meandrites, Montastrea annularis, Montastrae faveolata, Montastrea franksii*) that occur in great abundance at these sites. (graph 4.3.6). Overall, Playa Frans, South Bay, Karpata and Marine Reserve North score well on all resilience indicators related to water quality (graph 4.1.8), substrate conditions (4.1.7) and coral populations (4.1.5).

However, coral recruitment in some of the high coral cover and high environmental quality sites is relatively low compared to other sites surveyed (graph 4.3.4). For example, Playa Frans has 79 recruits (colonies sized 0-2.5cm) per 100 m^2, Karpata has 83 recruits per 100 m^2, and South Bay has 102 recruits per m^2, all lower than the overall average of 152 recruits per 100 m^2. This is often the case in healthier coral communities with higher coral cover where there is less space available for recruitment so this is not necessary a cause for worry, however it is important to ensure that coral mortality in these sites remains low by ensuring that the quality of the local environment remains high, i.e., unchanged.

A worrying trend is the increasing cover of *Trididemnum*, a tunicate that overgrows living coral, in northern sites (graphs 4.4.2 and 4.4.3) such as Marine Reserve North, Karpata and Playa Frans. Although the abundance of this tunicate is low at the moment (maximum 4.3% cover at 10m depth), there is anecdotal evidence that cover is increasing at deeper depths and this trend should be monitored given this species' ability to rapidly overgrow large patches of living coral.

A further worrying trend is the increasing population of damselfish as noted in Steneck et al, 2007, and this IUCN study confirms the trend. These small territorial fish garden turf algal 'yards' which they use as food sources and zealously protect them against invaders. However, they kill live coral to maintain and expand their yards, and are causing a lot of damage in Bonaire's reefs. Graph 4.5.6 shows Marine Reserve North, South Bay, Oil Slick Leap and Keepsake show the highest relative abundance of coral-destroying damselfish while Wayaka II and Playa Funchi exhibit the lowest relative abundances. The high resilience of sites such as Marine Reserve North and South Bay is thus potentially at risk if the trend of increasing damselfish populations continues.

Damselfish populations on Bonaire are likely controlled by predator populations (Vermeij et al, in preparation). Of all benthic and fish guilds considered, only the abundance of predatory fishes could be related to the local abundance of damselfish (Graph 4.5.7), with a negative correlation between damselfish and predator biomass. Damselfish *Stegastes planifrons* were observed on colonies of 12 different coral species, and only on four massive coral species (*Montastraea annularis, M. faveolata, M. franksi* and *Colpophylia natans*) did they occur in greater densities than expected. Clearly the damselfish prefer large, massive coral species over smaller branching, i.e., structurally more complex species (*Eusmilia fastigiata, Millepora complenata, Madracis decactis* and *M. mirabilis*). However, the abundance of damselfish's preferred habitat (*Montastraea* coral species) had no positive effect on the local abundance of damselfish (Graph 4.5.8). The abundance of *S. planifrons* was positively correlated with the local cover of turf- and crustose coralline algae and the proportion of local coral colonies that showed some sign of disease. These results show that in Bonaire predators control the population of damselfish rather than habitat, and that the more damselfish there are, the more turf algae and diseased corals there are too.

As predator fish are likely important for regulating the number of destructive damselfish, their populations are also important for coral reef resilience. The majority of predator biomass on Bonaire is made up of grunts and snappers, although Margate Bay also has high biomass of groupers (graph 4.5.4). It seems as if the high resilience of sites such as Margate Bay and Vista Blue are in this case is driven by good fish populations (graph 4.1.6) that can help mediate coral-algal interaction and competition. Both these sites are also next to a Ramsar site (i.e., salt plains), but it is possible that the salt discharge affects reef resilience as there is a wide layer of anoxic sediment at the discharge points. Graph 4.2.3 shows that Margate Bay and Vista Blue don't have the highest live coral cover (20.4% and 15.7% respectively), however they have among the highest coral recruitment (215 and 188 recruits per 100 m^2 respectively) indicating high potential for recovery.

Parrotfish scraping algae off the substrate. This action cleans the substrate and prepares it for coral colonization, and thus increasing reef resilience.

Denuding surgeonfish feeding on algae. Schools of these fish cruise along the reef eating algae and are vital for keeping algal growth in check thereby increasing reef resilience.

High resilience sites are characterized by high abundances (i.e, biomass) of important reef herbivores. South Bay has the highest biomass of parrotfish capable of scraping algae off the substrate and making it suitable for coral recruitment (graph 4.5.9). Margate Bay has the highest biomass of browsers (fish that feed on macroalgal fronds, e.g. chaetodons and pomacanthids, graph 4.5.10) and denuders (fish that remove epilithic algal turf from the reef substratum, but do not scrape the surface, e.g. acanthurids and microspathodon, graph 4.5.11), both crucial for keeping algal growth under control and thus preventing overgrowth and/or shading of neighbouring corals.

Finally, high resilience sites such as Playa Frans and South Bay have the most favourable calcification rates. A calcification rate higher than 1 indicates a growing reef, i.e., there are more calcifying organisms (live coral) than non-calcifyers (other substrate types). A calcification rate < 1 indicates a reef that is not growing due to the dominance of non-calcifyers over calcifyers. Playa Frans and South Bay have the highest calcification rates (0.77 and 0.73 respectively, graph 4.2.9), but they are still lower than 1 meaning that they may be susceptible to erosion.

This group of 'medium' resilience sites illustrates the complex nature of coral reef resilience. The group can actually be divided into 'higher' and 'lower' resilience categories as well. Within the medium resilience group, there is a gradient of resilience and sites such as Wayaka II, Playa Funchi (to the north) and Angel City (to the south) that are further away from Kralendijk have higher resilience scores than sites closer to Kralendijk such as Bari, Something Special, Bachelor's Beach and Cliff (graph 4.1.1). Wayaka II and Playa Funchi are located next to the protected Washington Slagbaai National Park, and there is little to no coastal development in the area. Sites on Klein Bonaire (a RAMSAR area with no coastal development at all) such as Keepsake, Mi Dushi and Carl's Hill also suffer less land-based stress and fall in the higher resilience category.

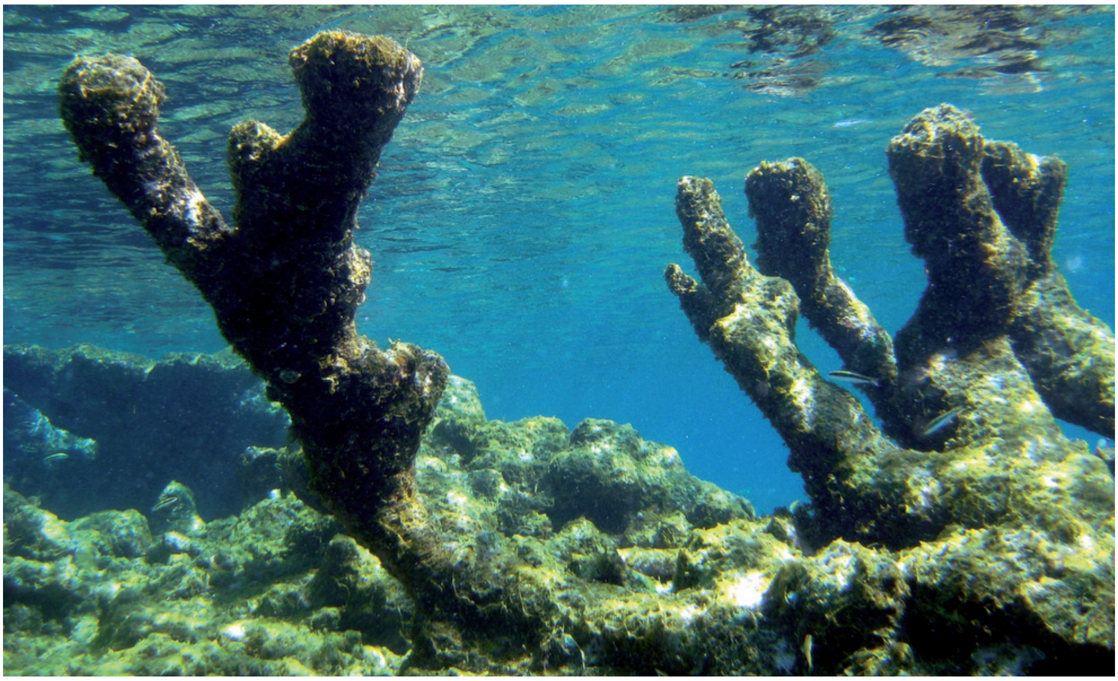
On the other hand, Something Special is located next to a marina with boats mooring directly on the reef and subjected to physical dumping of waste and affected by runoff from a large catchment area. Bari is located next to a pier, a residential area and an artificial beach. Cliff is located next

Salt plains to the south of the island. High salinity discharges from these plains could affect development of corals that are close to the discharge points such as Salt City or Tori's Reef.

to a water factory and is subject to runoff from a large catchment area as well as leaching from septic tanks. Bachelor's Beach is located next to a residential area and also subjected to nutrient run-off. The only sites that are far away from Kralendijk and that score poorly are Salt City and Tori's Reef which are both subject to land-based stress from the very high salt discharges directly on to them from the salt plains. In summary, land based human activities had great negative impacts on nearby reef communities and likely reduced their ability to recover from future (natural) disturbances.

There is one clear outlier identified by the data which falls into its own 'low' resilience category due to the degradation and impacts it suffers: Playa Chachacha. This site is right next to Kralendijk and suffers impacts of coastal development and run-off from land-based sources of pollution and sewage. This site scored poorly in resilience indicators relating to algae (graph 4.1.4), corals (graph 4.1.5), fish (graph 4.1.6, substrate quality (graph 4.1.7) and water quality (graph 4.1.8), which could all be related to the land-based impacts from Kralendijk. It has the lowest live coral cover (9.2%, graphs 4.2.2 and 4.2.4) and sensitive coral species are no longer present (graph 4.3.6), and has one of the lowest calcification rates of all sites (0.25, graph 4.2.9), meaning that it is highly susceptible to erosion. **This degraded and impacted site serves as a stark reminder of what can happen to coral reefs if they are not protected from the effects of land-based human stressors.**

However, it is a Fish Protected Area so it is hoped that fish populations will be able to recover over time and add a possible layer of resilience, at least to the food security provided by Bonaire's reefs. In fact, the Fish Protected Areas (Cliff, Bari, Something Special, 18th Palm, Something Special and Chachacha) are all to the lower end of the resilience spectrum (graph 4.1.1) because they are located around Kralendijk. Graph 4.3.1 illustrates this well. Fish Protected Areas all score badly on resilience factors relating to coral populations, substrate conditions, water quality, and anthropogenic stressors, yet they are positively correlated with fish populations. This shows that although the Fish



Dead Acropora stands. Acropora beds in the shallows were completely wiped out during Hurricane Lenny in 1999 and Hurricane Omar in 2008. Their recovery will depend on recruitment and environmental quality of the affected sites.

Table 4

Resilience rating	Sites	Management
High	Marine Reserve North	NDA
High	Playa Frans	NDA
High	Karpata	MPA
High	Margate Bay	MPA
High	Vista Blue	MPA
High	South Bay	MPA
Medium	Playa Funchi	MPA
Medium	Wayaka II	MPA
Medium	Oil Slick Leap	MPA
Medium	Cliff	FPA
Medium	Bari	FPA
Medium	Something Special	FPA
Medium	18th Palm	FPA
Medium	Bachelor's Beach	MPA
Medium	Angel City	MPA
Medium	Salt City	MPA
Medium	Tori's Reef	MPA
Medium	Carl's Hill	MPA
Medium	Mi Dushi	MPA
Medium	Keepsake	MPA
Low	Chachacha	FPA

Protected Area management seems to be working for fish, other land-based sources of stress override this positive effect and lead to loss of resilience. Degradation of water quality due to land-based activities thus appears to an acute threat to Bonaire's reefs that needs to be resolved.

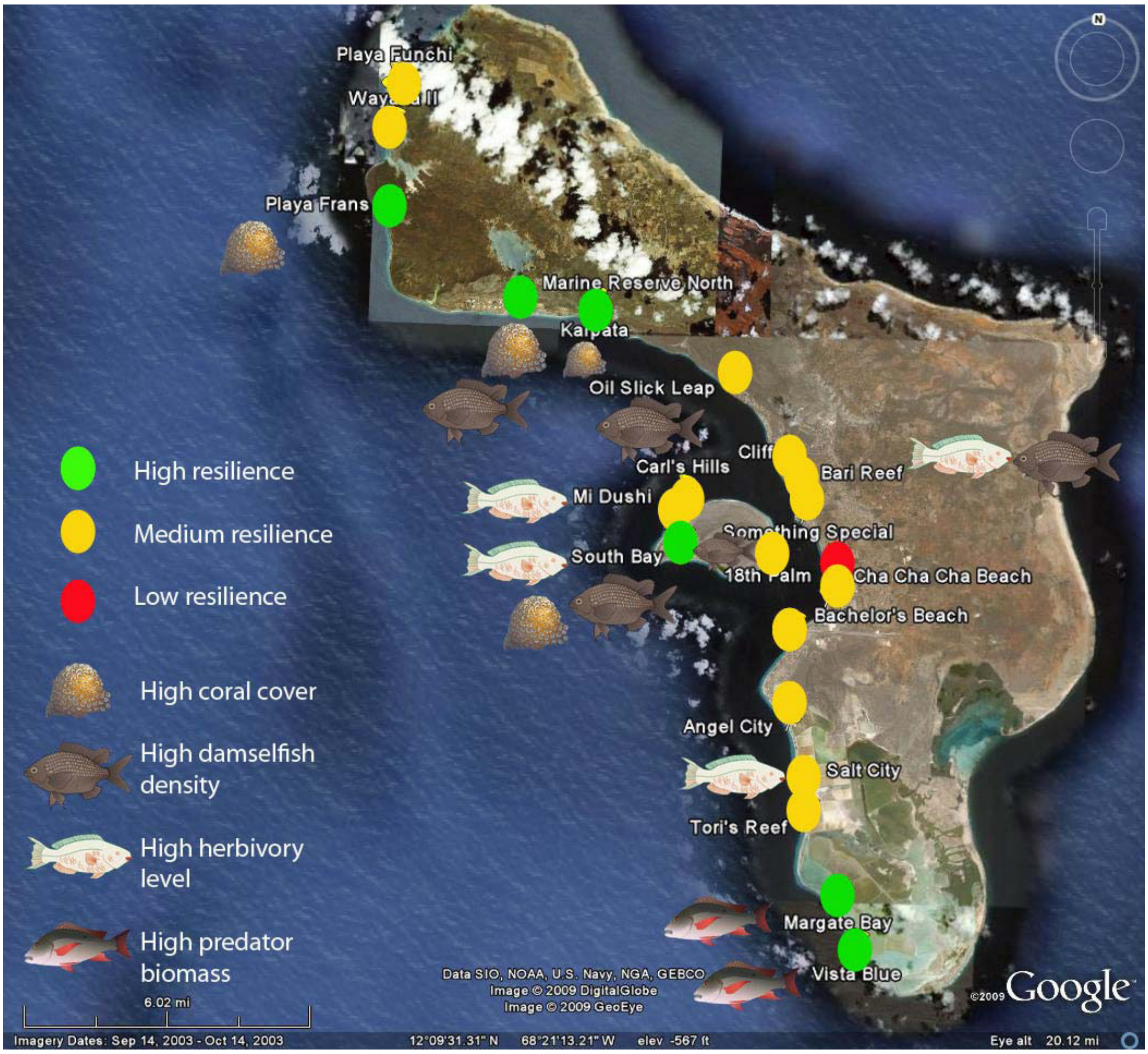
The map on the following page shows the resilience ratings and factors by site. High resilience sites (Marine Reserve North, Playa Frans, Karpata, Margate Bay, South Bay and Vista Blue) are marked by green circles. Medium resilience sites (Playa Funchi, Wayaka II, Oil Slick Leap, Cliff, Bari, Something Special, 18th Palm, Bachelor's Beach, Angel City, Salt City, Tori's Reef, Carl's Hill, Mi Dushi, Keepsake) are marked by yellow circles. Low resilience sites (Chachacha) are marked by a red circle.

Sites with high coral cover (Playa Frans, Marine Reserve North, Karpata and South Bay) are marked with a coral symbol.

Sites with high damselfish density (Marine Reserve North, Oil Slick Leap, South Bay and Keepsake) are marked with a damselfish symbol.

Sites with high herbivory levels (Bari, Mi Dushi, South Bay and Salt City) are marked with a parrotfish symbol.

Sites with high predator biomass (Margate Bay and Vista Blue) are marked with a snapper symbol.



2.2 Threats to Bonaire's coral reef communities

Coastal development and artificial beaches

Coastal development and construction is one of the major threats to the coral reefs of Bonaire. They are very vulnerable to pollution and sedimentation. Debris, sand, cement, stones and other runoff of coastal development and erosion that are washed in the sea can cause serious damage or mortality to corals by smothering them and blocking their access to the sunlight they need for energy. As corals use energy to clean themselves, even a small area of damage on a coral sets of a reaction that affects the whole coral colony. Clearing native vegetation in order to construct buildings on the coast destabilizes the topsoil and high winds or rainfall then blow or washes the soil into the sea. Creating artificial beaches, like the ones close to 18th Palm and Bari, also has a negative effect on corals. Artificial beaches require sea sand, not the crushed sand you can buy, and Bonaire does not have a supply of natural sea sand that can be used for this purpose. What sea sand the island does have is a scarce commodity, difficult to extract or occurs within protected areas, such as Lac Bay and the Wasington Slagbaai National

Park. Artificial beaches wash away gradually with time through natural processes and are removed immediately during conditions of wind reversal or high waves. Because of the highly negative impacts of sedimentation on coral reefs, the sites in Bonaire closest to highly developed coastal areas (e.g. Kralendijk and the port) have lower resilience ratings and overall health (e.g. Chachacha Beach) than those that are removed from coastal development (Marine Reserve North, Playa Frans, Karpata, Margate Bay, Vista Blue, South Bay).

The following excerpt is from the construction guidelines for Bonaire:

‘In an effort to minimize erosion and run off, the period of time spent in construction must be as short as possible. That is why you should not clear your location until construction begins. Especially during construction near the shore, erosion control techniques like silt screens and filter cloth, must be employed if fill material is left exposed. Following construction, the shoreline must be immediately stabilized with native vegetation…. Leave as much natural vegetation on the site as possible. The limited rainfall means it is difficult and expensive to grow and maintain plants. However, the native vegetation already on your property is very well adapted to the environment of Bonaire and requires no watering, so it is worth looking after. On our arid island, it is wise to leave as much existing vegetation as possible, using it as the basis of your garden. This saves you money by reducing costs of clearing the site and re-landscaping your garden as well as reducing costs for irrigation. This will also help conserve the islands vegetation and preserve your valuable topsoil. If you remove too much vegetation you will loose your topsoil. It will blow away, creating a dusty, barren yard, or will run off after rainfall. Reducing pollution from runoff is another way you can help the environment and marine life. Plants that are not native to the island require a lot of water, fertilization and pest control, non-native plants can also bring diseases. Water from rain and irrigation washes fertilizers and pesticides, soil and debris from your yard and off the streets into the sea. Therefore, by preserving as much existing vegetation as possible and choosing native and other drought resistant plants and trees this pollution can be reduced. Native plants, once established, do not require much, if any, water, fertilizer or pesticides. This will save you time and money. It also reduces pollution from excess fertilizer and pesticides that could wash off your yard. This is especially important on properties near the sea. Any irrigation with grey or black water, deposits extremely high quantities of nutrients (fertilizers) onto the coral reefs. These nutrients promote algal growth which kills the coral. If you have plants, like palm trees, that require irrigation, locate them as far away from the shore as possible…. It can take at least six weeks to get a building permit and numerous months to select a builder. Waiting until the last possible moment will help hold your topsoil in place, prevent erosion, and if you are building near the sea, it will keep the sediment off the reef.

The vegetation you must remove can be re-used. Wood can be used for wood chips and to produce charcoal. Trees can be transplanted. Topsoil that becomes available after removing the vegetation can be re-used in the landscaping. When you start construction, it is most important that you set up the building site in such manner that prevents pollution, erosion and damage to terrestrial and marine environment. Keeping the building site clean during construction is the best way to prevent this. It also saves you time and energy at the end of the construction because you do not have to clean as much and scrape off materials from the building site.

If you are not able to screen the whole site, you should at least screen the leeward side of the site to catch waste that can blow away or runoff. If your plans call for a fence or wall around your final construction, consider building it first. This way you will not have the added expense of a temporary screen.

is a very good start for your future garden. It also prevents soil run off and keeps waste materials from littering the streets, nature and the sea.

During construction be careful not to unnecessarily damage the existing vegetation when stacking materials or placing containers or equipment. Cement and concrete are especially harmful to plants and marine life.

It is prohibited to create artificial beaches on Bonaire and a permit is required to replenish naturally occurring beaches. Sand can wash or be blown into the sea and kill our coral reefs.

Bonaire has no fresh water supply. Therefore, all fresh water needs to be distilled from seawater through the process of reverse osmoses, which uses an enormous amount of energy, thus making water expensive. Filling and refilling your swimming pool with fresh water will cost you a lot of money. To keep the pool clean and bacteria free, chloral and other chemicals need to be added. However, you are not allowed to dispose of chlorinated water into the sea or on land. You are not allowed to fill the pool with seawater. This is because a pool with seawater needs a through flow to the sea, which may result in chemical or organic (algae) pollution.'

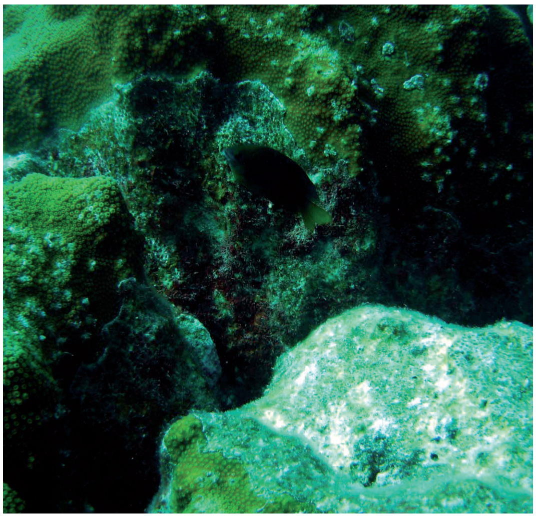
Recommendation: All coastal construction on Bonaire should be strictly regulated and follow the construction guidelines. The guidelines should become law in order to be enforced appropriately.

Leaching from septic tanks

A wide range of sewage impacts on coral reef communities has been reported. Little or no impact has been observed on some reefs in well-flushed waters that receive small quantities of effluent, whereas large discharges of effluent into poorly-flushed lagoons and bays have caused major changes in species composition and abundance. The 3 components of sewage effluent most detrimental to coral communities are nutrients, sediments, and toxic substances. Nutrient enrichment by sewage effluent may enhance benthic algal biomass and primary production in the water column. Increased primary production in the water column favours benthic filter-feeding invertebrates which, with the benthic algae, may out-compete corals and other reef-building organisms. Anthropogenic inputs of dissolved nutrients and organic particulate matter may also depress oxygen levels. While heavy sediment loads on corals may be lethal, lesser quantities may inhibit growth, causing changes in the growth forms of colonies, decreasing coral cover, altering species composition of reef-building organisms, and inhibiting coral recruitment. Toxic substances may induce metabolic changes in corals, decrease rates of growth and reproduction, or reduce viability of corals.

Recommendation: It is strongly recommended that Bonaire invest in appropriate sewage treatment facilities to improve water quality and increase the resilience of its valuable coral reefs. It is also recommended that a water quality monitoring program be set up and sustained.

Damselfish

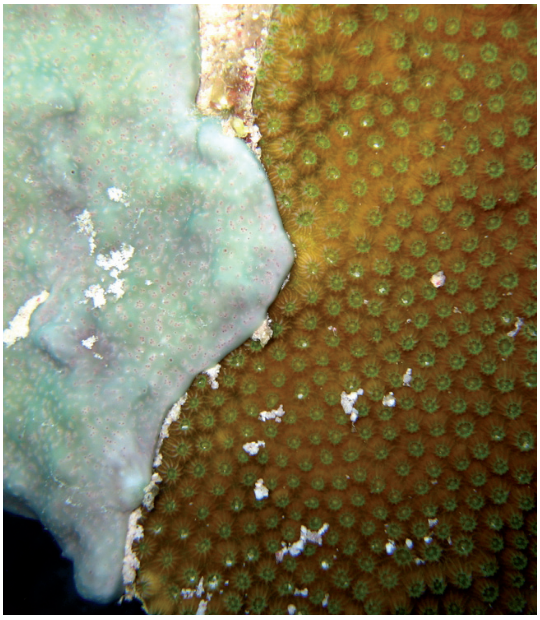


Damselfish protecting its algal yard. These territorial fish kill live coral to maintain and expand their algal yards

Territorial damselfish are a fish species that ‘garden’ algal turf ‘yards’ which they defend for food. Unfortunately, they maintain and expand their yards by killing corals. Populations of territorial damselfish have been observed to have increased recently (Steneck et al, 2008) and are causing coral mortality in many areas of Bonaire. This population increase hampers coral reef resilience and can stop reefs from recovering from stress and mortality events. Increasing damselfish populations is likely linked to overfishing of predators that feed on as there is a negative correlation between damselfish (*Stegastes planifrons*) and predator biomass, as shown by Graph 4.5.7.

Recommendation: It is recommended that the fishing of predatory fish species on Bonaire’s coral reefs be controlled and managed to a sustainable level to prevent population explosions of prey fish capable of modifying the reef habitat.

School of predatory snappers. It is important to maintain populations of predatory fish such groupers or snappers in order to maintain a balanced population on Bonaire’s reefs.

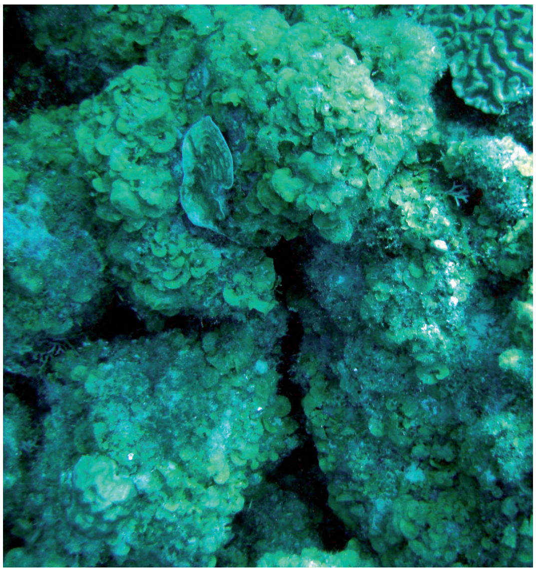


Tridemnum *(left) overgrowing live coral (right)*

Trididemnum* and *Lobophora

Trididemnum solidum cover, a tunicate that competes with and overgrows coral, has increased in northern sites (graphs 4.4.2 and 4.4.3) and in deeper sections of the reef. *Lobophora variegata* cover, a brown macroalgae that also smothers and overgrows coral, has also been observed to have increased in sites around the island (graphs 4.4.4 and 4.4.5). *Lobophora* population increases could be natural population cycles, but could also be linked to decreasing water quality and nutrient influx from land (e.g. septic tank leaching, fertilization by erosion of iron rich geological structures). *Trididemnum*, on the other hand, is possibly an invasive species.

Recommendation: It is recommended that the populations of *Trididemnum* and *Lobophora* are closely monitored and the factors contributing to the unnatural abundance of these coral-overgrowing organisms should be studied and then eliminated.



Brown algae Lobophora *overgrowing live coral*

2.3 Summary

Bonaire's economy is dependent on tourism, with between 50 and 70% of the island's economy attributed to this sector. 74,000 tourists visited the island in 2008, and of these approximately 52,000 used the BNMP and 36,000 were SUBA divers. Bonaire is known as a diver's paradise and is a major destination for North American divers, who make up 34% of all arrivals (DEZA, 2008). Because coral reefs are the major attraction for most tourists, their health and attractiveness to SCUBA divers could directly influence Bonaire's economy. Therefore, protecting this valuable natural resource is crucial for the livelihoods of the island's inhabitants and there is much to lose economically (as well as in terms of food security, biodiversity and other ecosystem services) and socially if the coral reefs become too degraded. Already some of Bonaire's coral reefs are at the tipping point of becoming functionally extinct, and we have identified Chachacha bordering Kralendijk as the most vulnerable site to become irreversibly damaged in the near future.

Therefore, protecting the resilience and health of Bonaire's coral reefs from the threats described in this report is of paramount importance to the island's welfare. The recommendations outlined above should be implemented in order to continue monitoring and finding solutions to protect the resilience of this valuable ecosystem. Bonaire should invest in appropriate sewage treatment facilities to improve water quality and increase the resilience of its valuable coral reefs. It is also recommended that a water quality monitoring program be set up and sustained. Fishing of predatory fish species on Bonaire's coral reefs should also be controlled and managed to a sustainable level to prevent population explosions of prey fish such as damselfish capable of modifying the reef habitat. *Trididemnum* and *Lobophora* should also be closely monitored and the factors contributing to the unnatural abundance of these coral-overgrowing organisms should be studied and then eliminated. Some of these threats are Bonaire-specific (damselfish, *Trididemnum, Lobophora*), so even though they may not be recognized as threats to coral reefs at a global scale it is crucial for managers to understand and take into account these local factors that influence coral reef resilience when designing and implementing management plans and monitoring programmes.

3. Detailed Methodology

3.1 Survey methods

Benthic cover

Benthic photographs were used to assess benthic cover. Photos were taken from about 1 meter above the substrate and were later analyzed using Coral Point Count software. Categories used were the following, with coral and algae further identified to the genus level.

Table 5 - Benthic categories for identification

Invertebrates	Algae	Other	Substrate
Coral	Fleshy algae	Microbial	Rock
Recent Dead Coral	Algal Assemblage	Seagrass	Rubble
Soft coral	Coralline Algae	Unidentified	Sand
Invertibrates	Halimeda		
Sponge			

Coral population structure

Coral population structure was quantified using fixed size classes of corals, from the smallest recruits to the largest adults at a site. A belt transect 25 m long and 1 m wide was used to record the number of colonies larger than 10 cm. For corals smaller than 10 cm, subsampling was done using six 1 m^2 quadrats at the 0, 5, 10, 15, 20, and 25 marks. Only colonies whose center lies within the sampled units were counted – large colonies with their center outside the transect were ignored. A 1 m stick was used to help guide estimation of transect width, mark the 1 m^2 quadrats and help guide size estimation of coral heads (Table 6a). Genera that covered a range of bleaching susceptibility from high to low (Table 6b), and that are generally common on Caribbean reefs were selected.

Table 6a - Size classes of corals for size class measurements.

Size classes (cm)	Sampling method
(1) 0-2.5 *(2) 2.5-5* *(3) 5-10*	Recorded in six 1m^2 quadrats per transect
(4) 10-20 *(5) 20-40* *(6) 40-80* *(7) 80-160* *(8) 160-320* *(9) > 320*	Recorded in 25*1 m belt transects

Table 6b - Selected species in classes of bleaching susceptible, intermediate and resistant.

Susceptible	Intermediate	Resistant
Acropora palmata *Acropora cervicornis* *Eusmilia fastigata* *Meandrina meandrites* *Montastrea annularis* *Montastrae faveolata* *Montastrea franksii*	*Agaricia lamarki* *Diploria clivosa* *Diploria labyrinthiformis* *Diploria strigosa* *Millepora spp* *Mycetophyllia spp* *Porites asteroides* *Siderastrea siderea* *Stephanocoenia intersepta*	*Colpophyllia natans* *Dendrogyra cylindrica* *Madracis decactis* *Madracis mirabilis* *Montastrea cavernosa* *Porites porites* *Agaricia agaricites*

Replication of transects depended on logistics at a site and the complexity of the coral community, varying between 2 and 4.

Fish community structure

Fish surveys focused on herbivore functional groups following Green et al (2009) and see IUCN-CCCR (2008), with size classes also estimated for other fish. Herbivory is important as it limits competition and obstruction by algae. Four functional groups of herbivorous fishes were used: non-denuding, denuding, excavators/scrapers, browsers (Table 7), each playing a unique ecological role in coral reef resilience.

Table 7 - Functional groups of herbivorous and predatory fishes recorded in this survey.

Functional group	Taxonomic groups	Function and notes
Non-denuding	Territorial Pomacentridae	Habitat engineers, create algal 'yards' on live coral and protect these yards against other herbivores. Responsible for coral mortality and retarded coral recovery.
Denuding	Acanthurids, Microspathadon	Algal control. Remove epilithic algal turf from the reef substratum, but do not scrape the surface, prevent coral overgrowth and shading by macroalgae.
Excavators, scrapers	Scarids	Bioerosion, colonization surfaces. Remove algae, sediment and other material by closely cropping or scraping the substrate.
Browsers	Chaetodons, Pomacanthids	Algal control. Feed on macroalgal fronds, reduce coral overgrowth and shading by macroalgae.
Carnivores	Lutjanidae, Haemulidae, Serranidae, Carangidae, Sphyraenidae	Predate on other fish, including herbivores. Responsible for keeping fish populations in check and avoiding population explosions.

Sampling was done in three 50 x 5 m belt transects. The transects were separated by at least 5 to 10m from the end of the previous transect. All fish in the above categories were counted.

Resilience Indicators

Resilience indicators were measured or estimated during each sampling dive, generally towards the second half of the dive to allow time for familiarization with the site. The indicators and their overall grouping is shown in the table below.

Table 8 - Indicators recorded.

Group	Factor	Variable
1-Cover	Coral Algae Substrate	Hard coral Gorgonians Fleshy Algae Dead coral with algae Coralline algae Rubble
2-Physical	Substrate Cooling & flushing Shading & screening Acclimatization	Topogr. Complex. - micro Topogr. Compl. - macro Sediment texture Sediment layer Currents Wave energy/ exposure Deep water (30-50m) Depth of reef base Aspect Slope (degrees) Physical shading Canopy corals Visibility (m)/ turbidity Exposed low tide Ponding/pooling
3-Coral community	Size/age Condition	Largest corals (3) Coral bleaching Mortality-new Mortality-old Recovery-old Coral disease
4-Coral associates	Positive Negative	Branching residents Competitors Bioeroders (urchins, nonfish) Bioeroders (internal, spo) Corallivores (negative)
5- Fish groups	Herbivory Fishing	Browsers Denuding Excavating Non-denuding Predators
6-Anthropogenic	Water Substrate Fishing Management	Nutrient input Pollution (chemical) Pollution (solid) Turbidity/Sedimentation Physical damage Storm damage Destructive fishing Fishing pressure MPA Resources ICZM

A semi-quantitative 5-point scale was used for estimation of most of the indicators, except for those (such as temperature, visibility) that could easily be measured or estimated quantitatively. Classification of the 5-point scale was done using local and regional knowledge. In the 5-point scale general principles were to assign them as follows: minimum (1), maximum (5) and moderate (3) level for each indicator for the region of application, and intermediate levels of low (2) and high (4).

For analysis, two operations had to be applied to the raw data collected in situ:

- For variables measured quantitatively, transformations were applied to assign them to a 5 point scale for consistency in multivariate analysis of the data. In general terms, the distribution of values could be even across sites (resulting in even numbers of sites assigned to levels 1 to 5), concentrated around the middle (large number of sites at moderate level 3), or strongly skewed to one side (most sits high or low for a variable).

- In situ estimation of 5-point scales were done based on the parameter itself, ie. from low to high. For consistent multivariate analysis, some indicators had to be reversed so that all values 'good' for corals scored 5, and all values bad for corals scored 1. For example, algal levels in the field might have been scored '5' for high levels, but in analysis, this was recoded as '1', being bad for corals.

Variables like visibility were estimated during the dive, however are best quantified using continuous data recorders.

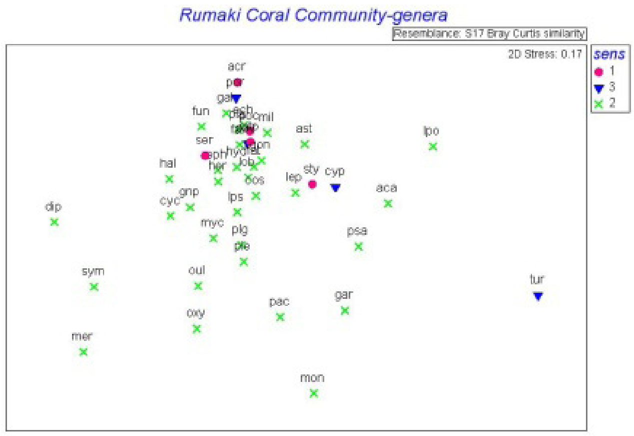
3.2 Analysis

Analysis proceeded through the following broad steps, for each dataset collected:

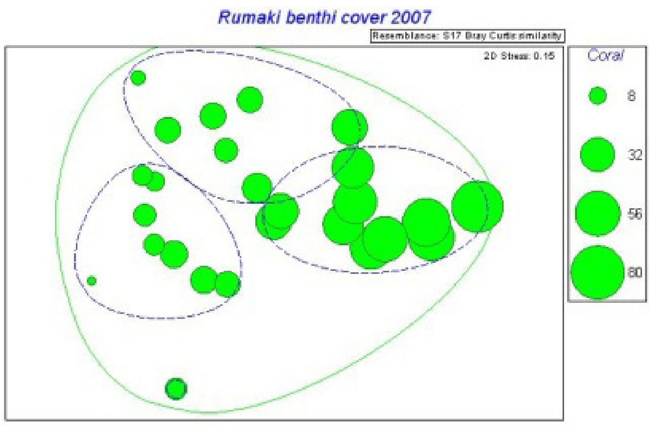
1) Calculation and plotting of basic distributions for each variable, across all study sites. These are done first to illustrate the basic patterns shown by individual variables and indicators

2) Multi-dimensional Scaling (MDS) analysis helps to reveal patterns in datasets that include multiple variables, and particularly usefulness where parametric tests (e.g. ANOVA) are not appropriate.

By projecting all variables onto x and y axes, an MDS plot helps illustrate which points are close to one another and which are distant. Thus the physical distance of points on the plot (Graph 3.2.1) illustrates their relative distance in the dataset. By superimposing a variable in the dataset on the points, where the size of a circle represents the magnitude of the variable, 'bubbleplots' (Graph 3.2.2) can help to illustrate which variables are most important in determining the relatedness among points on the plot. The circles around clusters of points illustrate significant groupings of sites, and help interpretation of the results.



Graph 3.2.1



Graph 3.2.2

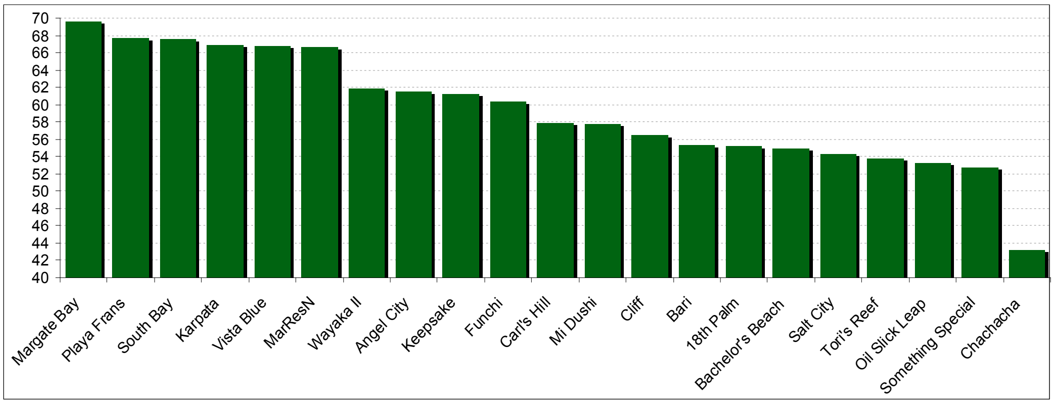
4. Detailed Results

Due to the complex datasets in this study, results and discussion will be presented together in numbered sections for each dataset, with more synthetic discussion and findings presented in section 3.

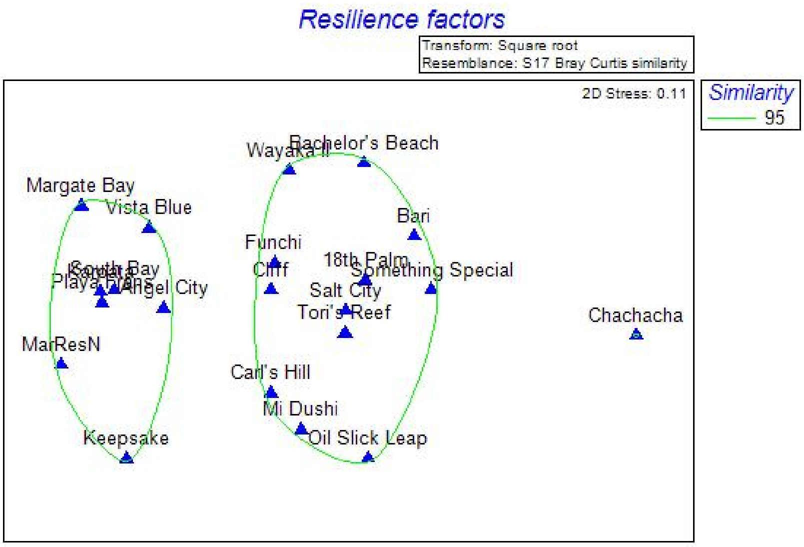
4.1 Resilence indicators

Table 9 : Each factor was scaled from 1 (poor conditions for corals) to 5 (good conditions for corals), and the sites ranked from highest overall resilience to the lowest.

Group	Explanation	Factor	Explanation
Cover	Benthic cover	Benthic	Benthic cover – combined estimates of hard and soft corals, and algae
Coral	Condition of coral community	Current	Current status shown by bleaching, disease, sexual recruitment and fragmentation of corals.
		Historic	Past impacts to coral community as shown by evidence of past mortality, evidence of recover potential and size class distributions
Ecological	Broader ecological factors that affect corals	Negative	Negative associates of corals – such as predators and epiphytes on coral surfaces
		Positive	Positive associates of corals, such as obligate feeders (butterflyfish) and invertebrates and fish in branching corals.
		Herbs	Herbivorous fish populations
Physical	Environmental and habitat features that affect corals	Acclimatization	Past and present temperature dynamics that may protect corals by acclimatization/adaptive responses
		Cooling & flushing	Degree of cooling/flushing of deeper and/or oceanic waters
		Shading & screening	Degree of shading or screening of corals by turbid water, reef slope, canopy corals, etc.
		Substrate	Substrate quality, such as sediment type and thickness, amount of rubble.
Anthropogenic	Human pressures on reef sites	Fishing	Degree of fishing, shown by fish populations and/or other data
		Substrate	Anthropogenic alterations to substrate – from sediment, damage, etc.
		Water	Anthropogenic alterations to water quality – from runoff, pollution, etc.

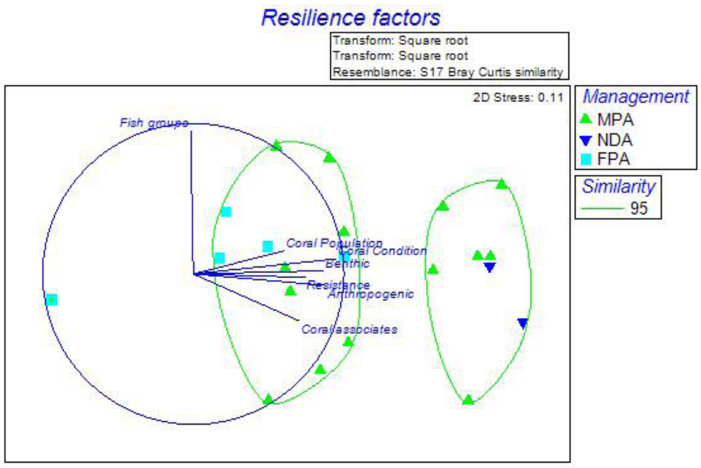


Graph 4.1.1



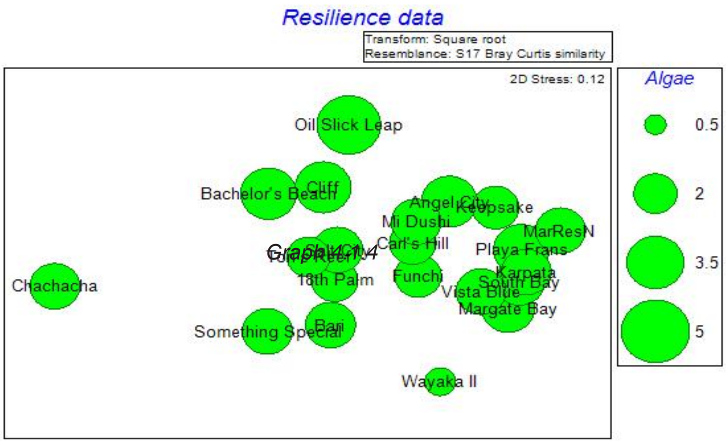
Graph 4.1.2

The graph 4.1.1 shows the aggregate scores of 1-5 resilience indicators for all sites and the graph 4.1.2 shows sites clustered together according to their relative resilience scores. It is clear that there are 3 defined clustered according to the sites' relative resilience. The 'high' resilience group includes Margate Bay, Playa Frans, South Bay, Karpata, Vista Blue and Marine Reserve North. The 'middle' resilience group includes Wayaka II, Angel City, Keepsake, Playa Funchi, Carl's Hill, Mi Dushi, Cliff, Bari, Eighteenth Palm, Salt City, Tori's Reef, Oil Slick Leap and Something Special. The 'low' resilience group includes only one site, Chachacha.



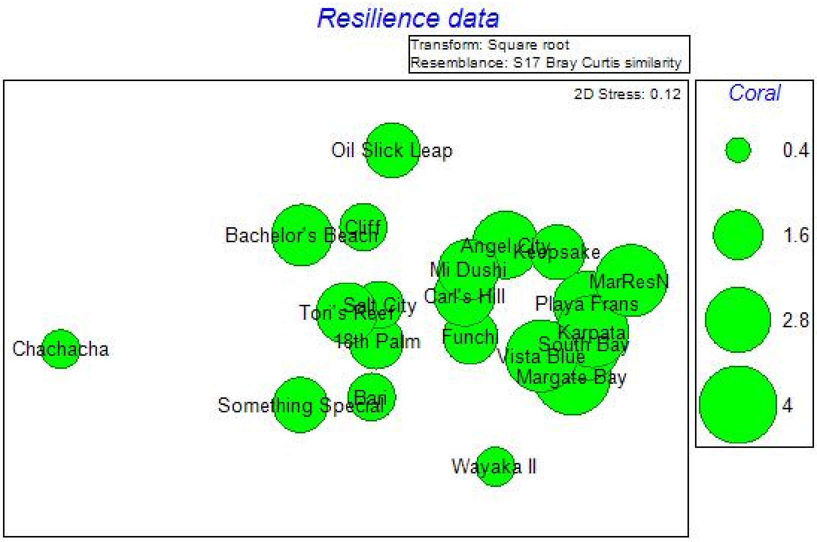
Graph 4.1.3

The plot 4.1.3 above shows the spread of sites according to their resilience scores and protection status. The vectors show resilience factors that are driving the differences in resilience. Sites to the left of the plot have lower resilience scores, sites to the right have higher resilience scores. It is clear to see that Fish Protected Areas fall to the left of the plot, and have lower resilience scores. This may be because the FPAs are located close to the urban centre Kralendijk and thus more vulnerable to additional anthropogenic stressors. FPAs are negatively correlated with all resilience factors except for 'Fish Groups', indicating that at least fish populations in FPAs are moving in the right direction. Conversely, No Diving Areas (NDAs) have the highest resilience scores and correlations with resilience factors. NDAs are designated to the north of the island, far from Kralendijk and anthropogenic stressors. Removing the additional stress from divers seems to be working well, and these sites appear to be among the most resilient to stress.



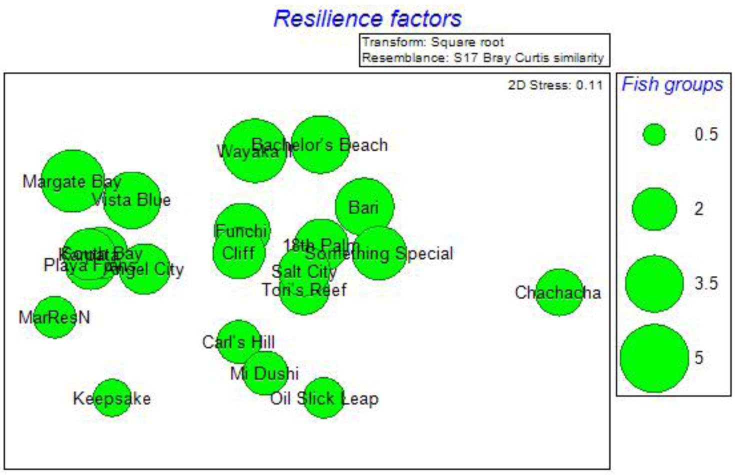
Graph 4.1.4

The bubble plot above (4.1.4) shows the relative effect of algal populations on the overall ecological resilience of sites. Large bubbles mean that algal populations are favorable for resilience, while small bubbles mean they are unfavorable. It can be observed that the sites with most unfavorable algal populations for include Wayaka II, Something Special, Bari and Chachacha.



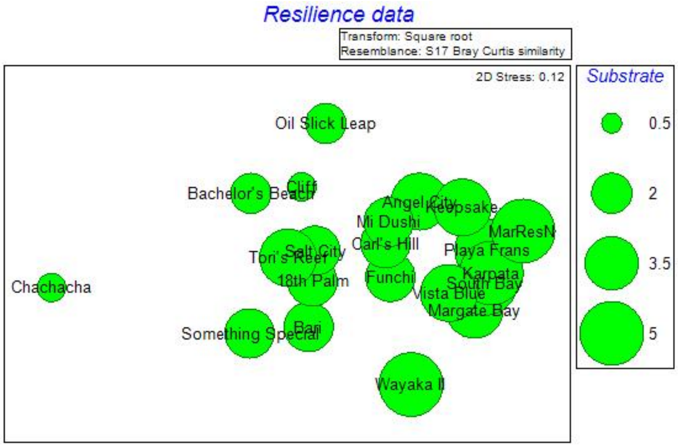
Graph 4.1.5

The bubble plot 4.1.5 shows the relative effect of coral populations on the overall ecological resilience of sites. Large bubbles mean that coral populations are favourable for resilience, while small bubbles mean they are unfavourable. It can be observed that Wayaka II and Chachacha have the unhealthiest, least resilient coral populations, while Marine Reserve North and Playa Frans have the healthiest, most resilient populations.



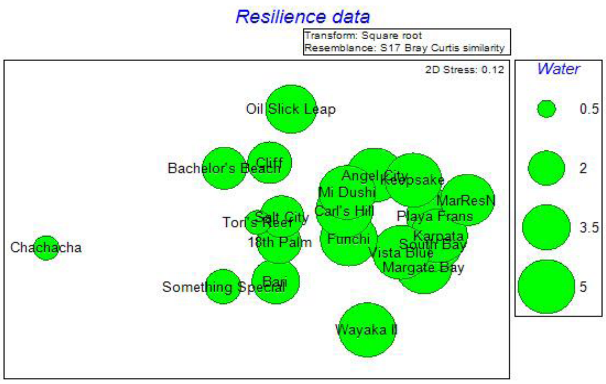
Graph 4.1.6

The bubble plot 4.1.6 shows the relative effect of fish populations on the overall ecological resilience of sites. Large bubbles mean that fish populations are favourable for resilience, while small bubbles mean they are unfavourable. It can be observed that fish populations are most favourable at Margate Bay and Wayaka II, while they are least favourable at Keepsake.



Graph 4.1.7

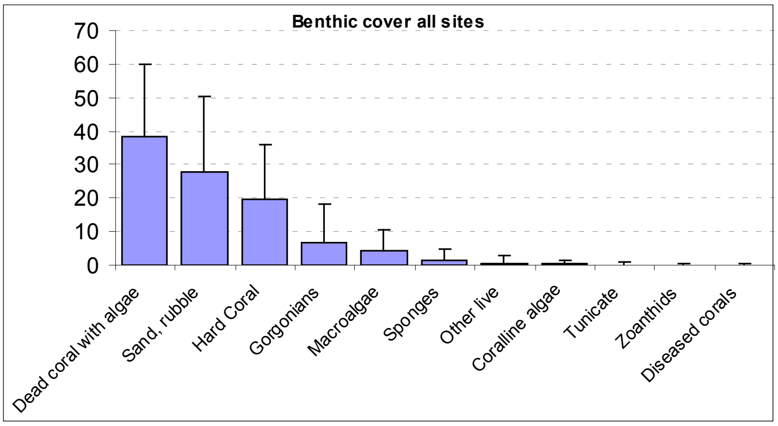
The bubble plot 4.1.7 shows the relative effect of substrate conditions on the overall ecological resilience of sites. Large bubbles mean that substrate conditions are favourable for resilience, while small bubbles mean they are unfavourable. It can be observed that Chachacha and Cliff have the most unfavourable substrate conditions, while sites to the right of the plot have the most favourable conditions.



Graph 4.1.8

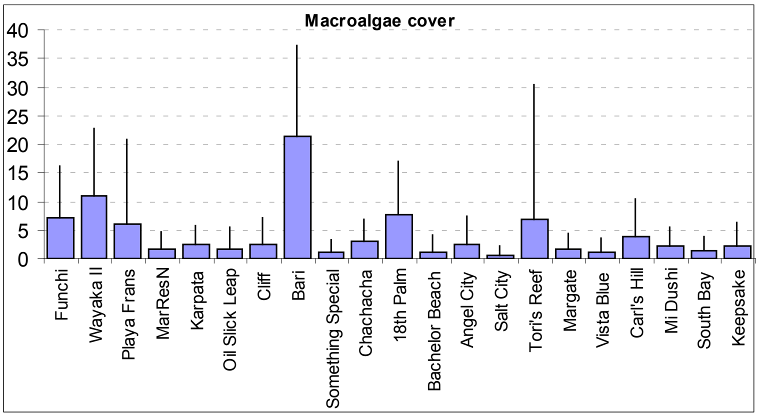
The bubble plot 4.1.8 shows the relative effect of water quality on the overall ecological resilience of sites. Large bubbles mean that water quality is favourable for resilience, while small bubbles mean that it is unfavourable. It can be observed that sites close to the urban centre Kralendijk such as Chachacha, Something Special, Cliff or Bachelor's Beach have the least favourable water quality, while sites further away from Kralendijk have more favourable water quality conditions.

4.2 Benthic cover

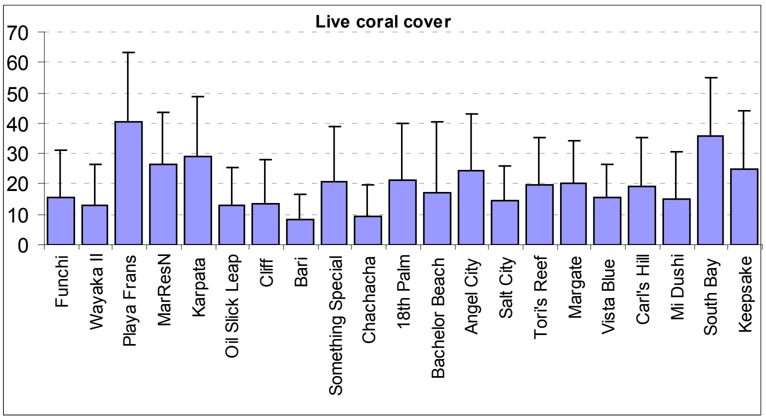


Graph 4.2.1

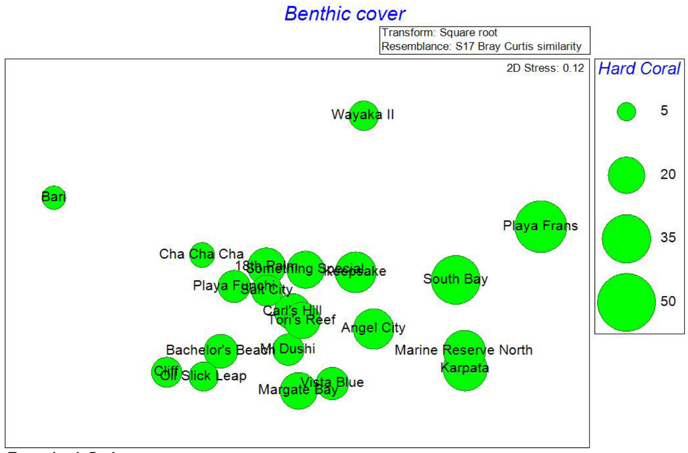
Dead coral overgrown by turf algae dominates the substrate, with an average cover of 38.2% (Graph 4.2.1). This may reflect coral mortality caused by damselfish 'yards' on large coral heads. Macroalgae cover is low, averaging 4.2%, indicating good herbivory levels. Hard coral cover averages 19.8%, which is high for the Caribbean region, however the high incidence of dead coral overgrown by algae is worrying.



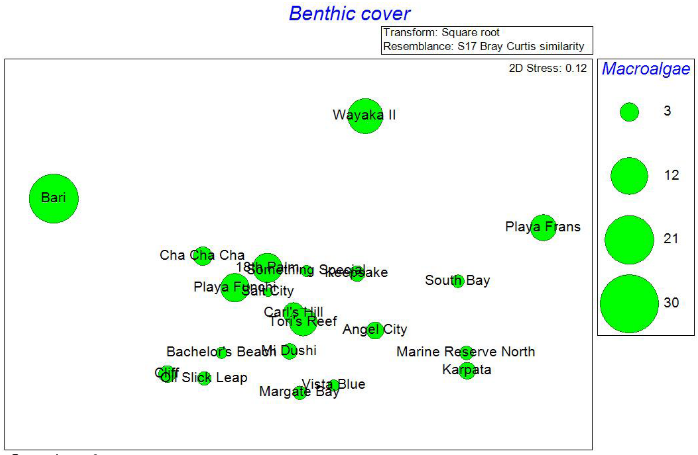
Graph 4.2.2



Graph 4.2.3

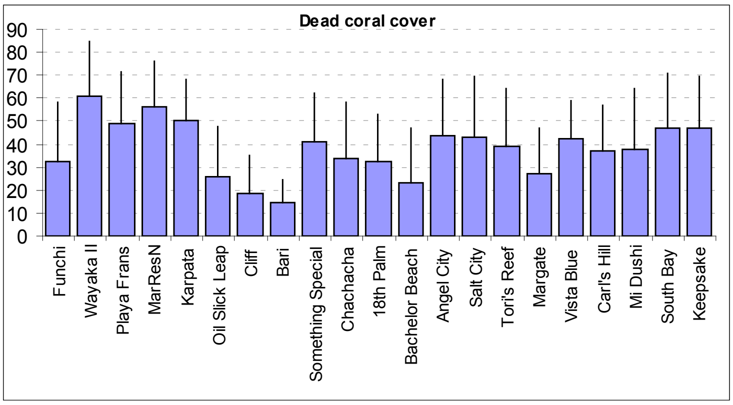


Graph 4.2.4

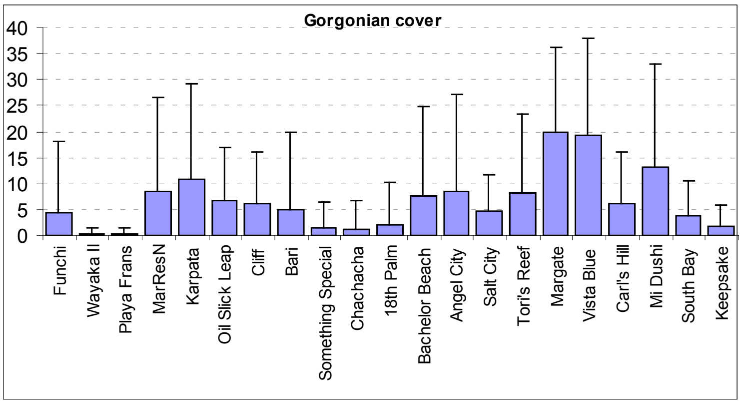


Graph 4.2.5

The bar graph 4.2.2 shows show that hard coral cover ranges from 40.2% in Playa Frans to 8.4% in Bari. The bar graph 4.2.3 shows that macroalgae cover ranges from 21.3% in Bari to 0.7% in Salt City. Macroalgae cover is low (under 10%) in every site except for Bari which exhibits 5 times the average macroalgal cover and appears to be suffering from macroalgal overgrowth and low coral cover (8.2% - the lowest of the sites surveyed). The highest hard coral cover sites are situated either on the northern coast of Bonaire (Playa Frans, Karpata, Marine Reserve North) or Klein Bonaire (South Bay, Keepsake). These sites also all exhibit among the lowest macroalgae cover (below 6%). The bubble plots (Graphs 4.2.4 and 4.2.5) provide a nice visual representation of the balance between hard coral and macroalgae cover.



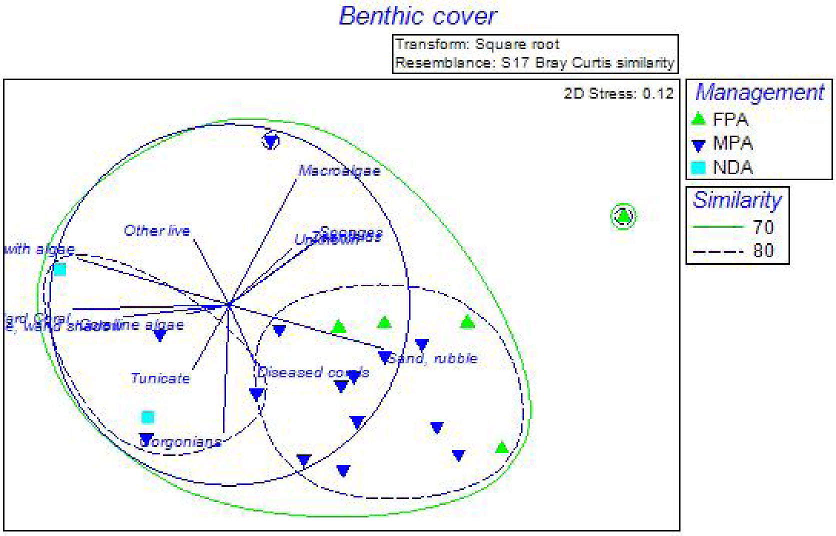
Graph 4.2.6



Graph 4.2.7

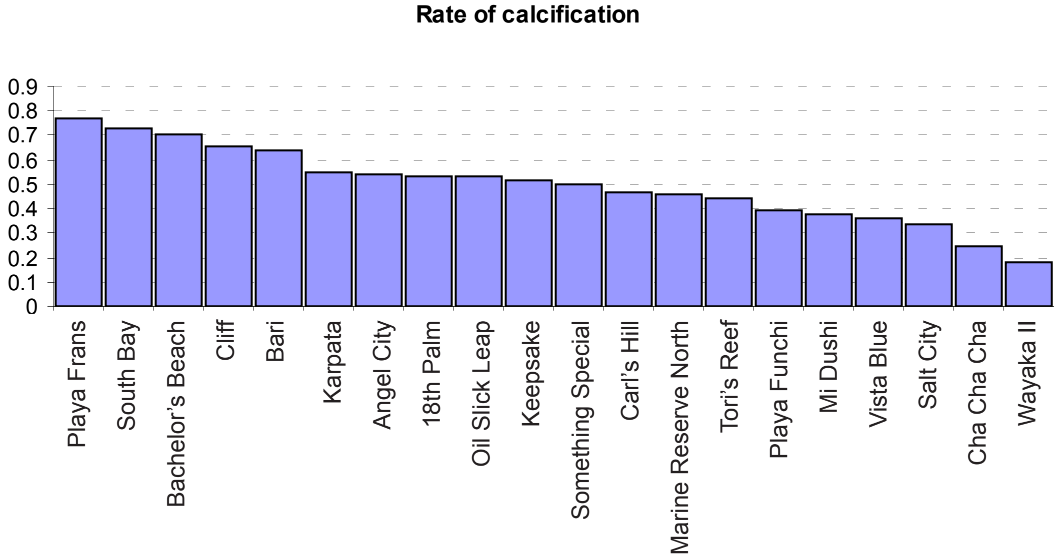
The graph 4.2.6 shows the cover of dead coral cover by site. Dead coral cover ranged from 60.9% in Wayaka II to 14.2% in Bari. Most sites exhibited high cover of dead coral overgrown by turf algae, and only 2 sites exhibited less than 20% cover of dead coral (Cliff and Bari) while half the sites exhibited dead coral cover of 40% or above. This high coral mortality is suspected to reflect increasing damselfish populations, storm damage from Hurricane Omar and declining water quality.

The graph 4.2.7 shows gorgonian cover by site. Gorgonian cover varies from 19.7% (Margate Bay) to 0.2% (Wayaka II and Playa Frans). Gorgonian cover is highest in southern sites (Margate Bay, Vista Blue) and lowest in northern sites (Wayaka II and Playa Frans), indicating a broad north-south gradient of decline in gorgonian cover.



Graph 4.2.8

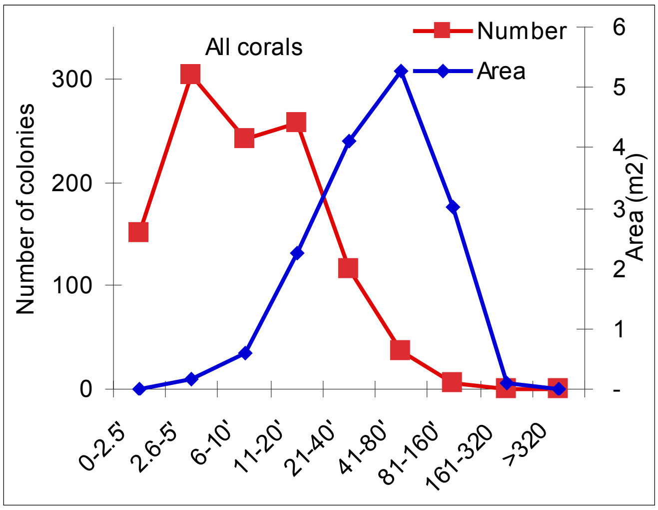
Multi-Dimensional Scaling analysis shows Bari as an outlier due to its high macroalgae cover (Graph 4.2.8). It also shows how that differently managed sites are characterized by different substrate covers. Fish Protected Areas are assigned close to the urban centre Kralendijk where the coral reef is most impacted by anthropogenic stressors, and are thus characterized by higher macroalgae and rubble cover. No Diving Areas tend to have the highest coral cover, and also the highest cover of dead coral overgrown by turf algae.



Graph 4.2.9

The graph 4.2.9 shows the calcification rates calculated for different reefs. The calcification rate represents the ratio of calcifying versus non-calcifying substrates on the reef. A calcification rate higher then 1 would indicate a growing reef, with more calcifying organisms (live coral) than non-calcifyers (other substrate types), while a calcification rate of less than 1 would indicate a reef that is not growing at an optimal level due to the dominance of non-calcifyers over calcifyers. Playa Frans and South Bay have the highest calcification rates (0.77 and 0.73 respectively) while Wayaka II and Chachacha and Wayaka II have the lowest calcification rates (0.25 and 0.18 respectively).

4.3 Coral population structure

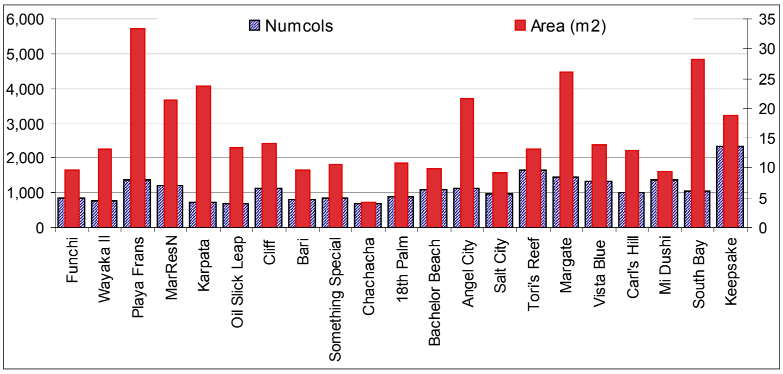


Graph 4.3.1

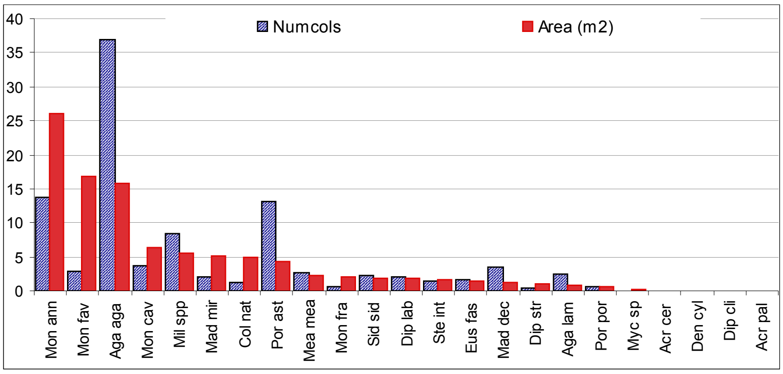
The distribution of size classes is shown by number of colonies, and by area of colonies for all size classes (Graph 4.3.1). On average, there were 1113 colonies in an area of $100m^2$, corresponding to 15.6 m^2 of coral colony surface.

The dominant size class by area was 41-80 cm. The low contribution of colonies larger than 1.6 m indicates that colonies are not reaching extreme old age due to some stress, or the low number of large colonies could indicate a mass mortality event in the past and that the reef is in a recovery phase.

The low number of coral recruits (colonies 0-2.5 cm in size) is indicative of low coral reproduction and recruitment for this cohort and could be linked to a recent stress and mortality event (e.g. Hurricane Omar in 2008).



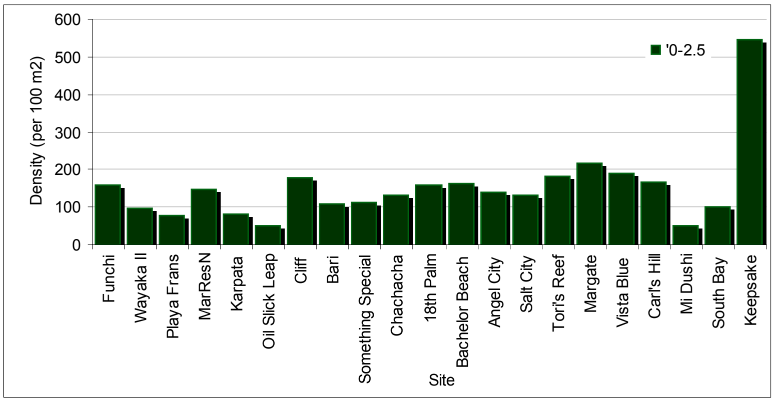
Graph 4.3.2



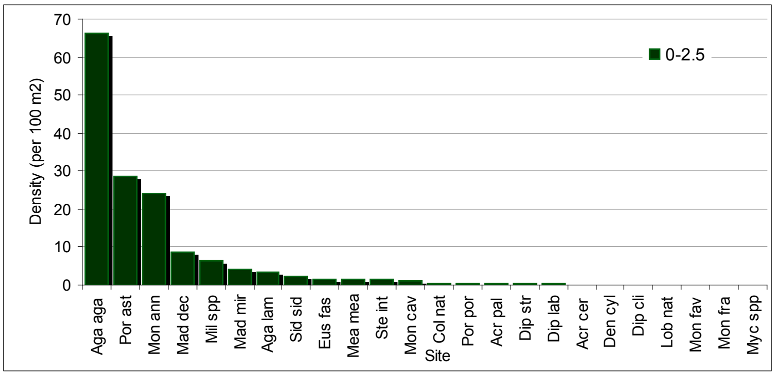
Graph 4.3.3

The table 4.3.2 shows the total number of colonies and the total coral cover area per site. The highest coral cover and number of colonies are in northern sites (Playa Frans, Marine Reserve North, Karpata), Klein Bonaire sites (South Bay and Keepsake) and a couple of southern sites (Angel City and Margate Bay). Sites are ordered from north to south and it is clear to see that sites closest to the urban centre Kralendijk (indicated with a thick horizontal bar), and thus impact from coastal development, have the lowest coral covers (Bari, Something Special, Chachacha, 18th Palm, Bachelor's Beach). Keepsake exhibits the highest number of coral colonies despite not having the largest area, indicating a dominance of smaller class sizes.

The figure 4.3.3 shows the total number of colonies and total cover area per coral species. Area is dominated by the slow-growing massive *Montastrea annularis* and *Montastrea faveolata*. The number of colonies is dominated by *Agaricites agaricites*. No *Acropora cervicornis* or *Acropora palmata* colonies were recorded, indicating the high impact of Hurricane Omar on these fragile branching species.



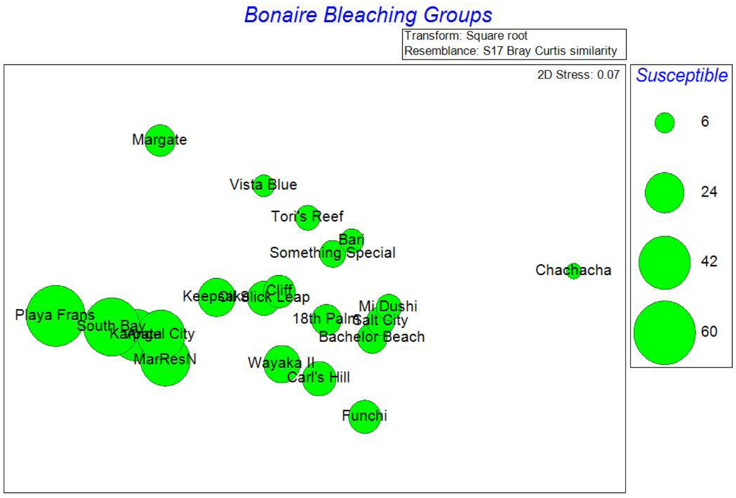
Graph 4.3.4



Graph 4.3.5

The table 4.3.4 shows total density of coral recruits (colonies sized 0-2.5 cm) per site. Keepsake stands out as having the highest density of coral recruits (545 recruits per 100 m2) while Oil Slick Leap and Mi Dushi have the lowest recruitment rates (50 recruits per 100 m2). In general, there is a gradient of recruitment from north to south, with lower recruitment in northern sites and higher recruitment in southern sites. This is because there is a higher abundance of brooding species (corals that reproduce with internal fertilization, releasing only sperm which is negatively buoyant and can harbor unfertilized eggs for weeks) in the south. Keepsake is located on the eastern side of Klein Bonaire in the channel between Bonaire and Klein Bonaire, and this location could promote high recruitment due to eddies that could occur in the channel leading to higher retention time and recruitment success.

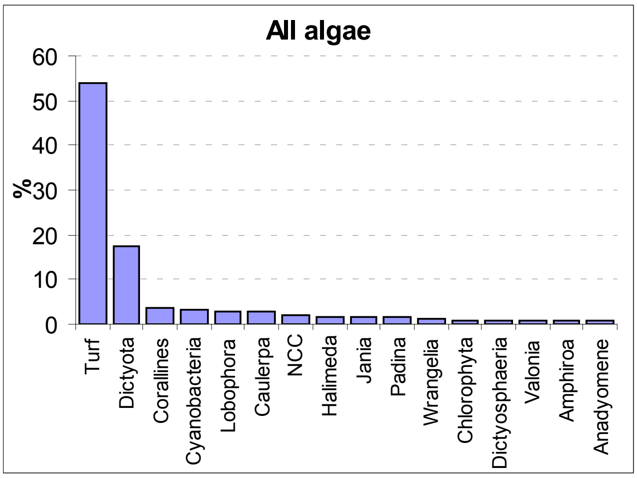
The table 4.3.5 shows total density of recruitment per coral species. Recruitment is largely dominated by *Agaricites agaricites*, followed by *Porites asteroids*.



Graph 4.3.6

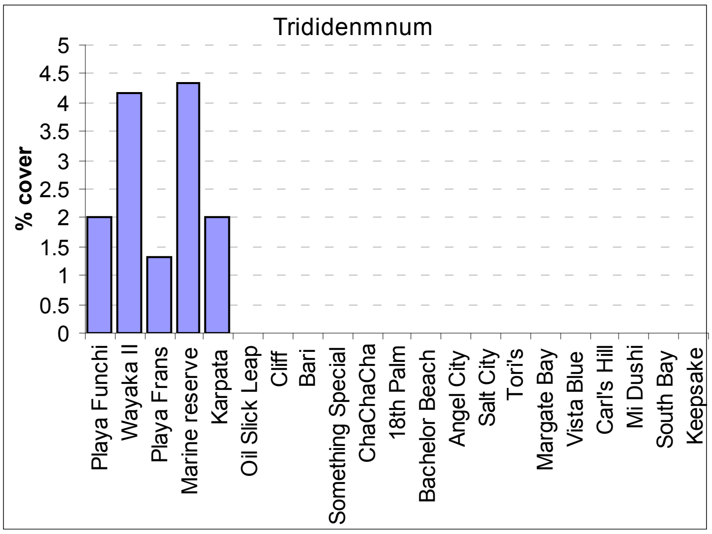
This bubble plot (4.3.6) to the left shows the density of susceptible coral species (for the purpose of this survey as follows, *Acropora palmata, Acropora cervicornis, Eusmilia fastigata, Meandrina meandrites, Montastrea annularis, Montastrae faveolata, Montastrea franksii*) in different sites. The more 'pristine' sites that have higher cover of susceptible species are Playa Frans, Marine Reserve North, South Bay and Margate Bay, all sites away from impact from urban and coastal development. The high impact site Chachacha is clearly an outlier due to its low coral cover.

4.4 Algae Populations

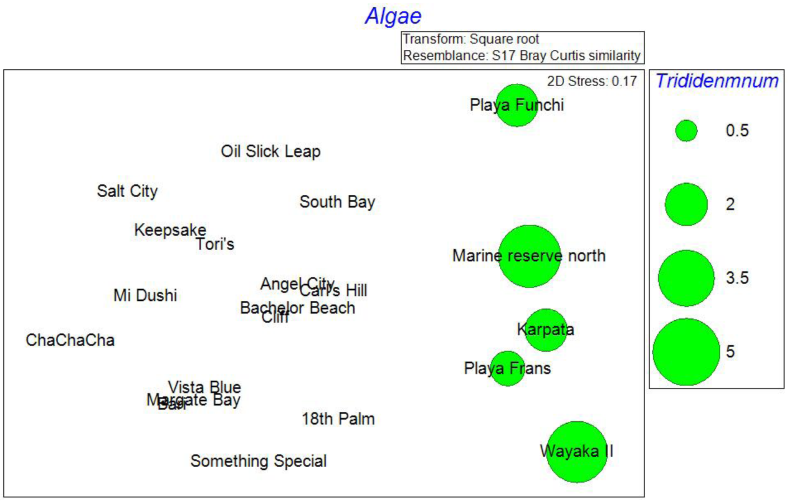


Graph 4.4.1

The graph above (4.4.1) shows that algal populations in Bonaire's reefs are dominated by turf algae, which covers 50.6% of the substrate. This is largely due to coral mortality and damselfish creating turf algae 'yards' on coral heads. The most common macroalge is *Dictyota*, a brown algae covering 8.0% of the substrate. Coralline algae cover is low at 3.6%.

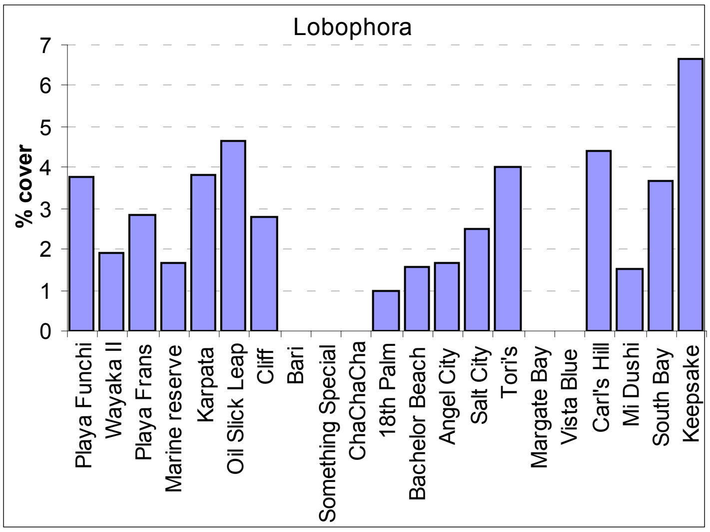


Graph 4.4.2

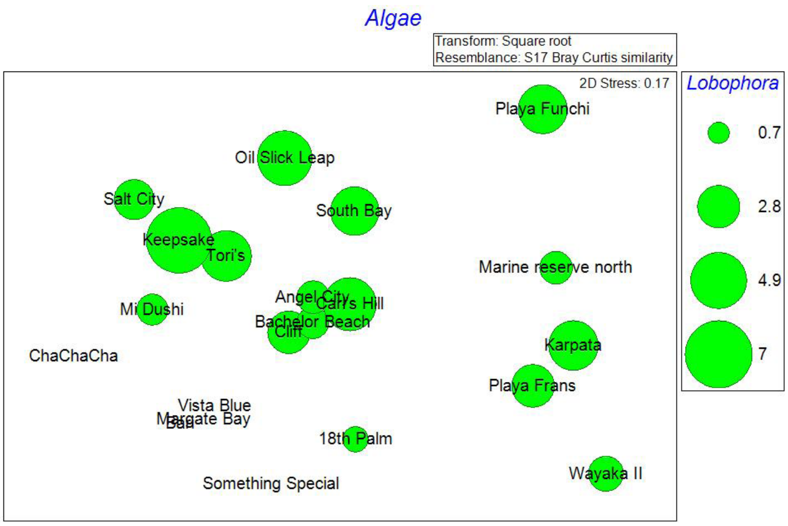


Graph 4.4.3

It is worth noting the cover of Lobophora (3.0%) a brown algae, and Trididemnum (2.8%) a tunicate that competes with corals, which although small at this sampling depth (10m) have been noted to be increasing, especially in deeper sections of the reef. The table 4.4.2 shows the % cover of Trididemnum, a tunicate that competes with overgrows hard coral. The bubble plot 4.4.3 provides a visual representation of relative Trididemnum cover. It is clear that Trididemnum is affecting only northern sites at this sampling depth, with highest covers in Marine Reserve North (4.3%) and Wayaka II (4.2%) and no Trididemnum present south of Karpata. There is anecdotal evidence that Trididemnum covers increase with depth and are smothering corals.



Graph 4.4.4

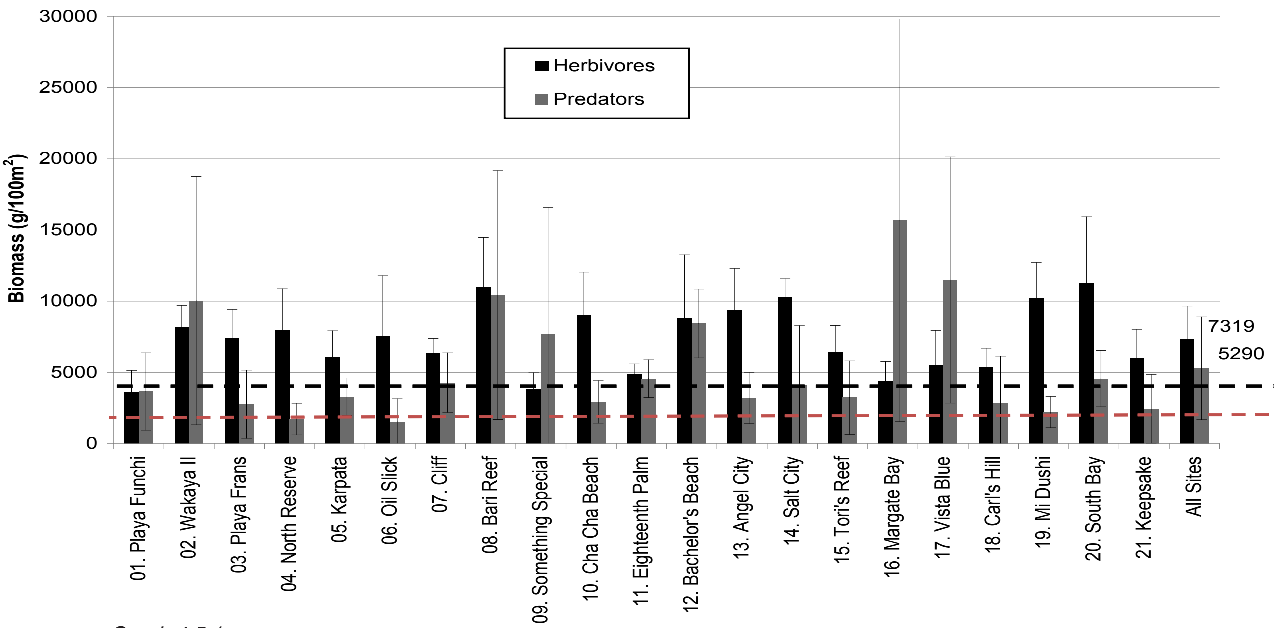


Graph 4.4.5

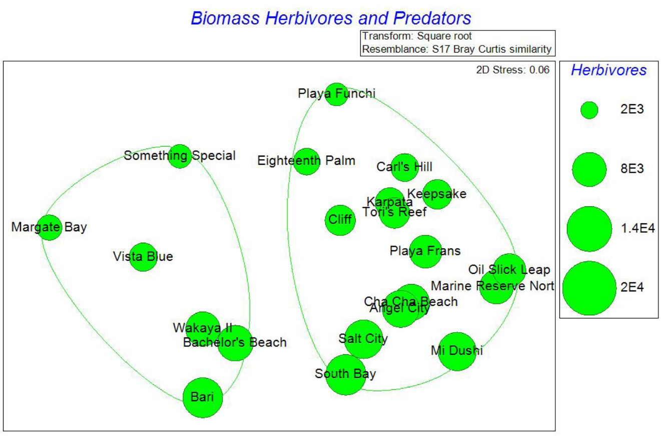
The graph 4.4.4 shows Lobophora cover, a brown macroalgae which competes with and overgrows corals. The bubble plot 4.4.5 shows relative Lobophora covers between sites. The site with the highest Lobophora cover is Keepsake (6.7%) on Klein Bonaire, followed by Oil Slick Leap (4.7%) and Carl’s Hill (4.4%). There was no Lobophora found at sites close to Kralendijk such as Bari, Something Special and Chachacha, and there was also very low cover at 18th Palm (1.0%).

4.5 Fish community structure

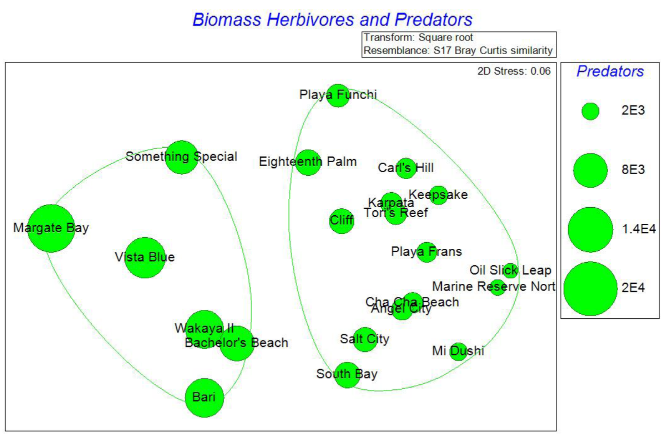
The graph 4.5.1 (below) shows herbivorous and predatory fish biomass for all sites surveyed. The bubble plot on the bottom left (4.5.2) shows relative biomass of herbivores per site, while the bubble plot on the bottom right (4.5.3) shows relative biomass of predators per site. Biomass of herbivores is higher than predators in most sites except for a few exceptions, notably Margate Bay and Vista Blue where large schools of grunts caused high numbers for predator biomass. Overall, average biomass for herbivores was 7319 g/m2 compared to 5290 g/m2 for predators. Sites with highest herbivore biomass were Bari Reef (an FPA), South Bay, Mi Dushi and Salt City. Margate Bay and Vista Blue had the highest predator biomass. The horizontal dotted lines represent average values.



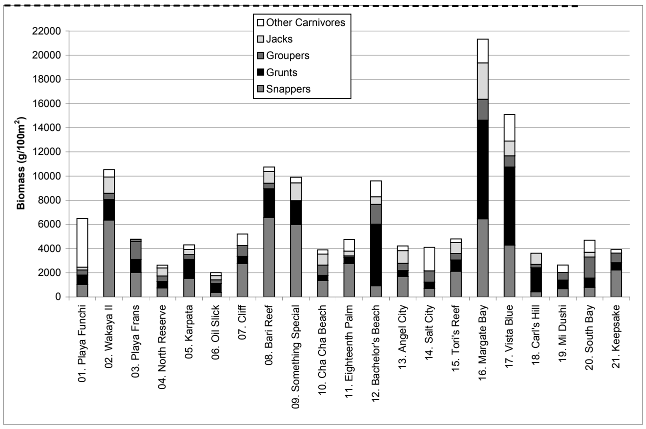
Graph 4.5.1



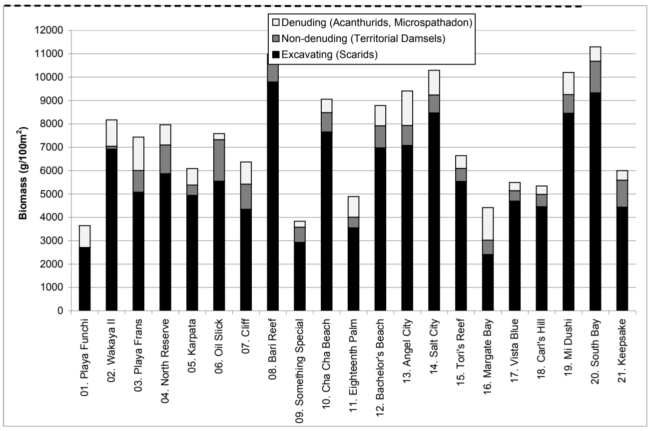
Graph 4.5.2



Graph 4.5.3

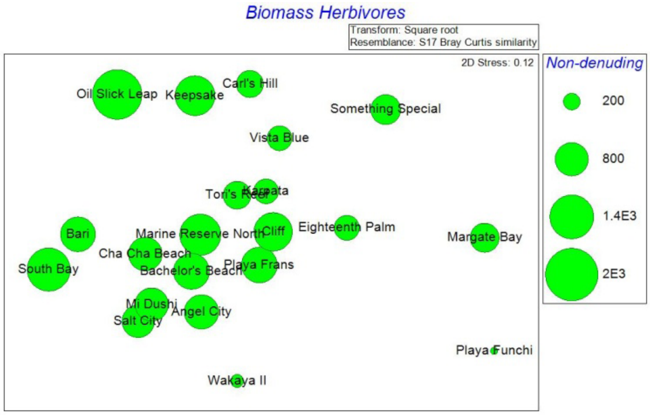


Graph 4.5.4

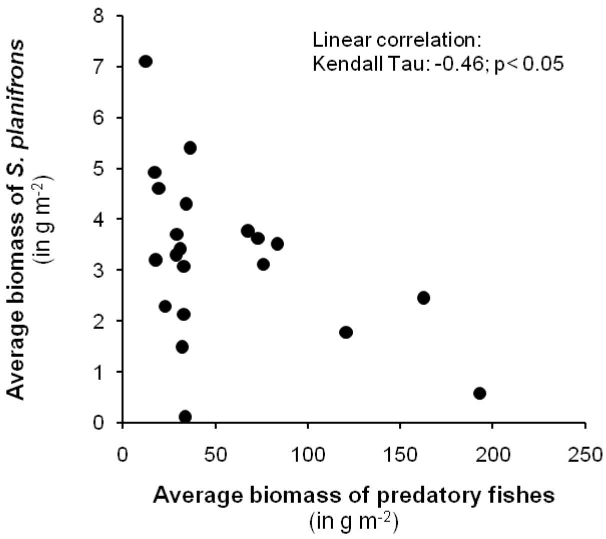


Graph 4.5.5

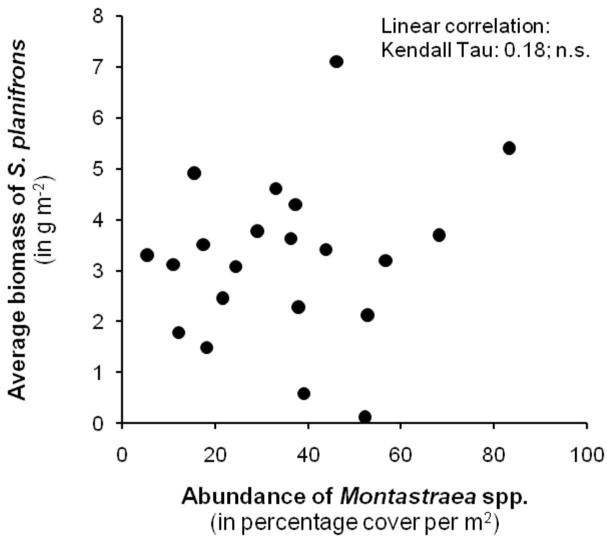
The graph on the above left shows the biomass of different predatory fish types by site. The graph on the above right shows the biomass of different herbivorous fish functional groups by site. The biomass of predators in most sites is dominated by snappers and grunts, and large populations of these predators give Margate Bay (over 21,000 g/100m2) and Vista Blue (over 15,000 g/100m2) in the south the largest predator biomass of all sites. Sites with the lowest predator biomass are Oil Slick Leap, Marine Reserve North and Mi Dushi. Sites with the highest grouper biomass are South Bay, Margate Bay, Bachelor's Beach and Playa Frans. The large majority of herbivorous biomass is made up of excavating scarids (parrotfish). Bari Reef, South Bay, Mi Dushi and Salt City have the highest scarid biomass, all over 8000 grams per 100m2. However Oil Slick Leap (1777 g/100m2) and South Bay (1351 g/100m2) have the highest damselfish biomass.



Graph 4.5.6



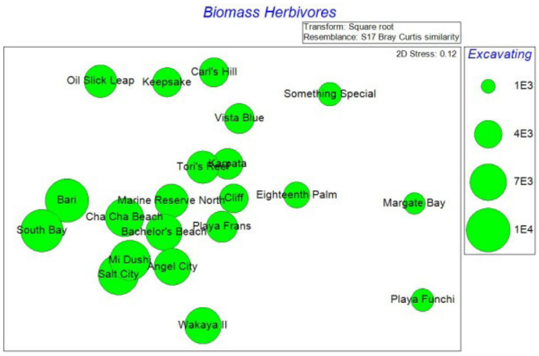
Graph 4.5.7 (from Vermeij et al in press)



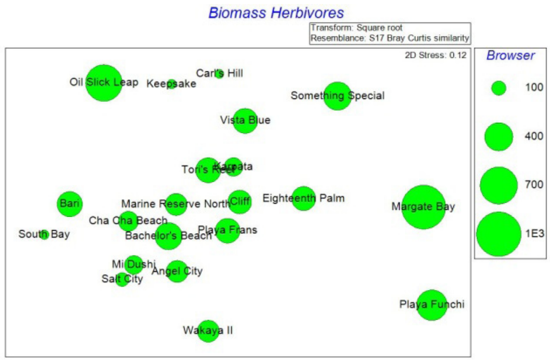
Graph 4.5.8 (from Vermeij et al in press)

The bubble plot 4.5.6 shows relative abundance of damselfish by site. Oil Slick Leap, Keepsake, Marine Reserve North and South Bay show the highest relative abundance of non-denuding damselfish, while Wayaka II and Playa Funchi exhibit the lowest relative abundances.

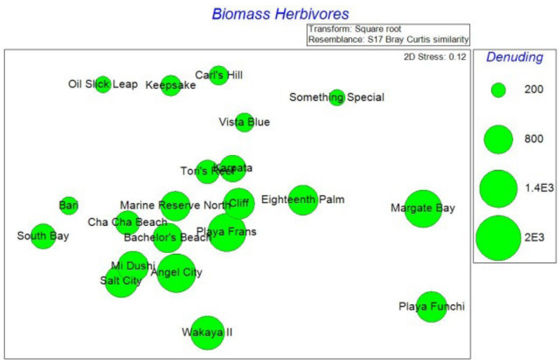
The graph 4.5.7 shows the relationship between average biomass of damselfish and average biomass of predators. There is a clear negative correlation between the two, suggesting that damselfish (Stegastes planifrons) biomass is controlled by direct consumption by predators. The graph 4.5.8 shows the relationship between S. Planifrons and their preferred habitat (Montastrea coral species). There is no clear correlation between the two, again suggesting that it is the predator biomass which is controlling the damselfish population.



Graph 4.5.9



Graph 4.5.10



Graph 4.5.11

The bubble plots above (4.5.9, 4.5.10 and 4.5.11) show the relative biomass of different herbivorous functional groups by site. To the far left are excavating scarids, in the middle are browsers (Chaetodons, Pomacanthids) and to the far right are denuding families (Acanthurids, Microspathadon). Most sites had relatively abundant excavating scarid populations, but sites with relatively smaller scarid biomass populations are seen to the right of the plot (Playa Funchi, Margate Bay, Something Special and Eighteenth Palm). The sites with the highest relative biomass of browsers are Margate Bay and Oil Slick Leap. Many sites had high relative biomass of denuding species, but sites with lower biomass can be seen to the top of the plot, including Bari, Oil Slick Leap, Keepsake, Carl's Hill, Vista Blue and Something Special.

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