An underwater photograph of a large, dark sea fan (a type of colonial invertebrate) against a blue background. A school of small, silvery fish is visible in the upper left and center of the frame. The sea fan has a thick, textured base and several long, branching arms with fine, feathery structures.

# PHYSIS

*Journal of Marine Science*

CIEE RESEARCH STATION BONAIRE  
TROPICAL MARINE ECOLOGY &  
CONSERVATION PROGRAM  
VOL. 1 FALL 2006

# φύσις

*Physis* (φύσις) is the Greek word for nature. It was used in ancient Greek philosophy as a versatile term describing, among many other things, origin, spring, birth, growth, nature of soul and spirit, order of nature, and creation. Aristotle used it to explain the entire universe with all its creative and regulative powers combined as a self-existent and self-sustaining entity.

Today *physis* is used in the medical world with reference to bone growth. In biology, it defines the progressive change a subject undergoes in its development toward becoming something else. Aristotle saw *physis* as an internal principal of change possessed by all living things allowing them to transform, while still maintaining species identity.

In “Healing the Ocean,” author Rod Fujita refers to *physis* as the restoration of natural processes that create and maintain environmental systems, ultimately allowing them to heal themselves. With this concept Fujita introduces yet another definition for the Greek word; natural self healing. It is this definition of *physis* that we have chosen to adopt for the title of our journal; for it illustrates some of the principles we examined in the CIEE Bonaire program.

Conservation, protection and environmental sustainability were some of the main focuses during our semester on Bonaire. We, the students of CIEE Bonaire Fall '06, have been involved in community education, conservation of resources, protection of Bonaire's environment, and participated in a number of environmental volunteer opportunities. Throughout the following pages of this journal you will find a collection of knowledge, all gathered here on Bonaire, regarding a wide span of biological and environmental topics. Although this span reaches from chemical and nutrient sampling to specific environmental restoration projects, each article is devoted to educating its reader on conservation related issues. We believe that environmental conservation and ideas of sustainable living are capturing interest all over the world.

If we are to protect and restore the environment, we must first understand it.

We present Volume 1 of *PHYSIS: Journal of Marine Science* as a tribute to environmental conservation and awareness. Maybe someday people will allow nature to breathe again and the environment will be permitted to heal itself. Until that day, we will continue to explore the many systems of nature, strive to understand the deepest workings of the environment, and do our best to raise awareness.

Enjoy!

Hannah Underdahl

## PHOTOGRAPHS

Front Cover: Crinoid at Bisé Morto by Zac Kohl

Table of Contents Photos: A by Christy Clemenson, all other photos by Linda Kuhnz

Caribbean/Bonaire map by Linda Kuhnz

Back Cover: CIEE Fall '06 by Rita Peachey

φύσις  
**PHYSIS**

**JOURNAL OF MARINE SCIENCE**

**CIEE RESEARCH STATION BONAIRE  
TROPICAL MARINE ECOLOGY &  
CONSERVATION PROGRAM  
VOL. 1 FALL 2006**



## Foreword

The Council on International Educational Exchange (CIEE) is an American non-profit organization with nearly 100 study abroad programs in 35 countries around the world. Since 1947, CIEE has been guided by its mission...*to help people gain understanding, acquire knowledge, and develop skills for living in a globally interdependent and culturally diverse world.* As a membership organization, composed of mainly U.S. institutions of higher education, CIEE responds quickly to the changing academic needs and desires of its member institutions.

The Tropical Marine Ecology and Conservation program in Bonaire is one of the newest programs offered by CIEE and is an example of our ability to foresee the need for science-based programs abroad. Our goal is to provide a world-class learning experience in Marine Ecology and Conservation. Our program is designed to prepare students for graduate programs in Marine Science, Environmental Science, or for state and federal jobs in Natural Resource Management. Student participants enroll in five courses: Coral Reef Ecology, Scientific Methods using SCUBA, Human Ecology, Marine Resource Management and Independent Study. In addition to a full program of study, this program provides dive training that prepares students for certification with the American Academy of Underwater Scientists, a leader in the scientific dive industry, at their home universities.

The proceedings of this journal are the result of each student's Independent Research project. The research was conducted within the Bonaire National Marine Park with permission from the park and the Department of Environment and Nature, Bonaire, Netherlands Antilles. Students presented their findings in a public forum on 1 December 2006 at Buddy Dive Resort, Bonaire.

The Independent Research Advisors for the projects published in this journal were: Rita B.J. Peachey, Ph.D, Linda Kuhnz, M.S. and Caren Eckrich, M.S. Brief biographies of the advisors are presented on the next page.

*Photographs on this page by R. Peachey*

## Independent Research Advisors

**Dr. Rita Peachey is the Resident Director in Bonaire. She received her B.S. in Biology and M.S. in Zoology from the University of South Florida and her Ph.D. in Marine Science from the University of South Alabama. Her research interests include coral biology and how UV affects the early stages of life in the ocean. In addition, she has studied how pollution can enhance the detrimental effects of sunlight on larval crabs, corals and oysters. Rita has years of experience conducting ecological research in a variety of ecosystems such as oyster reefs, seagrasses, coral reefs, and mangrove swamps.**

***Primary Advisees: Hannah Underdahl, Zac Kohl, Christine Martynuk and Joshua Karnowski***



***Rita Peachey, Ph.D  
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**Linda Kuhnz is a Marine Ecologist with the Monterey Bay Aquarium Research Institute where she currently studies deep-sea habitats. Most of her work focuses on changes in marine ecosystems due to both human-caused and natural events. She holds a B.S. in Marine Biology with a minor in Chemistry from San Jose State University in California and an M.S. from Moss Landing Marine Laboratories near Monterey, California. Linda has been a SCUBA instructor for 15 years and has had the opportunity to conduct underwater research in a wide variety of tropical, temperate, and polar environments.**

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**Caren Eckrich is the new Assistant Resident Director and, as a resident of Bonaire for the last eight years, she brings local experience and a wealth of information on diving and marine ecology in Bonaire. She is a SCUBA instructor and has taught Marine Ecology in Puerto Rico, Curacao and Bonaire. Her educational background includes a B.S. in Wildlife and Fisheries from Texas A&M University and a M.S. in Biological Oceanography at the University of Puerto Rico in Mayaguez. Caren's research interests include fish behavior, seagrass ecology, sea turtle ecology and coral disease.**

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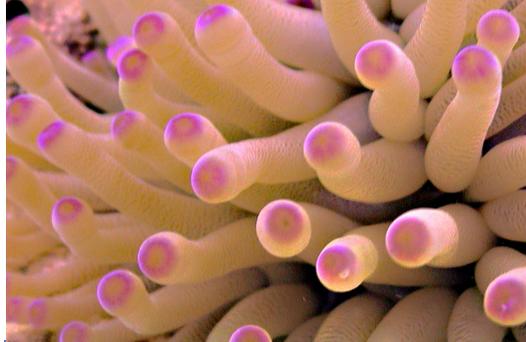
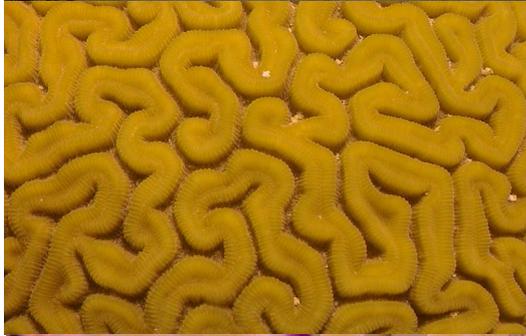
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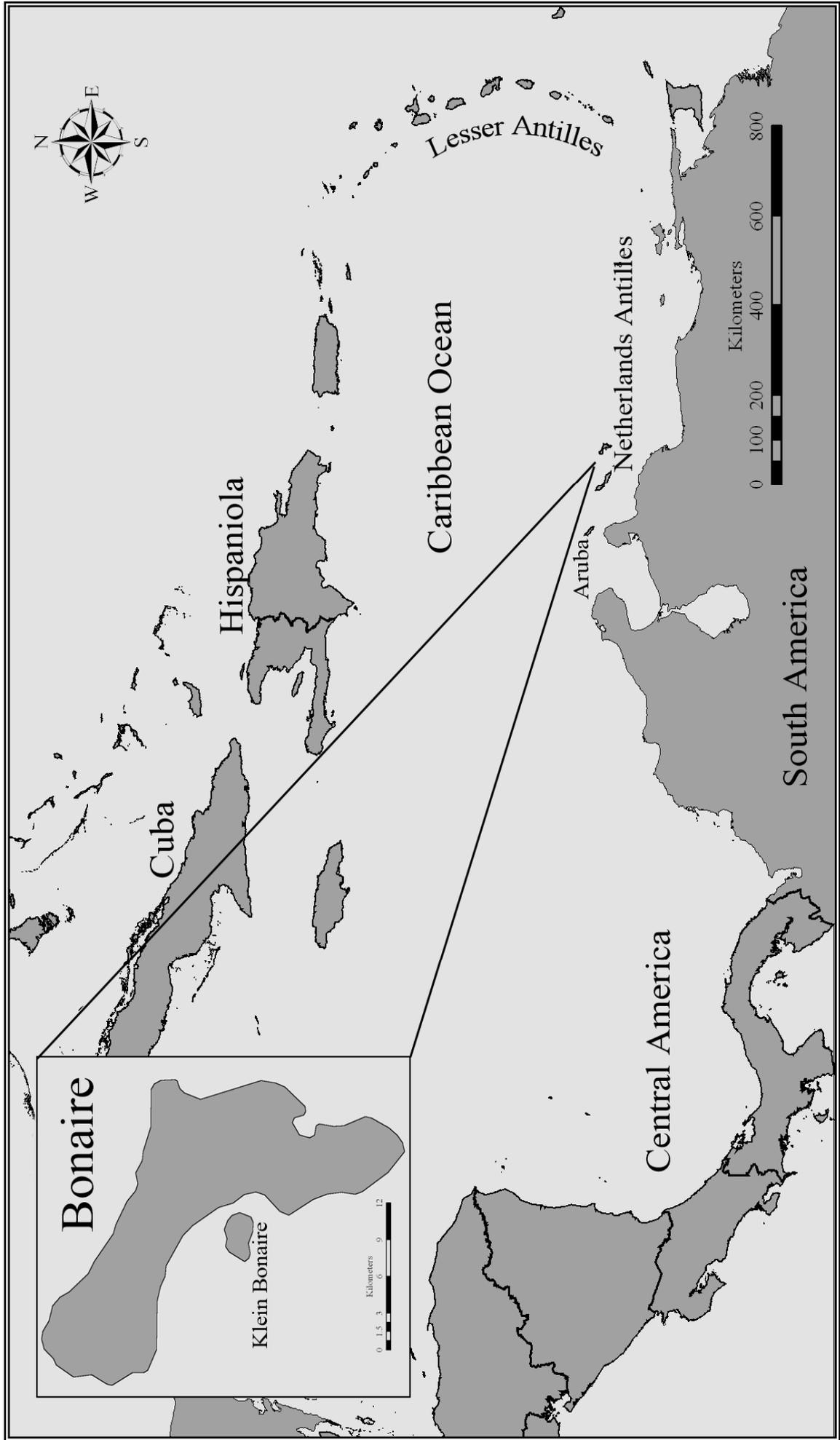
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# CORAL GROWTH ON ANTHROPOGENIC VS. NATURAL SUBSTRATES IN BONAIRE, N.A.

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## ABSTRACT

Specific anthropogenic substrates demonstrate the ability to aid new coral growth among Caribbean reefs in Bonaire, N.A. In this study I documented the total percent coral cover on tires, concrete, and metal objects then compared it to nearby natural reef. I also documented the percent cover for individual coral species. Natural substrates exhibited the highest percent total coral cover (mean = 64.5 %), followed by concrete (mean = 21.5 %) and metal (mean = 22.9 %); tires supported the lowest mean coral cover (mean = 3.5 %). Coral species diversity was highest on metal substrates (11 spp.), followed by concrete (9 spp.), natural reef (8 spp.) and tires (2 spp.). These data suggest that concrete may be the most appropriate artificial substrate in efforts to aid reef regeneration and restoration in this region.

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## INTRODUCTION

According to Spalding (2001), 100% of coral reefs in the Netherlands Antilles are at risk. In total, 58% of the world's reefs are at risk, 27% of which have recently been categorized as high risk (Byrant et al. 1998). Reefs face both natural and anthropogenic disturbances which threaten their health and sustainability.

Symbiotic algae, called zooxanthellae live inside most corals. These one-celled organisms aid coral by providing nutrition and enhancing calcification. Calcification is the process corals use to create a hard outer shell by depositing an organic matrix and calcium carbonate; this supports and protects the coral (Houlbreque et al. 2004). Most hard corals cannot attach and grow without a rough, hard surface. A commonly described ideal artificial recruitment substrate is limestone from calcification of dead reef building corals (Birkeland 1997). In many areas where disturbances have reduced coral cover, lowered availability of substrate poses problems (Birkeland 1997).

Violent storms in the Caribbean, such as Ivan (2004) and Lenny (1999) caused significant damage to reefs, especially those closest to shore. The dumping of rubble and tons of sand can suffocate reefs and prevent growth for a period of time (Spalding et al. 2001). While small, infrequent disturbances can increase diversity and improve the quality of reefs (Birkeland 1997) global warming may be increasing both the severity and occurrence of storms, potentially causing reefs to become less capable of regenerating between each storm strike. Predictions are that the intensity of hurricanes should increase as the global mean temperature increases, and enhanced tropical cyclone destruction could be a result of future warming (Emanuel 2005).

In addition to natural disturbances, anthropogenic

changes to shorelines and surrounding areas are increasing. The growing desire for people to reside near coastal areas is increasing at a rapid rate. In 2001, over half the world's population lived within 200 km of the coast. This coastal population growth accelerates pressures on nearby environments, causing alterations to habitats and destruction of many vital ecosystems ("The ever more popular coasts" 2003). In 2003, United States coastal counties alone provide 53 percent of housing for U.S. residents (approximately 153 million people), with numbers projected to increase in future years (Crossett et al. 2004). With expected increases of coastal populations and further development in both the United States and abroad, reefs around the globe will continued to be threatened, as limited space often times causes construction projects to be built directly on top of reef communities (Bryant et al. 1998) or in areas that directly contribute to reef damage. Overall, the destruction of reefs worldwide is increasing, and the ability for reefs to regenerate is seriously threatened (Spalding et al. 2001).

Many reef corals are able to grow on various man-made objects. These anthropogenic substrates include tires, concrete blocks, and metallic items (boat engines, ship wrecks, etc.). Some workers are trying to find ways to provide replacement substrate in areas where coral reefs are degrading and natural substrate is less available. This strategy requires the purposeful and strategic use of anthropogenic substrates. Experiments have already begun in places such as India and the Philippines, and demonstrate promising results thus far.

In 2004, researchers in the Philippines designed a concrete substrate called Acanthasia and began testing their success in recruiting and growing reef organisms. The product was tested in Duka Bay by using six substrate replicates, three controls and three with transplanted coral fragments. Unaltered substrates (natural control and substrate replicates) had little

growth after two years, indicating that degraded reef ecosystems could be slow to recover. Models with transplanted coral fragments showed an increase of more than 5 cm (*Acropora spp.*) in coral width and height within a year of sampling. These results show that transplanting corals may be a good way to aid reef growth and recovery (Alfeche et al. 2006).

Shortly after Hurricane Lenny affected coral reefs in the Southern Caribbean, people began to consider ways to assist in the regeneration of reefs off the island of Bonaire. A plan was implemented by the Sand Dollar Beach Resort. They submerged concrete “Reef Balls” in the shallow water (10ft) to attract reef fish. Results so far show the recruitment and early development of reef organisms (Weterrings, personal communication Oct. 2006).



**Figure 1.** Reef Balls at Sand Dollar Resort, Bonaire (Photo from “Sand Dollar Bonaire Lends A Helping Hand with Coral Reef Expansion.”)

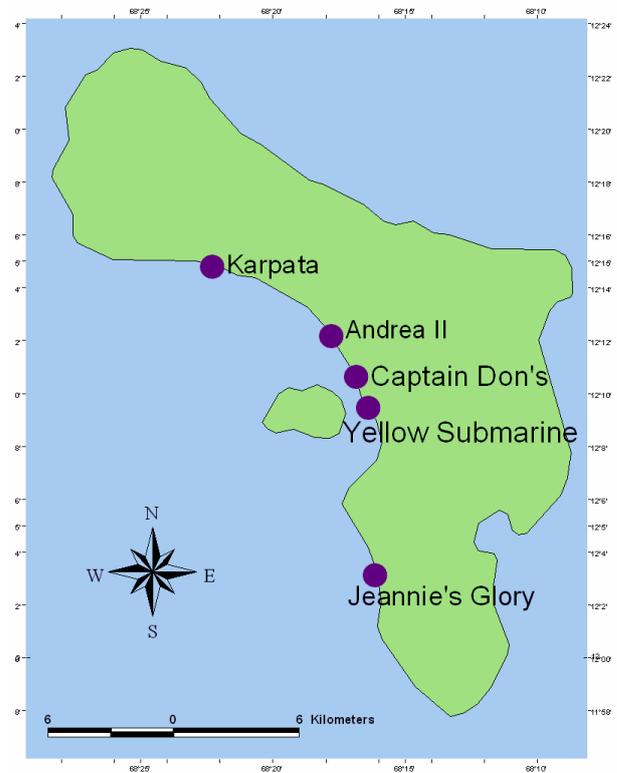
The purpose of my study was to observe which anthropogenic substrates host reef corals and to determine species diversity and abundance on three types of artificial substrates found in Bonaire. I compared these substrates to natural reef habitat. Data from this study can be used locally and perhaps regionally to provide information regarding the use of successful anthropogenic substrates in order to promote coral re-growth and to ultimately re-establish biological communities in shallow water where corals have been degraded or disappeared.

I hypothesized that the highest percentage of coral would be on natural substrates. With regards to anthropogenic substrates, I expected to find that concrete hosts the greatest amount of coral coverage since it provides the rough, hard surface necessary for coral growth and is most similar to natural substrates (i.e. coral rubble). I also expected to find the highest coral species diversity on concrete substrates compared to tires and metal objects.

## METHODS

I surveyed anthropogenic substrates (metal, concrete, and tires) at five sites on the leeward shore of Bonaire (Figure 2). Substrates were chosen haphazardly as they

were encountered during SCUBA surveys. The depth and geographic location (Garmin Geko model 101) were recorded for each object. Natural substrates were chosen by surveying the area adjacent to each anthropogenic object (and within 5 m depth).



**Figure 2.** Dive sites along the leeward side of Bonaire where anthropogenic and natural substrates were sampled coral cover. Individual coral species were documented for each object sampled.



**Figure 3.** Determining coral cover on barrels at Karpata (Photo by Linda Kuhn 19 Sept. 2006).

I used 25 cm x 25 cm (0.0625 m<sup>2</sup>) quadrats to sample barrels, concrete blocks, and other similarly-sized items

(Figure 3). I used a 10 cm x 10 cm (0.01 m<sup>2</sup>) quadrat to sample tires. Quadrats were randomly placed on substrates and most objects were large enough to conduct three replicates. I documented the percent of each coral species present at random points within the sampled area (Random Point Contact method).

I used a two-way ANOVA to determine statistical significance in the mean percent cover of corals between anthropogenic and natural substrates (Systat v 11).

## RESULTS

### CORAL COVER

At all sites, natural reef had the highest mean percent coral cover. Natural substrate had a significantly higher mean percent coral cover ( $p < 0.001$ ) when compared to anthropogenic substrates (Figure 3). There was no difference in the mean percent coral cover on substrate between dive sites ( $p = 0.139$ ). Tires supported little coral settlement or growth. Concrete had a greater mean coral cover than metal at Andrea II and Jeannie's Glory, but metal had a higher mean at Yellow Submarine and Karpata (concrete was not found at Captain Don's) (Figure 4).

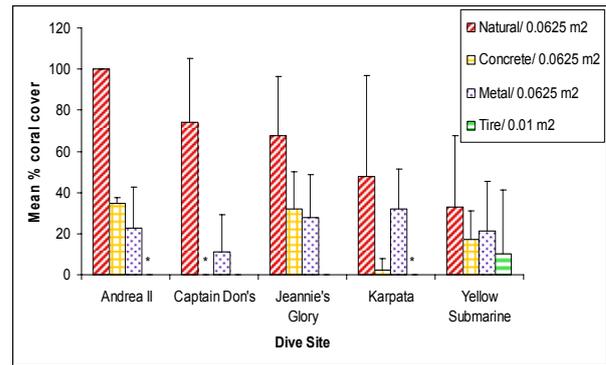
### ABUNDANCE OF CORAL SPECIES

The abundance of individual coral species varied depending on the substrate observed. *Montastrea*

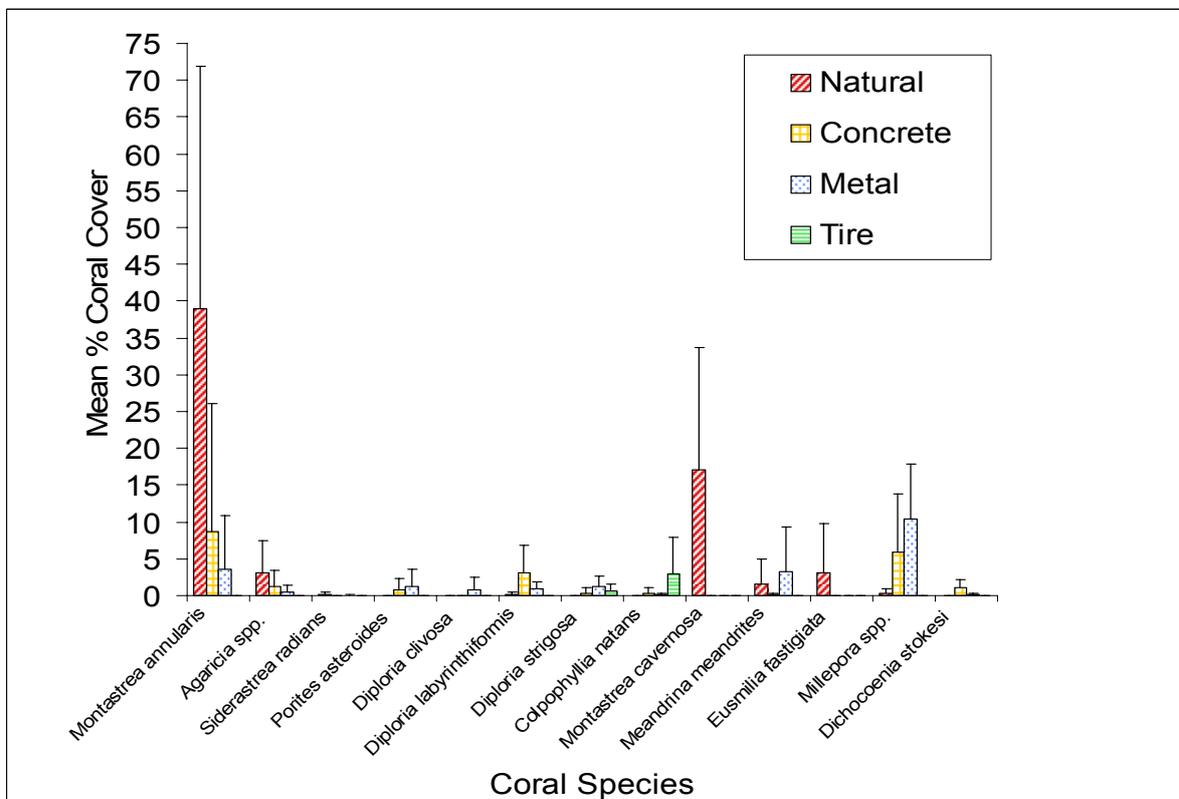
*annularis* was most abundant on both natural and concrete substrates. *Millepora* spp. was most abundant on metal substrates, while *Colpophyllia natans* was most abundant on tires (Figure 5).

### DIVERSITY OF CORAL SPECIES

There were thirteen different coral species in my samples (Figure 5). Metal supported the greatest number of species (11 spp.), followed by concrete (9 spp.), natural reef (8 spp.), and tires (2 spp.). There was no coral species that was found on every substrate type observed.



**Figure 4.** Mean percent coral cover per substrate type at specific dive sites. Asterisks denote the absence of the specific substrate type that site. Error bars = standard deviation.



**Figure 5.** Mean percent for each coral species by substrate type. Error bars = standard deviation.

## DISCUSSION

### SUBSTRATE SUCCESS

Coral growth on natural substrates was almost three times greater than growth on concrete and metal, and almost eleven times greater than growth on tires. Of the anthropogenic substrates, concrete and metal appeared to provide the substrate that supports the most coral growth. This could be due to physical characteristics that make them similar to natural substrates (hard, rough surface), whereas tires present a smoother surface with little resemblance to natural surroundings. Differences in the percent cover of coral growth on various substrates may also be due to the depth, location, and length of time individual objects were in their present locations. For example, most tires were at shallower depths, whereas concrete and metallic substrates were found at deep and shallow depths. Some anthropogenic substrates I tested may have been present for relatively short periods of time.

### CORAL SPECIES

The most abundant coral species found was *Montastrea annularis*. It was found on two of the three anthropogenic substrates, but not on tires. Colonies were large and covered sizeable areas. *Montastrea cavernosa* and *Millepora spp.* were also more abundant and covered more area than other species. The presence of certain species on anthropogenic substrates was not always consistent with the presence of these same species on nearby natural substrates. This suggests that some corals are more capable of growing on anthropogenic substrates than others (such as *Diploria spp.*).

Some local coral species were not found on my surveys. This does not mean that these species do not have the potential to recruit and grow on man-made objects. Certain species, like *Acropora palmata* or *Acropora cervicornis*, were not in close proximity and appear to have very specific habitat requirements other than substrate preference (light, water clarity). To test this theory, more sites should be studied that have these coral species.

### SUCCESS IN USING ANTHROPOGENIC SUBSTRATES AS ARTIFICIAL REEFS

Fitzhardinge and Bailey-Brock (1989) studied coral growth on anthropogenic substrates at two sites in the Hawaiian Islands using metal, concrete, and tires as substrates. Their results showed that the highest coral recruitment was on metal, and the lowest was on tires. However, they recommend that concrete be used for the construction of artificial reefs because of its similarity to coral, its durability and because it can be shaped. They also suggested the use of slowly degrading metal structures as an alternative for artificial reef construction.

Artificial reefs have been installed in areas of the

Maldives to rehabilitate mined reefs and restore shallow reef-flat areas which naturally show slow recovery rates (Clark and Edwards 1999). This experimental program was launched in 1990 and tested the feasibility of using bio-engineered reefs to “kick-start” natural recovery by installing 360 tiles of concrete structures at various depths and topography in areas of high mining impact. These artificial structures exhibited similar to greater species richness and diversity in fish species compared to control reefs, and indicated substantial coral recruitment within only a year of their installment.

Oren and Benayahu (1997) conducted research off the northern Gulf of Eilat, Israel in which they tested the use of anthropogenic substrates as artificial reefs, and success in transplanting coral recruits to these substrates. Their reef was composed of PVC piping and wire. Transplanted corals were placed along the artificial reef at different depths, and in different orientations. Survivorship of recruits depended on the structural features of artificial reef. This research demonstrated success in both the use of an artificial reef and the transplanting of coral recruits.

These three case studies, in addition to those mentioned earlier, exhibit positive results in using anthropogenic substrates to compose an artificial reef structure for the recruitment, growth, and rehabilitation of reefs with respect to coral species. Successful coral re-growth also aids in fish and invertebrate recruitment, ecosystem vitality and overall reef health.

### LOCAL SUCCESS

Sand Dollar Resort has thus far exhibited success with their Reef Balls. The balls are a basic hollow circular shape with 6-8 openings drilled into them (Figure 1). Coral spat is growing on the insides of these objects. Inside some of the reef balls, coral rubble is stacked. Reef balls containing coral rubble have more fish, and more visible coral spat growing. Furthermore, most reef balls show a greater growth of coral than the natural coral rubble located in the same area, and generally appear to host more fish.

### FURTHER RESEARCH

With more money and time, further research in this area could produce more conclusive results. More dive sites from around the island could be observed to collect information on coral growth on anthropogenic substrates, specifically areas that demonstrate greater coral diversity. More anthropogenic substrate types could be tested, like plastic and wood, and an attempt to age all anthropogenic substrates could be made. The possibilities of using man-made objects, such as reef balls, could be further explored and tested in hopes of speeding coral recruitment and growth.

### ACKNOWLEDGEMENTS

This research has been facilitated by Linda Kuhnz with

her continual guidance, support and transportation to various sites, as well as Rita Peachey, PhD. who provided transportation and advice. Materials were supplied through CIEE Research Station Bonaire. I would also like to thank Jorgen Weterrings, Caren

Echrich, and Jerry Ligon for their contributions and assistance, as well as STINAPA for allowing me to conduct my research in the Bonaire National Marine Park.

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# CONTACTS BETWEEN RECREATIONAL SCUBA DIVERS AND CORAL REEFS IN BONAIRE

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## ABSTRACT

The number and type of diver contacts with coral reefs on Bonaire and Klein Bonaire's fringing reefs were studied in fall 2006. The goal of this study was to observe the number of contacts recreational SCUBA divers are making with the local reefs. Twenty four divers were chosen haphazardly and followed for 30 minute observation periods on three shore dives and seven boat dives. Forty-one percent of observed divers came in contact with the reef substrate at least once during the observation period for a total of 84 contacts. Contacts were categorized as fin taps, body bumps, skin contacts, sediment upsets and equipment dragging. The majority of observed contacts were fin taps, followed by skin contacts, sediment upsets, equipment dragging and body bumps.

The following diver attribute categories were analyzed to determine the relationship between contact rate and diver attributes: dive access type (shore vs. boat), gender of the diver, skill level of the diver (beginner vs. advanced), and presence or absence of camera equipment. Shore dives, female divers, beginner divers and underwater photographers all demonstrated higher numbers of contacts than their counterparts with female divers contacting the reef nearly twice as often as males. A one-way ANOVA was used to analyze the number of contacts between the divers in each of the above categories. There were no statistically significant differences in number of contacts within any of the categories. The lack of statistically significant differences may be a result of the relatively small sample size, short study period, or a combination of the two.

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## INTRODUCTION

Coral reefs are one of the world's most diverse and valuable ecosystems. Roughly 4,000 fish species and 800 species of reef-building corals have been identified and coral reefs provide over \$375 billion worth of resources to people living near coral reefs every year (Bryant et al. 1998). However, as a result of recent anthropogenic activities, coral reefs are under a great deal of stress worldwide. Coastal development, boating activities, snorkeling, SCUBA diving and walking along reef flats can damage coral reefs (Tratalos & Austin 2001, Medio et al. 1996, and references within). Diving on coral reefs has increased greatly over the past two decades due to increased numbers of annual certifications and better accessibility to reefs worldwide (Zakai & Chadwick-Furman 2002, and references within). As a result of heightened interest and participation in recreational SCUBA diving, the potential for damage by divers has increased (Schaeffer et al. 1999). Diver damage to coral reefs can occur in a number of different ways, including sediment upset, though most damage occurs is a result of direct contact (Tratalos & Austin 2001). While breaking coral branches is an obvious form of damage caused by divers; it is also possible to injure or kill a coral by touching it (Beckman 2000).

In a study on the effects of recreational SCUBA diving on Caribbean coral and fish communities in Bonaire, comparisons were made between coral coverage on dived (receiving up to 6,000 divers annually) and undived sites (Hawkins et al. 1999). The analysis of coral and fish community health indicated that damage

as a result of direct diver impact was relatively minor (Hawkins et al. 1999). Tratalos & Austin (2001) compared high use, low use and no use sites in the West Bay of Grand Cayman in the Cayman Islands. Transects of the area were filmed to determine recreational SCUBA diving effects on reefs based on the amount of coral cover present at sites with differing levels of use. In areas of high diver intensity, percent coral cover was significantly lower and significantly more coral rubble was present.

In reference to Bonaire, van't Hof (2001) stated that there is no "100% proof that a certain impact is directly related to [a diver]." However, other scientists have chosen to study the effects of SCUBA divers on coral reefs by following divers and documenting diver behaviors and actions. Shaeffer et al. (1999) estimated diver disturbance during the summer 1997 in Monterey Bay, California. Divers were followed through kelp beds and physical contacts were recorded. The average diver contacted the substrate 43 times within a 30 minute period. Medio et al. (1997) followed divers in Ras Mohammed National Park, Egypt to observe the effects of briefings on rates of damage to corals by SCUBA divers. Divers that received a pre-dive briefing on environmental awareness came in contact with the reef less frequently during a 7 minute observation period than divers who did not receive the briefing. Tagle (1990) followed divers to count physical interactions between recreational divers and coral reefs communities. Twenty-six percent of divers came in contact with the reef at least once. And lastly, Zakai & Chadwick-Furman (2001) followed divers in the Red

Sea and observed the impacts of tourist divers on the reefs. Each diver contacted the reef about 10 times during a 10 minute observation period by causing sediment upset or stony coral breakage, or both.

Bonaire is one of the world's most popular dive destinations, hosting about 62,550 tourists in 2005 (Bonaire Insider 2006, Simon and Webster 2006). An estimated 23,000 divers visited one or more of the 86 dive sites within the year (Simon and Webster 2006). With dive sites hosting up to 6,000 dives per annum (Dixon et al. 1993) and a growing tourist industry, the potential for diver damage on Bonaire's reefs continues to grow. The impact of divers on Bonaire's reefs must be understood so that measures can be taken to protect the reefs if necessary. Van't Hof (1985, as cited in Tratalos & Austin 2001) suggested that the establishment of a marine protected area (MPA) in an already popular dive location may attract more visitors to the area. It is inferred that the benefits received by coral reefs as a result of MPA status may be overridden by the potential damage due to increased numbers of divers (Tratalos & Austin 2001).

Although there has been a study that analyzed the effects of diving on the coral and fish communities at dive and control sites in Bonaire (Hawkins et al. 1998); no studies have been published in which divers were actually followed and the number of reef contacts were recorded (*sensu* Schaeffer et al. 1999, Tagle 1990, Zakai & Chadwick-Furman 2001). In this study, the direct effects of SCUBA divers on Bonaire's coral reefs was observed by following divers and recording the number and type of contact each subject had with any part of the reef substrate.

## METHODS

The study was conducted on the leeward side of Bonaire, including Klein Bonaire, in the Netherland Antilles during the fall of 2006 (Figure 1). Direct contacts between recreational SCUBA divers and the coral reef substrate were observed by following divers. All dive subjects were unaware that they were being followed. Some dive sites were accessed by boat and others were accessed directly from shore. Sites that were accessed by boat were chosen by the management of Yellow Submarine, a local dive shop that donated boat trips to conduct this study. The shore dive sites were chosen based on available transportation.

Shore dive subjects were chosen haphazardly; the first two paired divers to enter the water were followed casually and contacts were recorded on a dive slate.

Subjects on boat dives were not chosen using a specific selection method, but rather all divers on each boat dive were followed in groups of 1-3 by at least one observer to avoid a biased selection method. Boat diver subjects were told that the observers were conducting a preliminary study on coral coverage in the area. It is

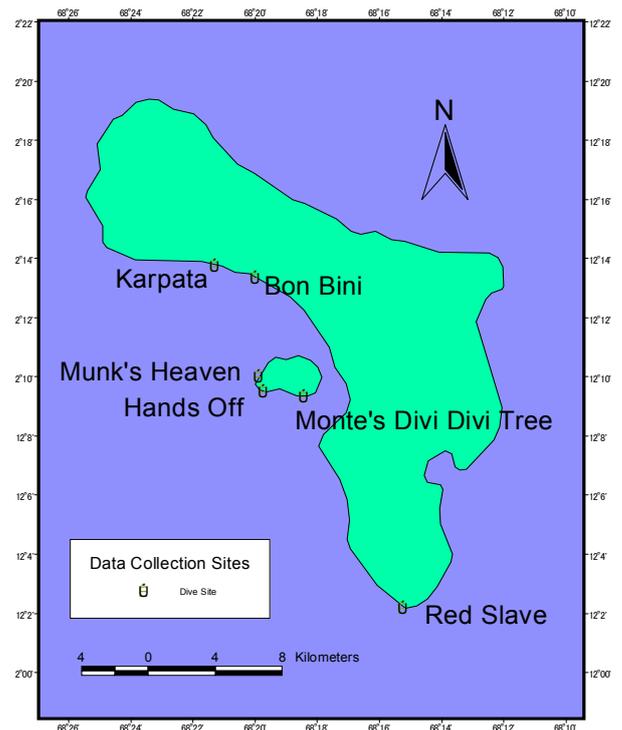


Figure 1. Map of Bonaire, Netherland Antilles and data collection sites.

assumed that divers behaved normally during the data collection period. Observations of diver behavior (shore and boat) began when the subjects were completely submerged and continued for the first 30 minutes of the dive. Following each dive, subjects were informed of the research being conducted and their experience level was noted.

## Contact types

Five contact types were observed: fin taps, sediment upset, body bumping, equipment dragging, and direct skin contact. Fin taps were recorded if a diver's fin came in contact with any part of the reef substrate, either momentarily or for an extended period of time. Sediment upsets were recorded when sediment was stirred up into the water column. Body bumps were recorded when a diver's body part, other than hand, bumped into the substrate. Equipment dragging entailed a physical contact between a diver's equipment (gauges, slate, camera, second stage regulator, etc.) and the reef. Skin contacts were recorded when a diver's skin, usually hand, came in contact (finger tip push-offs, or grasping) with the reef. Distinctions between intentional and accidental contacts were not made.

Since other studies have reported that fin contacts are the most common type of diver contact (Zakai & Chadwick-Furman 2002); I expected to observe more fin contacts than any other contact type. Given that most divers wear exposure suits and are briefed prior to their

dive on the importance of not touching corals, I predicted that skin contacts would be infrequent.

### Diver attributes

The following attributes of each diver were recorded: male or female, camera or no camera, shore or boat diver, and skilled (>50 logged dives) or unskilled (<50 logged dives). The diver attributes were of interest because I wanted to understand what characteristics might be useful for predicting the number of contacts a diver has with the reef.

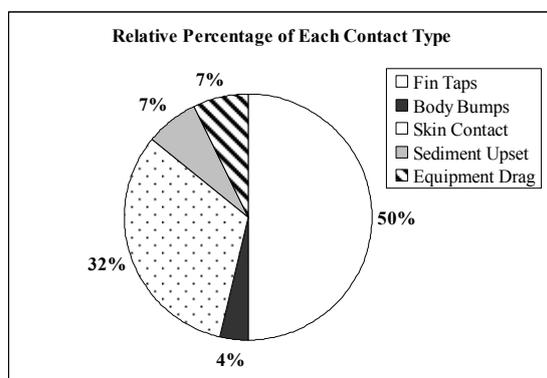
In previous research, inexperienced divers and divers with camera equipment had higher numbers of contacts with

the reef (Dixon 1993). Therefore, I hypothesize that inexperienced divers and divers with camera equipment will have the greatest number of contacts in this study. Finally, I predict that there will be no difference in the number of contacts based on gender or dive access, type, boat or shore.

## RESULTS

### Contact types

A total of 24 divers were followed on 3 shore dives and 7 boat dives for a total of 11 dives at 6 sites on Bonaire and Klein Bonaire (Red Slave, Karpata, Hand's Off, Munk's Heaven and Monte's Divi Divi Tree)(Figure 1). Out of the 24 divers observed, 10 came in contact with the reef at least once during the first 30 minutes of their dive and a total of 84 contacts were recorded. Fifty eight percent of the subjects never came in contact with the reef, and many divers hovered a couple of meters from the substrate throughout the duration of their dive. On average, divers came in contact with the reef 3.5 times within the 30 minute observation period. Within the five contact groups, divers exhibited a mean of 1.75 fin taps, 1.13 skin contacts, 0.25 sediment upsets and 0.13 body bumps per observation period. Fifty percent of the total 84 observed contacts were fin taps, followed by skin contacts, sediment upset, equipment dragging and finally body bumping (Figure 2).



**Figure 2.** Relative percentages of the five types of contacts divers had with the reef

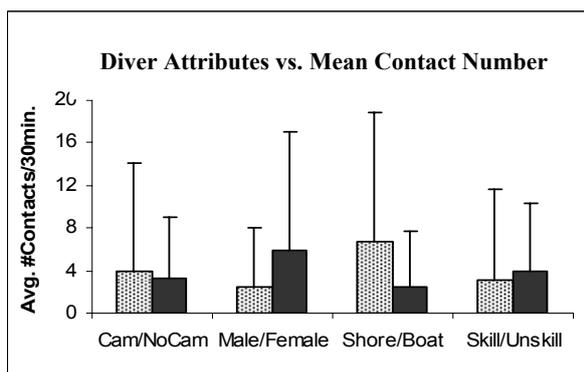
**Table 1.** One-way ANOVA of contact type versus the number of contacts divers made with reefs. P-value = 0.06264, F crit = 2.45057.

Groups	Count	Sum	Average	Variance
Fin taps	24	42	1.75	13.413
Body bumps	24	3	0.125	0.375
Skin contact	24	27	1.125	11.0707
Sediment upset	24	6	0.25	1.06522
Equipment drag	24	6	0.25	0.36957
Source of Var.	SS	df	MS	F
Between Groups	48.45	4	12.1125	2.30333
Within Groups	604.75	115	5.2587	
Total	653.2	119		

A one-way ANOVA was conducted to determine if there were statistically significant differences in the number of contacts (dependent variable) among the 5 contact types (independent variables). There were no significant differences in the number of contacts among the 5 contact types (Table 1, p = 0.06). Therefore although 50% of all contact types were fin taps, there were not significantly more fin taps than any other type of contact.

### Diver Attributes

Shore divers had the greatest mean number of contacts per observation period, 6.67, whereas boat divers had the lowest average number of diver contacts, 2.44 (Figure 3). Female divers had the second highest number of contacts with a mean of 5.86 while male divers had an average number of contacts of 2.53. Unskilled divers had the third highest mean number of contacts (3.91) in comparison to skilled divers with a mean of 3.15. And lastly, mean contacts of divers with cameras (3.89) was higher than divers without cameras (3.27). The results support my original hypothesis that shore divers would have less contact than boat divers, unskilled divers would exhibit higher contact averages than skilled divers and divers with cameras would have higher contacts than divers without cameras. I did not, however, anticipate such high average contact rates for female divers when compared to male divers. The mean number of contacts (5.86) for female divers was almost 42% higher than the average number of male contacts (2.53). However, the high number of female contacts is the result of a single subject that contributed more than 35% of all observed contacts.



**Figure 3.** The average number of reef contacts by divers within a 30 minute observation period using the following diver attributes: camera vs. no camera, male vs. female, shore vs. boat dives and skilled vs. unskilled.

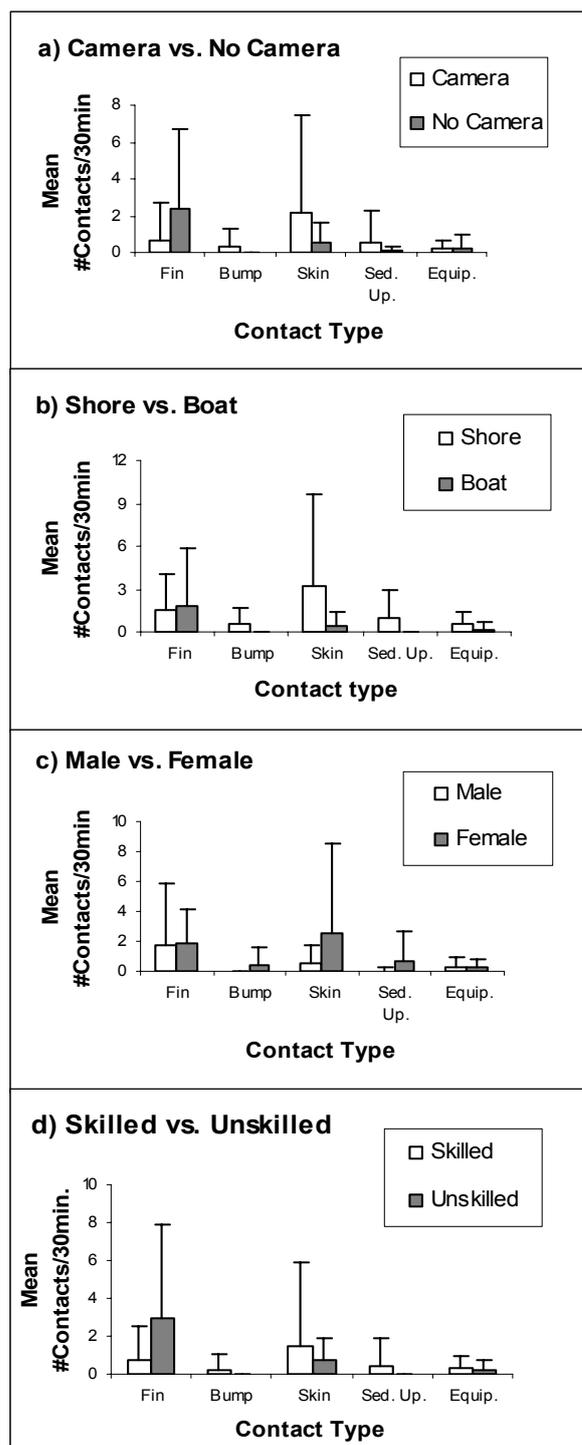
A one-way ANOVA was conducted to compare the average number of contacts per 30 minute observation period for each of the diver attributes examined. There were no significant differences within any of the 4 attributes (Table 2). The difference in number of contacts for each attribute did not vary by more than 14 contacts for any of the attributes studied (Table 2).

**Table 2.** Results of one-way ANOVA of number of diver contacts with the reef within the four diver attributes examined are listed with respective attribute sums.

Diver attribute	P-value	Sum 1 vs. 2
Shore vs. Boat	0.24	40, 44
Camera vs. No Camera	0.84	49, 35
Male vs. Female	0.33	41, 43
Skilled vs. Unskilled	0.81	41, 43

Graphs comparing contact type within all four diver attributes were constructed to determine any relationships between mean contact number, contact type, and diver attribute (Figure 4). Divers with camera equipment contacted the reef in all five categories as well, while divers lacking camera equipment never “bumped” a coral and only one incident of sediment upset was recorded (Fig. 4a). Regarding shore dives, skin contacts were the most common with divers exhibiting an average of 3.17 contacts per 30 minutes and no bumping or sediment upsets were observed on boat dives (Fig. 4b). Females contributed almost 70% of all skin contacts, and males had 70% of all observed fin taps (Fig. 4c). Unskilled divers only contacted the reef 3.5% more often than skilled divers on average. However, contacts to the reef by skilled divers were observed in all five categories, while unskilled divers were only observed exhibiting fin taps, skin contacts and equipment dragging (Fig. 4d).

Following the dive, divers were informed that they had been part of a study. Most divers were supportive and interested in the study with one exception. A female diver who had the highest number of contacts with the reef of all divers (31 contacts) was defensive when told



**Figure 4.** Mean number of reef contacts by type for each diver attribute: a) camera vs. no camera, b) shore vs. boat, c) male vs. female, and d) skilled vs. unskilled divers. Skilled divers were categorized as having >50 logged dives and unskilled divers had <50. (Fin = fin tap, Bump = body bump, Skin = skin contact, Sed.Up.= sediment upset, Equip. = equipment dragging).

about the study and would not disclose any information regarding her dive experience and knowledge of the reef. Most divers were very cooperative and interested in the research project.

## DISCUSSION

The mean number of contacts per diver was found to be 3.5 within a 30 minute observation period. The mean for my study is small in comparison to that observed by Schaeffer et al. (1999) in Monterey Bay. Schaeffer et al. (1999) observed an average 41.0 contacts with the bottom by certified divers within a standardized 30 minute observation period.

Fifty percent of all contacts recorded in this study were categorized as fin taps, which is similar to the findings of Zakai & Chadwick-Furman (2002) where 50 % of diver contacts were also fin taps. As a result of STINAPA's briefings and the presence of exposure suits worn by divers, I did not expect to observe a great deal of skin contacts. However, 32% of all recorded contacts were direct skin to coral contact.

The mean number of contacts by female divers was greatly inflated by one female diver with a very high number of contacts with the reef. I had originally hypothesized that there would be no difference in contact numbers between males and female, however the results show that females contacted the reefs 42% more often than males. I had also not expected to observe a difference in contact numbers with regards to dive site access type. However, shore divers were much more apt to contact the reef. I predicted correctly that unskilled divers would exhibit more contacts with the reef and my results supported that hypothesis. The sample size ( $n = 24$ ) of my study was limited by the short amount of time available during the semester to conduct the study and is not large enough to detect statistically significant differences. In order to improve the results of this study, more samples would be needed. However, the results of this study do show that divers are coming in contact with the reef and could potentially harm the reef.

Bonaire receives roughly 23,000 tourist divers every year. Assuming that those divers visit for one week and log roughly 10 dives during their stay, it can be estimated that Bonaire hosts 230,000 tourist dives per annum. If the number of dives is divided evenly among the 86 dive sites around the island and Klein Bonaire, there would be 2,674 dives per site per year. This figure is well under estimates made by the World Bank in 1991 and the carrying capacity for Bonaire's reefs was determined to be 4,000-6,000 annual dives (Hawkins et al. 1999). If the most heavily dived sites on the island host ~6,000 every year, and if divers make an average of 3.5 contacts within the first half of their dive (assuming that each dive lasts one hour), one could estimate upwards of 42,000 contacts per site per year. The magnitude to which this number of contacts could potentially affect a site is difficult to estimate, but more robust studies on types of diver damage caused by contacts and the recovery time for corals would facilitate a better understanding. Further study could

determine which sites are in need of diving regulations and/or protection based on a better estimate of the number of divers visiting the site each year. Since the results of this study are compromised by small sample size, the above estimates are merely a discussion point and may provide little insight into the potential future of Bonaire's reefs.

Bonaire is not easy to travel to, there are no long white sandy beaches, the night life is lacking, hotels are expensive and shopping is sparse. Most of Bonaire's tourists are advanced divers who are attracted by the island's world class diving reputation (De Meyer 2006, Volk 2006). In addition, Bonaire's dive sites are within the BNMP and every diver must purchase an admission tag and pay a Nature Fee of \$10 per day or \$25 per year. Divers are also briefed on the importance of marine conservation and the BNMP's rules and regulations, which include not touching or removing anything (alive or dead) from the marine environment. The briefing is given to shore divers as well as boat divers. It can be assumed, then, that all divers diving within the BNMP are aware of the rules and regulations and have been encouraged to act in a marine environmentally friendly manner. Medio et al. (1997) suggests that the presence of a briefing before divers enter the water can significantly decrease the mean number of contacts per diver with the reef. Furthermore, Zakai & Chadwick-Furman's (2002) showed that introductory divers caused greater damage to corals. If the divers visiting Bonaire's reefs are briefed and generally more advanced divers then the number of contacts will likely be lower than for other dive destinations where divers are not briefed or the site is popular for inexperienced divers.

The preliminary data collected in this study has shown some interesting relationships that need to be better understood and future studies on Bonaire could clarify some of the relationships between divers and how they interact with the reef. As Bonaire's tourist industry continues to grow and more divers arrive per year, the need for understanding diver impacts on reefs will become increasingly crucial to the health of the marine park. More divers will mean more contacts per site per year, which could lead to higher levels of damage to reef communities. Effects of recreational diving on coral reefs will not be constant and the need to monitor trends in contacts and the number of divers visiting the dive sites around Bonaire will be ongoing.

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# INFAUNAL COMMUNITY DIFFERENCES ALONG A SEDIMENT MOISTURE GRADIENT IN A HYPERSALINE LAKE IN BONAIRE, NETHERLANDS ANTILLES

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## ABSTRACT

From the abyssal plain to the intertidal zone, benthic fauna are adapted to a variety of extreme physical environments. Shallow water soft-sediment infauna must face rapid environmental changes that could result in fluctuations of oxygen levels, salinity, temperature, or water availability. In the case of closed systems where rainfall is the only significant source of water input, some infauna must adapt to desiccation and high levels of salinity. The result of this dynamic environment is an infaunal community demonstrating an evolutionary path of morphological and behavioral adaptations to periods of environmental stressors. The infaunal community structure of a hypersaline inland lake along a sediment moisture gradient was examined in Saliña Matijs, Bonaire, Netherlands Antilles. Saliña Matijs is a very shallow hypersaline lake comprised of soft, anoxic muddy sediment with a heavy algal layer consistently exposed to high heat intensity. The weather pattern on Bonaire results in high rainfall for short periods of time, followed by prolonged sun exposure. This results in a very dynamic environment where the lake becomes quickly expanded and irregularly saturates the drier sediments. Twelve infaunal core samples and four sediment samples (7.5 cm diameter, 5 cm depth) were collected at four locations with decreasing sediment moisture (20 m to -15 m from the water line). There were gastropod juveniles and adults at all locations, with higher numbers of juveniles in cores with lowest moisture content. The presence of fish scales in every core suggested the presence of a population of small fish. Cluster analysis results show the highest community similarity between the second driest core and the core taken 15 m into the lake.

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## INTRODUCTION

### INFAUNAL BIOLOGY

Previous evolutionary theories portray the environment in black and white, accepting or rejecting genetic diversity based on random mutational processes. According to Herbert et.al. (2002) factors affecting mutation rates suggest that the environment can alter the rate of genetic variation, or even the type of new mutations. Two such factors are ultraviolet (UV) radiation and high salt concentrations. UV radiation can impact the fidelity of DNA replication and repair, while high salinity levels devastate proteins. Organisms in saline lakes are frequently exposed to both factors, creating an environment where evolutionary adaptations are required to tolerate such harsh environments. The result of this dynamic environment is an infaunal community demonstrating an evolutionary path of morphological and behavioral adaptations to periods of desiccation (Herbert et. al. 2002).

Within the last several decades a considerable amount has been learned about a poorly understood group of organisms, benthic meiofauna and macrofauna. The term meiofauna describes infauna smaller than 0.5mm, and macrofauna refers to animals greater 0.5 mm, to a size easily seen by the human eye (Peterson 1979). The types of fauna found in muddy marine sediments can be similar regardless of specific habitat. They tend to be dominated by annelid worms, molluscs, and arthropods, representing more phyla and containing more diversity.

Polychaete worms are often the single most important and diverse groups found in marine mud. Marine bivalves are also very diverse and dominant members of the community, feeding using suspension or deposit methods. Insects are rare, and restricted to the intertidal zone. Pericarid and decopod crustaceans are also common (Lopez 1988).

Benthic animals are often classified into groups based on several natural history characteristics; mobility, modes of feeding, position in the sediment, and food source. Woodin (1983) placed organisms into groups according to their feeding methods and corresponding affect on the physical stability of the sediment. Benthic modes of feeding include shredders, deposit feeders, filter feeders, collectors, scrapers, piercers, and predators (Woodin 1983, Cummins and Klug, 1979). Deposit feeding and scavenging are the most common types of feeding methods in infaunal communities, followed by carnivorous predators. For smaller-grained sediment such as mud, suspension and deposit feeding is optimal, whereas larger-grained sediment such as sand is optimal condition for scavenging and predation (Long 1994). For most deposit feeding organisms, both microbial and detrital foods are necessary for meeting nutritional demands (Lopez and Levinton, 1987). In addition, virtually all marine soft-bodied micro and macro invertebrates exhibit active transport mechanisms for transepidermal uptake of small molecules, such as amino acids, which can be taken up actively and used metabolically (Stephens 1982).

The importance of biological processes and responses to extreme environmental changes is still not completely understood, despite the fact that the largest habitat on earth by volume is deep-water pelagic systems or by surface area the soft-bottom benthos (mud, silt, or clay bottoms as opposed to rock) (Peterson 1979; Kuhn personal communication). As new studies emerge, habitats previously unstudied such as muddy sediment and beach sand yielded a considerable amount of fauna with a wide array of morphological adaptations to severe environments (Peterson 1979). Many of these organisms spend their life, or at least a period of their life cycle, within water-covered sediment. Organisms in this habitat may face physical challenges, such as limited access to dissolved oxygen, less successful recruitment of larvae onto the proper substrate, and maintaining a stable living position in order to obtain food (Lopez 1988, Jackson 1974). It is the adaptations to these factors which fuel niche partitioning. Distributional range is a very important component of a species' realized niche. It is influenced by factors such as geological age, genetic variability, physiological tolerance, and mode of reproduction and dispersal, as well as geographic barriers (Hesse et al. 1951). These adaptations are important because they show how convergent evolution in a number of unrelated taxonomic groups led to a number of morphological and behavioral features, interpreted as adaptations to life in severe environments. Examination of niche partitioning, species richness, and resource partitioning by infauna in soft-sediment ecosystems allows a glimpse into the evolution of these communities (Fenchel 1978).

#### PHYSICAL CHALLENGES

Some organisms can overcome environmental challenges. Certain ranges of salinity have a distinct faunal community because most marine fauna have limited tolerance ranges (Pennack 1985). Rapid changes in water availability may occur gradually or in an instant with an occurrence or lack of rain or tides, potentially having a severe affect on a community. Organisms living in the intertidal or littoral zone, the area between the high and low water marks, must face rapid changes in oxygen levels, salinity, and water availability. Some of these changes may be cyclic and parallel the life cycles of shorter lived animals, allowing them to avoid severe conditions. Animals with longer life spans may be "caught off guard" at any stage in their life cycle (Bleakney 1972). The more resilient macrofauna may have the ability to quickly adapt to small microhabitats and coexist. Those less tolerant organisms either die out or encyst themselves in a suspended state until environmental cues stimulate their reanimation (Barnes 1982).

One of the most extreme marine environments is the hypersaline lake. Hypersaline systems contain salinity levels above the 35-36% salt content of normal sea

water, and are often enclosed water bodies deriving salt from the sediment (Gunter 1961). Marine hypersaline waters are also: a) are connected to the sea b) are intermittently connected to the sea and not subject to complete drying during periods of cut-off, or c) were connected to the sea but have not become permanently cut off without, and have not yet been subjected to complete drying (Bayly 1972).

There are three known types of biological gradients that correspond with salinity gradients. Sessile or only slightly motile marine organisms have optimal salinity ranges for best growth, and when the salinity varies away from the optima, the population is stunted (Gunter 1961). A second correlation is between the size of the organism and salinity. In general smaller or younger organisms thrive best in high salinity waters. Finally, over a severe salinity gradient the fauna changes, and typically the number of species increases until full seawater is reached. In these settings, undiluted seawater near the shore is optimal for the greatest number of species of animals (Gunter 1961).

Closed hypersaline systems typically rely on rain for input and tend to have dry periods with low water levels. During these periods salinity may increase drastically, subjecting the community to high stress (Sanders et. al. 1965). The epifaunal community faces the worst of these fluctuations, and is often poorly represented in such an environment. The infauna, living under more stable salinity conditions, make up the vast majority of the fauna. The periodic short-term fluctuations in the water salinity stabilize sediment salinities and subject the infauna to less physiological stress than that imposed on the epifauna (Sanders et. al. 1965). The infaunal community may be comprised of relatively large invertebrates such as worms or clams, in addition to tiny interstitial organisms which inhabit the spaces between sand grains (without displacing them).

In addition to salinity fluctuations, the lack of water causes desiccation in animals, and can be fundamentally limiting to growth and reproduction. For the same reason hypersaline systems are susceptible to variations in saline, these waters are particularly conducive to animals with drought-resistant stages which are essential for permanent populations.

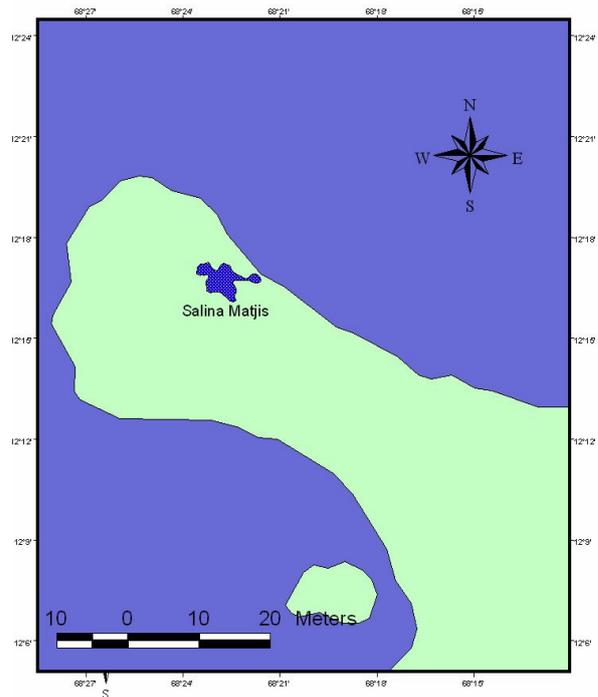
Oxygen level fluctuations are also a problem faced by marine soft-sediment benthos. Many poorly mixed bodies of water experience unpredictable periods and frequencies of hypoxia, lowered oxygen levels, or anoxia, a lack of oxygen. The water overlying organic-rich muds is especially susceptible to oxygen depletion during periods of stagnation. Shallow systems that receive little to no current or tidal mixing are also at risk to lowered levels of oxygen, especially in areas of high solar radiation which may increase microbial respiration (Lopez 1988). Many types of marine organisms can

live for a few hours or even months in an environment without oxygen. One example of this is the larvae of the fly *Chironomus anthracinus*, which stops growing completely during summer stagnation, but resumes normal growth rates after the following overturn. In some cases they larvae can survive two to four months of oxygen depletion each summer during stratification (Jonasson 1972). Larger infaunal organisms that inhabit anaerobic sediment must create a means in which to obtain oxygen, and therefore construct burrow-systems which have a surface opening. By drawing a current into the burrow, surface sediment or water containing oxygen can be drawn down, creating an oxygenated environment. The current also supplies a food source if actively maintained. This behavior allows the presence of infaunal animals in such harsh environments, to a maximum of 10 centim (Barnes 1982; Kuhnz, personal communication).

Not all marine infauna are capable of surviving such prolonged lengths of time without oxygen. Organisms in the intertidal region are particularly vulnerable, as saturation levels are variable (Lopez 1988). The clam *Mulinia lateralis* is particularly capable of maintaining high feeding and locomotor rates under anoxic stress. By maintaining the same rate of metabolic heat dissipation under anoxic and oxic conditions, it not only thrives in variable conditions, but may overtake the habitat of other infauna not as well adapted (Shumway et al, 1983). Certain types of marine meiofauna are almost completely restricted to oxygen reduced sediments. Organisms such as Gnathostomulida, jaw worms, and certain turbellarian, or flatworm, families may not be obligate anaerobes, but exhibit adaptations to deal with long term exposure to a lack of oxygen (Lopez 1988).

#### SALIÑA MATIJS

One example of dynamic moisture sediment changes is the body of water at Saliña Matijs (Figure 1). Located in Washington Slagbaai Park, Bonaire, Saliña Matijs is an isolated, shallow, soft-sediment hypersaline lake. Although connected to the sea from a distance, the tides do not dramatically affect the saliña (WSNP 2003). After a heavy rain the bordering flats become flooded, expanding the lake boundaries and saturating the drier sediments. The dynamic nature of the lake results in several different potential infaunal habitats. These specific habitat barriers remain for an indefinite period of time until dried by the sun, or the advent of fresh rain. With heavy rain follows the saturation of muddy sediment within several m of the shore, altering the habitat and corresponding community. A similar body of water located north of Saliña Matijs is Pos Mangel. Preliminary samples were conducted at Pos Mangel prior to heavy rains approximately 61 m from the water line.



**Figure 1.** Saliña Matijs, located in northern Bonaire within the Washington-Slagbaai National Park.

In this study infaunal community structure was sampled at four locations with presumed varying levels of sediment moisture content. I collected and analyzed sediment cores to a) examine the change in infaunal community structure along a sediment moisture gradient and b) to establish sediment moisture content differences in the sampled areas. I hypothesized that there would be a marked difference in infaunal community structure between testing sites with perpetual water cover versus sites with occasional cover, and sites that were more persistently dry. These differences would result in lower species diversity and abundance.

#### MATERIALS AND METHODS

Sixteen core samples were taken from four different locations along a transect perpendicular to the water line of Saliña Matijs. Each core was 7.5 cm in diameter and 5 cm in depth. I took “A” cores 20 m from the water line, “B” cores 10 m from the water line, “C” cores at the water line and “D” cores 15 m beyond the water line, I measured sediment temperature at the surface and a 5cm depth at each site, for further identification. Data was statistically analyzed using a Bray-Curtis Dissimilarity matrix and cluster analysis (Systat v. 11).

Cores collected for sediment moisture content analysis (n = 1 at each location) were weighed, dried overnight at 105 degrees °C, and then re-weighed dry. Soil moisture was recorded as percent moisture, where moisture content (%) = ((wet weight - dry weight)/(wet weight)) x 100.

Cores collected for infaunal analysis (n = 3 for each location) were sieved (0.5 mm mesh) with water from the lake; animals were preserved in 70% ethanol. Infaunal organisms were counted and identified to the lowest taxa possible, then sent to various taxonomic experts

Salinity levels of overlying water were measured using a YSI 85D meter, and I recorded the depth and temperature. I flagged the water level during my initial sampling and later observed for fluctuation.

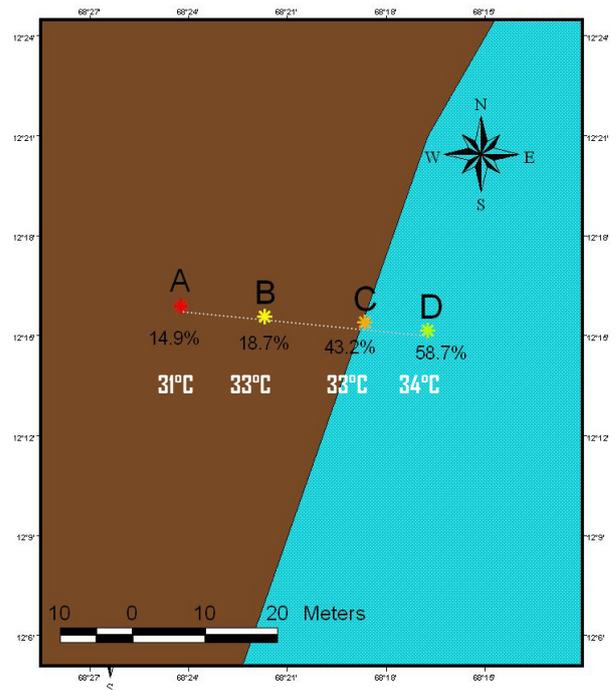
## RESULTS

Preliminary cores were collected at Pos Mangel in September 2006. No further cores were collected there due to heavy rain; the route to this site was closed when sampling took place. Core sampling was completed at Saliña Matijis in October 2006 (Figure 2). Salinity was measured at this site, but was outside of the range for the YSI 85D meter (>80 parts per thousand). Two weeks later, I measured the salinity again with the same result.

Figure 2 illustrates the gradient used, beginning with A and ending in D. Below the core locations are the moisture availability percentages, and below that the sediment temperature taken five centimeters under the sediment with the exception of core D, which was taken in the water.

On the day of sampling, a flag was placed on the water line where cores were taken at location C after a period of heavy rain (2.14 inches) in one week. Two weeks later after no rain, the flag was 9.1 m from the water line (Figure 3).

Figure 4 illustrates the anoxic layer immediately underneath the surface at the water line. Anoxic mud was found in every core, varying in depth and thickness (Table 1).



**Figure 2.** Configuration of cores collected at Saliña Matijis in October 2006. Below the core locations are the moisture content percentages, and the temperature of the sediment at a depth of 5 cm.

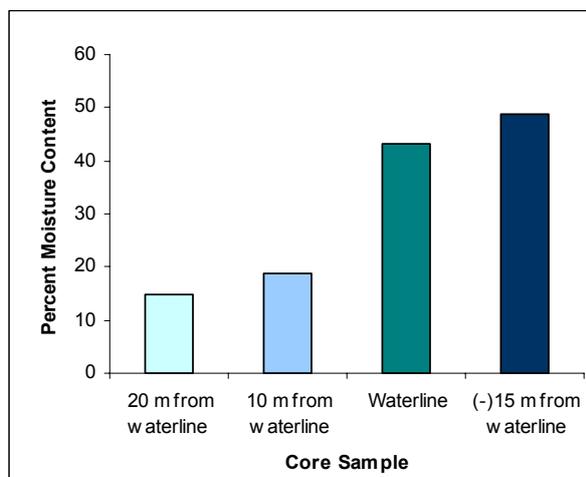


**Figures 3 and 4.** On top, the flag placed at the water line of Saliña Matijis during initial sampling was 4.8 m from the water line after 2 weeks with no rain. At 3 weeks it was 9.1 feet lower. On the bottom, an anoxic layer was present just under the surface at the waterline.

**Table 1.** Core characteristics at each location. Note the distance from the waterline in parentheses.

	A	B	C	D
Makeup	Large rocks, sand	Small rocks, sand, clay	Sand, clay	Fine Clay, algal mat
Depth of Anoxic Layer	<5 cm	<5 cm	>5 cm	>5 cm
Other Findings	Insect carapace fragments	Insect carapace fragments	Insect carapace fragments	Insect carapace fragments
	-----	Fish scales	Fish scales	Fish scales
	-----	Crustacean fragments	Crustacean fragments	Crustacean fragments
	Small seeds	Small seeds	Small seeds	Small seeds
			Flamingo feather fragments	Flamingo feather fragments
			Small live crab (1.2 cm carapace length)	Fish vertebra
Surface temperature (°C)	30.8	34	32.7	32.2
Temperature 5 cm in sediment	31.2	32.5	31.7	32.7

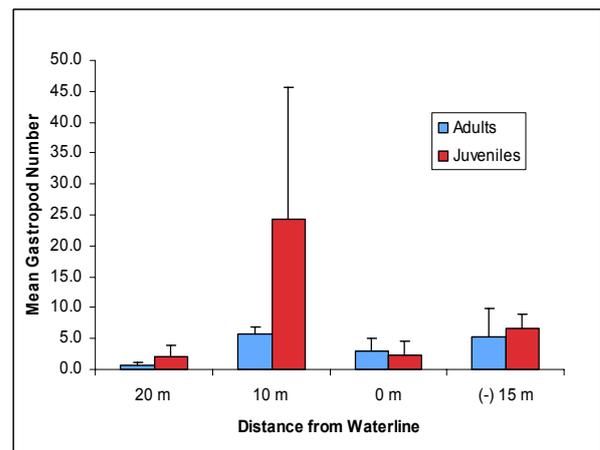
Moisture content per core sample was measured by weighing the sample, baking it until dry, reweighing it, and finding the difference. Sediment moisture levels decreased with distance from the waterline and were highest in the submerged location (Figure 5). The percent sediment moisture ranged from 14 to 50%.



**Figure 5.** Percent moisture content for cores taken along a sediment moisture gradient in Saliña Matijs, Bonaire.

Types of infauna included gastropods, nematodes, holothurians (preliminary identification of fauna of non-polychaete fauna with sediment-filled guts), one isopod, harpacticoids, and podocopid harpacticopids, (Figure 6). Preliminary identification of the gastropods suggests that they belong to the family Hydrobiidae, a widely-distributed group of marine gastropods). One consistent finding was the presence of these gastropods at every location. There was a higher ratio (0.33 and 0.23 respectively) of adults to juveniles in cores A and

B. In cores C and D the opposite was true, with an adult to juvenile ratio of 1.29 at the water line, and 0.80 in the water (Figure 6).



**Figure 6.** Mean gastropod number per core sample, with a higher ratio of juveniles in cores 20 and 10 m from the water line, and a higher ratio of adults at the water line and 15 m in the water

Community similarity was compared using a Bray-Curtis Dissimilarity matrix and cluster analysis (Figure 7). The chart showed greatest similarity between cores taken 15 m (D) into the water and the water line. The next closest in similarity is the core taken 10 m (C) from the water line. The core taken 20 m (A) from the water was the least similar to the other cores in community structure. Figure 8 illustrates the organism abundance per core, with gastropods representing the highest number of organisms present.

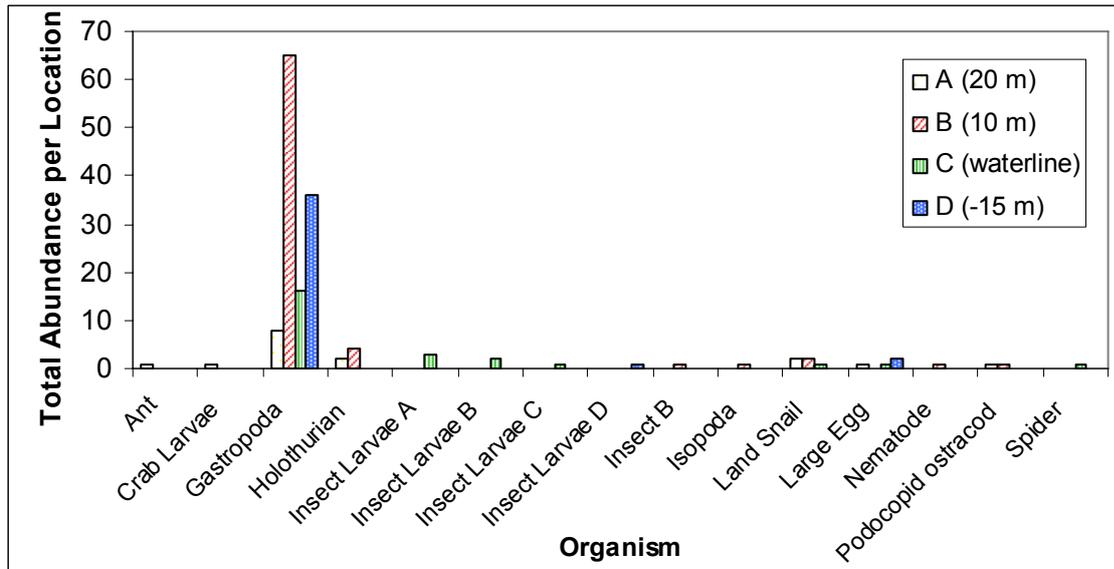


Figure 7. Infaunal community per location. Note distance from water in parentheses.

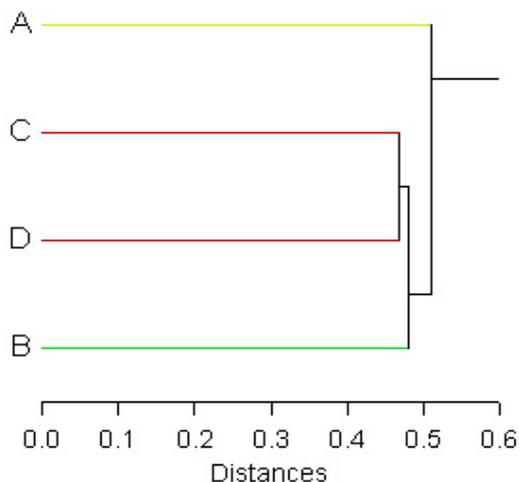


Figure 8. Cluster analysis using a Bray-Curtis Dissimilarity matrix. Numbers closer to zero are more similar, while numbers closer to one indicate dissimilarity. (A = 20 m from water line, B = 10 m, C = water line, D = 15 into the lake).

Other findings: In the preliminary core 61 m from the water line at Pos Mangel, the surface sediment temperature was 51°C. Core analysis revealed ostracods, nematodes, juvenile gastropods, and harpacticoids with eggs.

## DISCUSSION

### INFAUNAL COMMUNITY

Gastropods were consistent at all locations. Marine gastropods exhibit a high range of salinity tolerance as well as resistance (Berger and Kharazova 1997). Tolerance is determined by cellular mechanisms of adaptation, and includes reversible changes of protein and RNA synthesis, alteration of the pattern of multiple molecular forms of different enzymes, and the regulation of ionic content and cell volume. The

resistance of gastropods is based mainly on an impeded water-salt exchange with the external medium due to mantle cavity hermetization. The efficiency of resistance and tolerance adaptations to salinity changes vary in different species and habitats, as well as in different phenotypes of the same species (Berger and Kharazova 1997).

Khlebovich and Kondratenkov (1973) explored saline tolerance level adaptation in the White Sea gastropod *Hydrobia ulvae*. By exposing *Hydrobia* to step-wise lowering or increase of the habitat salinity and allowing for acclimatization to successive levels in a time sufficient enough for non-genetic adaptation, it was discovered that the gastropod could greatly extend its limits in one generation. The tolerance limits obtained are assumed to be indicative of the capacity for non-genetic adaptation and to serve as a genotypical characteristic (Khlebovich and Kondratenkov 1973). These findings support the adaptive capabilities of gastropods to areas of high or invariable salinity and water content, explaining why individuals were found along the entire sediment moisture gradient. Additionally, many gastropods can tightly seal their operculum in the shell opening, sealing water inside (Gibson 1970). This private store can be used in the interim until water is once more available. The presence of a higher ratio of juveniles to adults in the two driest cores vs. those at the water line and in the water was unexpected. One explanation is that the small body size of the juveniles makes the amount of water sealed inside adequate to deal with the lack of moisture. The adult's larger size may require more water than is possible to store. Another explanation could be attributed to a life cycle stage where there are more juveniles at that stage, but with time may be reduced. Also, as Gunter (1961) suggested, there is a correlation between the size of organisms and salinity.

In general, smaller or younger organisms thrive best in high salinity waters. It may be that the water content in the drier sediments is saltier.

The presence of fish scales and vertebrae in all but the driest core suggests that the salina supports a population of fish. The presence of organisms such as crab larvae or nematodes in the driest two cores (<19% moisture content) was unexpected. Upon revisiting the site however, the extreme variability of the water level at Saliña Matijs was evident. At the time the samples were collected, 35 m separated the driest core samples and the cores that were completely covered in water. Within three weeks, the water line had dropped a total of 9.1 m, vastly increasing the distance between the driest core and the water line. A lack of rain within those several weeks had a substantial effect on the sediment moisture content as well; sediment previously submerged appeared dry to the point of cracking. With such an incredibly dynamic system, it is no surprise that the driest point of sampling could be completely submerged given a steady series of rain storms.

#### SOURCES OF POTENTIAL ERROR

Due to the mesh size of the sieve, only organisms greater than 0.5 mm were captured and identified. By using a sieve with a smaller mesh size, the meiofaunal component of the community along the gradient could also be observed. Due to possible osmotic problems, I sieved with water from the salina; this may have introduced organisms in the samples that were only found in the surface water or overlying algae. Immediately preserving infauna in Formalin would reduce the risk of degradation of the samples over time. Repeating the procedure farther into the salina, perhaps 50 to 100 m into the body of water, would allow me to look at infauna that were always in a water-covered habitat. The water line fluctuation of the salina could also be documented immediately after a period of heavy rain and monitored to see how long it took to recess once again. Additionally, the salinity of the water before and after a rain event could be measured to establish a mean range of tolerance for these organisms. Using a salinity meter with a broader range would be necessary for future experiments. Washington-Slagbaai National Park in Bonaire contains several salinas, and repeating this experiment in each and comparing the results would be beneficial to understanding the community structure in this extreme environment. Repeating the procedure in areas of high flamingo concentration may also provide different or more

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diverse communities, as the flamingos aggregate near a food source. Hurlbert and Chang (1983) described that upon removing the Andean Flamingo from a small habitat much like Saliña Matijs, diatom, nematodes, amoebas, and ciliates. The effects on the marine community in Bonaire would also be interesting to investigate.

Community studies in Pos Mangel would also be interesting to investigate. The presence of such a variety of animals in various stages of life cycles in a temperature exceeding 51°C suggests that these are not animals temporarily existing in this circumstance until water is once again available, but thriving and reproducing. The distance from the water is also important to note, due to the fact that unless there are significant rain events for weeks at a time, the water line would not be expected to expand to saturate the sediment. Such a variety of organisms persisting in such an extreme environment was unexpected, and deserves further study.

#### CONCLUSION

This study at Saliña Matijs was directed at a very small habitat in which volume and area collectively comprise only a very small fraction of the total aquatic environment on Bonaire. The equally dynamic and much more extreme temperature of Pos Mangel makes this site an interesting candidate for future research. Like other extreme habitats worldwide, small hypersaline environments are of great interest to ecologists, physiologists, and evolutionary scientists. These habitats are very unusual because they confront potential colonizing organisms with severe adaptation and osmotic problems, but which nevertheless contain characteristic inhabitants. Through evolution of special mechanisms these organisms have achieved a remarkable degree of tolerance of their environment. The evolutionary significance of such tolerance to extreme environments is vast, potentially creating a clearer understanding of early evolution from much more severe, yet comparable habitats.

#### ACKNOWLEDGEMENTS

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# ALGAL COVER AND THE EFFECTS OF VARIOUS NUTRIENT LEVELS ON BONAIRE'S (NETHERLANDS ANTILLES) CORAL REEFS

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## ABSTRACT

A reoccurring problem facing a majority of the coral reefs in the Caribbean for the past few decades has been the fear of a changing community structure from primarily reef-building corals to algal dominance. A shift in such ecosystems could inhibit coral growth and recruitment, eventually killing corals and lowering the diversity of fish in the area. Recent developments in agriculture and technology have advanced the dispersal of various inorganic nutrients into water systems, where excess nitrogen or phosphorous levels may lead to an increase in algal photosynthesis and thus growth. For my study I looked at relationships between algal growth and nutrient levels in seawater, specifically ammonia and nitrates + nitrites. Using photography and underwater transects I looked for differences in the amount of algae at sites with high or low nutrient levels as measured in March 2006 by the Bonaire Marine Park (BMP). The site with the highest nitrate + nitrite levels had a mean algal cover of 30.6% (std. dev. 30.4), which was not statistically different from the site with lowest concentrations (mean algal cover = 22.9%, std. dev. = 23.1). Algal cover was highest at 18 Palms (mean = 38.6% std. dev. = 39.5), where the lowest ammonia concentration was found. This research showed that nutrient levels did not influence the percent algal cover at my sites. Possible reasons for these findings are discussed.

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## INTRODUCTION

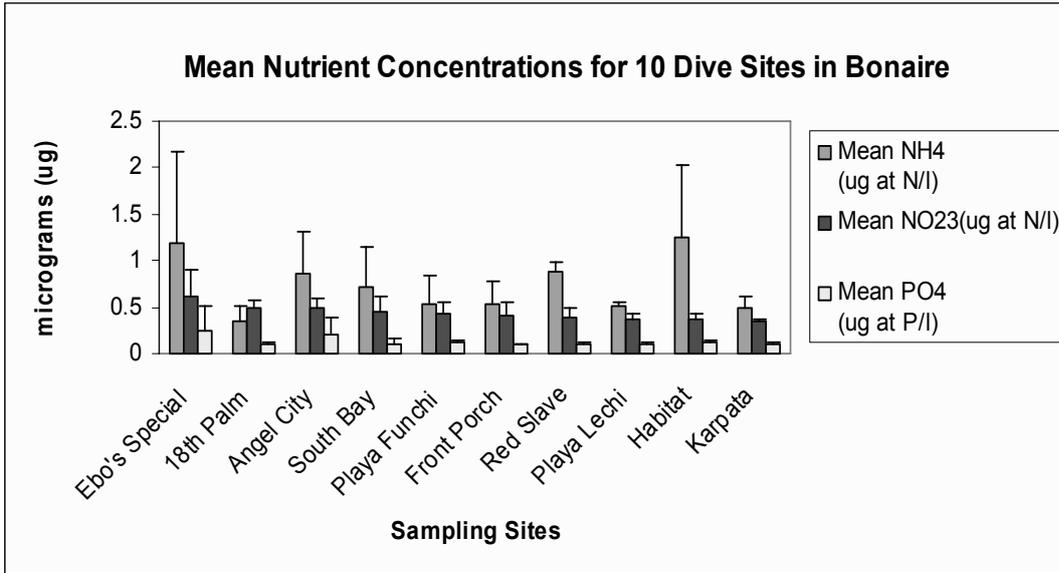
A phase shift in marine ecosystems from primarily reef-building corals to algal dominant communities has become increasingly common in the Caribbean since the 1970's (Smith 2001). This altering community structure is often attributed to a lopsided competition for resources between corals and different species of algae where algal growth tends to be dominant (McCook 2001). An overgrowth of algae in a coral reef ecosystem is thought to be the product of many different factors (i.e. decreased grazing, increased photosynthesis, etc), including those both naturally occurring and those brought about by anthropogenic (human-induced) causes. One such human-related factor effecting algal growth is the input of nutrients into marine systems. According to a study on the effects of herbivory and nutrient enrichment on benthic community dynamics, nutrient enrichment in a reef ecosystem can independently support shifts in benthic algal community structures (Smith 2001).

Organic and inorganic forms of the elements nitrogen (N) and phosphorous (P), can be attributed to a change in oceanic algal growth (Szmant 2002). Reef algae are considered somewhat nutrient limited and any addition of nitrogen and/or phosphorous has been known to accelerate photosynthetic rates thus increasing growth of algae (Smith 2001). An overgrowth of algae could potentially stress corals by means of increased sedimentation (inhibiting light input), increased algal cover (decreased coral cover preventing coral

recruitment), or by the consumption of dissolved oxygen in the water following the decomposition of dying algae (Szmant 2002).

Some natural occurrences such as upwelling and groundwater distributions have been known to cause temporary fluctuations in nutrient concentrations in reef habitats (Smith 2001). Also, recent developments in agriculture, transportation, waste management, etc., have increased the development and dispersal of many inorganic nutrients into water systems. These nutrients may break down and provide the essential nitrates/nitrites necessary for an accelerated rate of photosynthesis in algae. Ammonium for instance, must be broken down through nitrogen fixation (which can be accomplished by specific species of blue-green algae) into simpler nitrates before it can benefit algae. In fact if not broken down, it has been suggested that ammonia can actually inhibit photosynthesis and growth of certain algae (Abeliovich 1976).

Concerning ammonium fixation, the manufacturing of artificial fertilizers is attributed to approximately 57% of human induced fixation of nitrogen; making it beneficial to plants and allowing it to travel through plant and animal cycles. This production of nitrogen based fertilizers has been increasing at a rate of approximately 5% a year since the 1940's. By artificially fixating these amounts of nitrogen, increased concentrations are being transported into waterways by means of agricultural runoff and poor sewage treatment



**Figure 1:** Nutrient levels for 10 dive sites in Bonaire. The mean value for  $\text{NH}_4$ ,  $\text{NO}_{2,3}$  and  $\text{PO}_4$  is shown in micrograms (ug). Concentrations were measured in March 2006 by the BMP. Error bars = standard deviation.

where it may adversely affect coral reef habitats. (Jordan 1996)

My study focused on measured concentrations of phosphate, ammonia ( $\text{NH}_4$ ) and nitrates + nitrites ( $\text{NO}_{2,3}$ ), and the possible effect that various concentrations of each has on the growth of algae on Bonaire's coral reefs. Using data provided by STINAPA and the Bonaire Marine Park (BMP), I selected sites with high and low nutrients levels, then

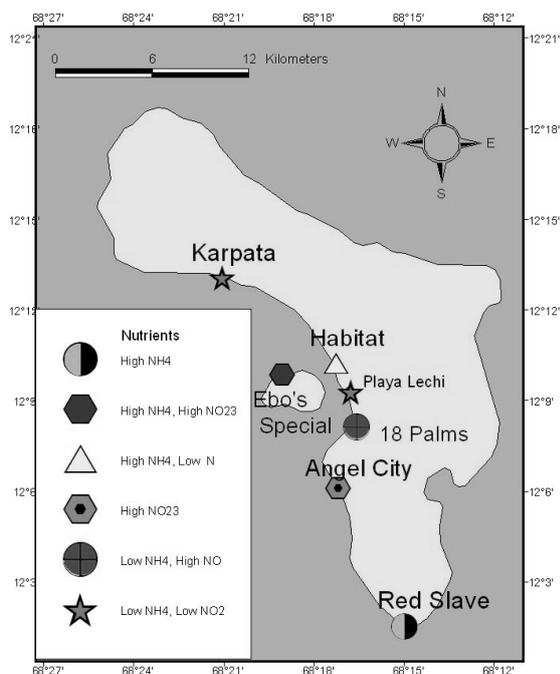
compared the percent of algal cover at those sites. I hypothesized that where there were higher concentrations of nitrites/nitrates, there would be a higher percent cover of algae due to increased rates of photosynthesis.

#### METHODS

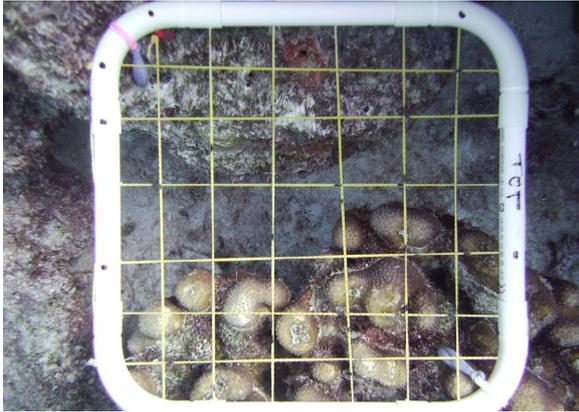
I selected specific sites along the coast of Bonaire, each having either a high or low concentration of ammonia ( $\text{NH}_4$ ) or nitrates/nitrites ( $\text{NO}_{2,3}$ ) as measured by the BMP in March 2006. The calculated means were based on 4 measurements at each site; 2 at the top of the reef and 2 at 60 feet.

I chose six locations for each nutrient: three locations of highest and three of lowest concentrations (Figure 1, 3) for each (7 overall sites due to overlap). Phosphate ( $\text{PO}_4$ ) levels were low and there was little variation so I did not include them in my study.

Three  $10 \text{ m}^2$  transects were surveyed at each dive site. They were placed 20 kick cycles apart, and parallel to shore below the sand/rubble flat at the top of the drop-off zone (ranging from 15 to 40 ft deep). For each transect, I photographed six  $25 \text{ cm} \times 25 \text{ cm}$  ( $0.0625 \text{ m}^2$ ) quadrats at randomly selected locations along the line (Figure 3).



**Figure 2:** Transects on algal growth for 7 different dive sites on the island of Bonaire. Sites were chosen according to high or low nutrient concentrations (3 highest, 3 lowest).



**Figure 3:** 25 cm x 25 cm quadrat; 6 were photographed on each of 3 10m<sup>2</sup> transects at each site. Photographs were analyzed for the percent cover of algae using the Random Point Contact method

I calculated the mean percent cover of sessile invertebrates and algae using 16 of 36 randomly selected points within the quadrat (Random Point Contact method).

### RESULTS

Nine categories were used to describe the sessile invertebrates and algae found on transects. These included algae, sand, dead coral, coral, sponge, tunicate, gorgonian, anemone, and unknown. The unknown category included holes in the coral or unidentifiable objects.

The percent cover of algae was highest at 18 Palms (mean = 38.6% std. dev. = 39.5), where the lowest NH<sub>4</sub> concentration was found in March 2006 (Figure 4). Habitat, which had the highest NH<sub>4</sub> level, also had relatively high algal cover (mean = 34.7% std. dev. = 17.2).

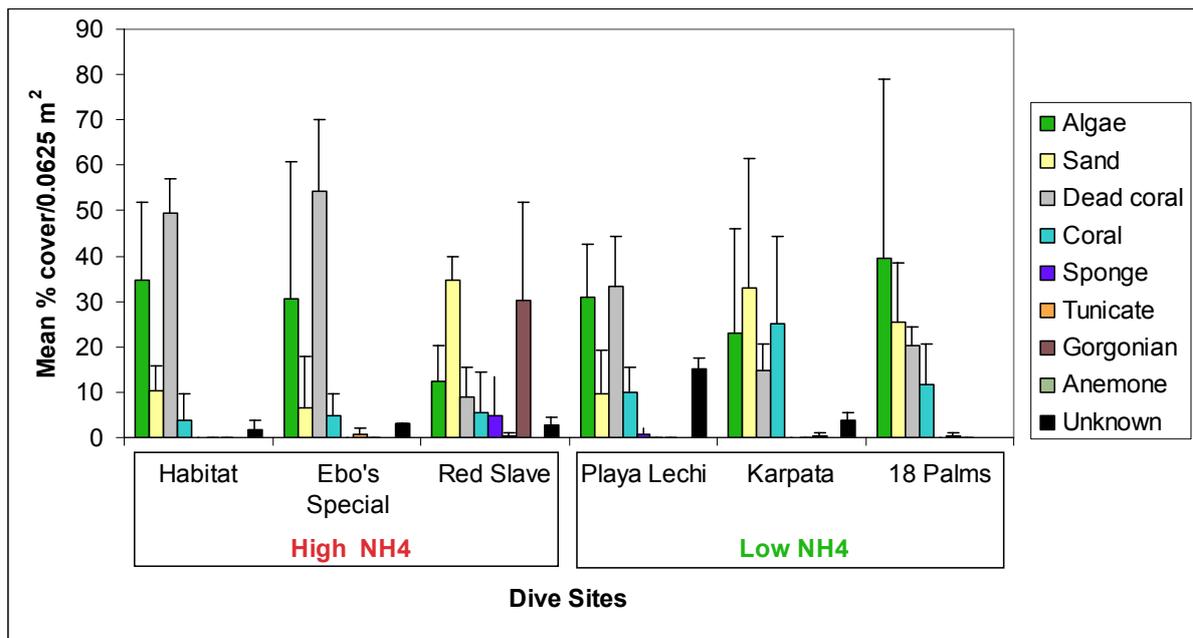
Algal cover was lowest at Red Slave (mean = 12.5%, std. dev. = 7.6) where ammonia was high. The percentage of total algal cover for sites with the three highest concentrations of NH<sub>4</sub> was not statistically significant different from the sites with low concentrations.

The results for algal cover at the high and low NO<sub>2,3</sub> sites were similar to those of NH<sub>4</sub> in that there was little variation between the high and low concentrations (Figure 5). Percentages varied from 39.6% (18 Palms, the second highest NO<sub>2,3</sub> content) to 22.9% (Karpata, having the lowest NO<sub>2,3</sub> content).

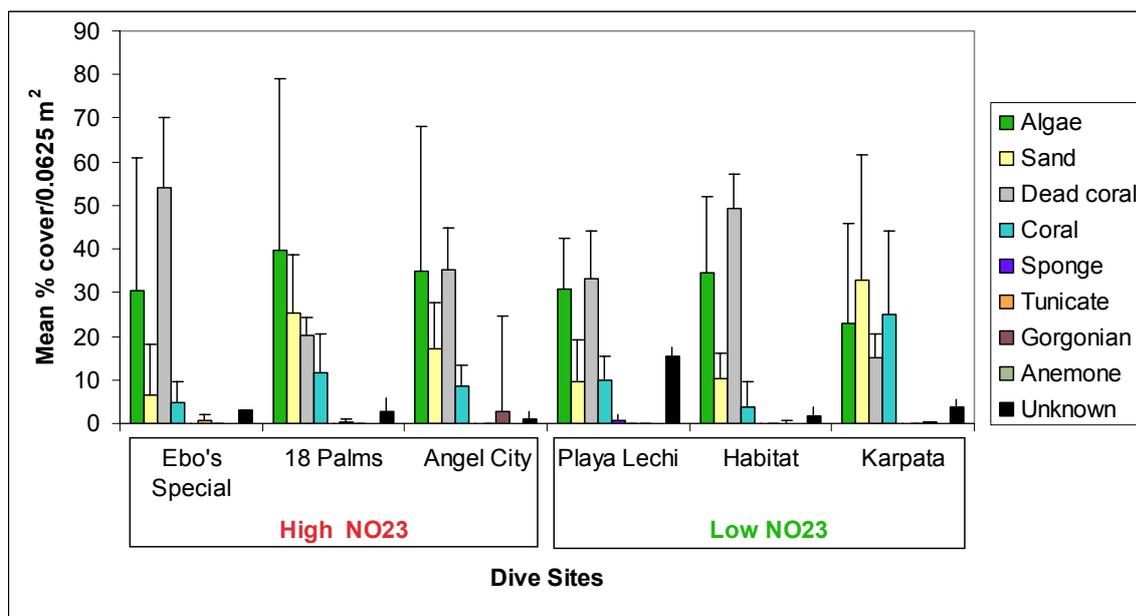
For these seven sites at the top of the reef, coral cover was highest at Karpata (mean = 25% std. dev. = 19.3) and 18 Palms (mean = 11.8% std. dev. = 8.7).

### DISCUSSION

Algal overgrowth can be attributed to many different factors; eutrophication, reduction in herbivory (overfishing or die-offs of herbivores), and other environmental stressors such as disease or climate (Smith 2001). The NO<sub>2,3</sub> levels were the highest at Ebo's Special, and according to my hypothesis this site should have a higher percent cover of algae than other locations. Instead, algal presence was not significantly different compared to the other dive sites. This could be due to other factors such as high levels of grazing by herbivores or coral successfully out-competing algae for places to settle. Or that the nutrient levels may not be high enough to induce a change in algal cover.



**Figure 4.** Percent cover for nine categories of sessile invertebrates and algae for sites with the highest and lowest measured concentrations of ammonia (NH<sub>4</sub>) as measured for sites on Bonaire by BMP in March 2006. Error bars = standard deviation



**Figure 5:** Percent cover for nine categories of sessile invertebrates and algae for sites with the highest and lowest measured concentrations of Nitrites + Nitrates (NO<sub>2,3</sub>) as measured for sites on Bonaire by BMP in March 2006. Error bars = standard deviation

Another explanation for my results is that the original nutrient concentrations may have been ephemeral. Measurements were taken once per site, so if an abnormal amount of ammonia or nitrogen was in the area at the time the samples were collected, nutrient concentrations would have been higher than normal. For example, when taking water samples if any concentrated animal wastes were present, nitrogen levels would have been higher than normal (Ramon de Leon, personal communication).

The BMP will continue to measure nutrient levels for their ongoing monitoring program, so it will be interesting to see if the nutrient concentrations fluctuate at each site. The reef crest varied at each site so I couldn't use a consistent depth throughout the experiment. One specific depth for each site could have given different results due to variations in sediment loading, temperature, etc. that could have resulted in changes to algal growth.

Ebo's Special and Habitat were the sites with the two highest concentrations of ammonia, though they also had the two highest standard deviation values. This implies that the higher average was not the result of consistently larger numbers, but rather lower numbers with high outliers (Figure 1). There was also large

variations in the percent algal cover at some sites (Figure 4, 5). For instance, Ebo's Special had the highest algal cover and the second highest concentration of NO<sub>2,3</sub>, though it also showed the highest variation in algal cover. In this case, a few areas with dense patches of algae resulted in a high average for the entire site.

With additional resources, I would conduct more transects at each site, monitor nutrient inputs more closely and document herbivorous fish activities at these sites. I would also like to directly test the effects of nutrients inputs, by creating a device that would allow slow diffusion of certain nutrients onto a small patch of reef.

#### ACKNOWLEDGEMENTS

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# THE DISTRIBUTION OF BLACK BAND DISEASE ON BONAIRE CORALS IN RELATION TO ENVIRONMENTAL FACTORS

Katie Stroud

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## ABSTRACT

In the 1970s, black band disease (BBD) emerged as a mass coral killer and caught the attention of scientists. Although BBD has been studied for more than thirty years, it continues to confound scientists due to the complexity and composition of the bacterial mat which varies among BBD cases. In previous studies, BBD was found in correlation with small environmental changes. Because the distribution of BBD has not been previously documented for Bonaire, I studied its distribution and measured environmental parameters (depth, temperature, pH, phosphate and nitrogen) at six sites. I also recorded the number of BBD incidents on 3 replicate transects, each 10 m<sup>2</sup> in area and 10 m apart at both 15 and 30 feet. BBD was found at Andrea II (both depths), Angel City (both depths) and Jeannie's Glory (15 ft), but not at Karpata, Captain Don's, or Yellow Submarine. Informal surveys at other dive sites on Bonaire and Klein Bonaire showed BBD cases at Monk's Haven, Monte's Divi, and Handsoff reef, but it was not present at Boca Bartol or Nukove. Most BBD cases were found shallower than 20 feet. I found no statistically significant differences between environmental parameters and observed BBD cases.

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## INTRODUCTION

The degradation of coral reefs has risen exponentially during the last several decades (Harvell et al. 1999). Environmental issues such as global warming, pollution, and eutrophication have taken their toll on these sensitive animals (Harvell et al. 1999). Diseases, in particular, were discovered infecting reefs and many studies have been done to gain a better understanding of the problem (Frais-Lopez et al. 2004, Harrabin 2006, Harvell et al. 1999, Miller 2005, Richardson 2002). Coral disease was first found on reefs in the 1970's, and is now known to affect multiple coral species throughout the world (Birkeland 1997). BBD primarily affects the family Faviidae, mainly *Diploria spp.*, *Colpophyllia spp.*, and *Montastrea spp.* (Birkeland 1997). BBD is characterized by a 1-30 mm migrating black band that sweeps from the top of the coral to the base. Cyanobacteria, particularly *Phormidium corallyticum*, in combination with other sulfide-oxidizing bacteria such as *Beggiatoa spp.* and sulfur-reducing bacteria *Desulfovibrio spp.* produce an anoxic, sulfide rich mat that is toxic to the coral tissue (Richardson 2002b).

In Bruckner's *Priorities for the Effective Management of Coral Disease*, he examines several studies that found that BBD may transmit itself through the water column (Bruckner 2002). In infected areas of moderate turbidity, coral colonies that are down current have developed BBD, suggesting water movement as a possible transmission vector (Bruckner 2002). Water movement may carry the disease or the conditions that affect its prevalence to remote areas that are seemingly free from anthropogenic effects.

There is no one single pathogen responsible for BBD and the etiology of the black band itself is under much

debate. According to a study done by Frias-Lopez et al. in 2004, the mat consists of a combination of various bacteria, mainly cyanobacteria. By using Terminal-restriction fragment length polymorphism (T-RFLP), a microbial consortium was found to inhabit the band. T-RFLP uses primers that amplify a particular rRNA sequence; in this experiment 16S rRNA genes that are specific to cyanobacteria were used. Using PCR amplifications, the primer is mixed with DNA from the bacterial mat taken from corals infected with BBD. The bacterial community from healthy and diseased corals was analyzed. Frais-Lopez et al. found a strong resemblance between the bacterial community of healthy corals and that of the pathogenic mat suggesting that corals somehow undergo a "switch from a healthy to diseased profile" (2004). Perhaps there are slight changes in the environment that enable the pathogens to infect coral tissue. For example seasonal changes in temperature, turbidity, and rainfall (and thus salinity) may work together to alter the bacterial community of the coral resulting in BBD. These changes may directly effect the growth and abundance of the bacteria themselves or indirectly contribute to a decrease in coral's resistance to infection.

In the Western Atlantic during summer and fall, there is an increase in BBD cases due to the seasonal temperature increase, and the number of cases significantly diminishing in the winter (Bruckner 2002). In another study conducted by Richardson et al., the photosynthetic activity of *P. corallyticum* increases with temperatures above 28 °C, and decreases at temperatures less than 25 °C (Richardson 2002a). These temperature ranges parallel the observed seasonality of BBD and point to *P. corallyticum* as the primary driving force behind the disease.

The distribution of BBD occurs mostly in clear calm warm waters, yet it is able to infect under a wide range of conditions (Birkeland 1997). Clumps of BBD are often observed during all times of the year; some reefs have multiple BBD occurrences in a year or even continuous infection (Richardson 2002b). In a comparison of different coral shelves on the Great Barrier Reef in Australia, shallower inner and mid-shelf reefs were found to have a significantly higher frequency of BBD compared with the deeper outer shelf (Miller 2005). Water depth may contribute to BBD prevalence due to variability in light penetration, temperature and pressure, all of which may affect coral susceptibility to infection. Similarly, a recent Caribbean study found BBD only in waters less than 6.6 m in depth (Kuta 2002).

Increased anthropogenic CO<sub>2</sub> emissions are reportedly affecting the pH of the ocean (Harrabin 2005, Burke 2004). Scientists believe that the pH has fallen by about 0.1 units and may continue to fall from a pH of 8.0 to as low as 7.6 (Harrabin 2005). Increased CO<sub>2</sub> levels dissolved in the ocean decrease coral's calcification rates (Burke 2004). Subsequent decreases in levels of other reef-building compounds such as aragonite have further reduced coral calcification and the decline of hermatypic reefs (Burke 2004). Many scientists believe that the significance of this change may cause the coral reef systems to collapse (Harrabin 2005).

Kuta and Richardson of the Department of Biological Sciences of Florida International University studied the correlation between nitrogen and phosphate compounds, temperature, light, turbidity, salinity, coral cover, and coral diversity on 200 sites in the Florida Keys (Richardson 2002b). Their research found a significant correlation between water depth, water temperature, coral diversity, and levels of ortho-phosphate and nitrite (Richardson 2002b). Their results support previous research findings that BBD is most prevalent at higher temperatures and at shallower depths. My experiment will compliment the work of Richardson and Kuta by examining environmental parameters including temperature, salinity, pH, and concentrations of nutrients at six sites on Bonaire. To my knowledge, the distribution of BBD along Bonaire's reefs has not yet been documented. Mapping the distribution of BBD may help the National Bonaire Marine Park in their management of the reef by providing a baseline for future research regarding this coral disease.

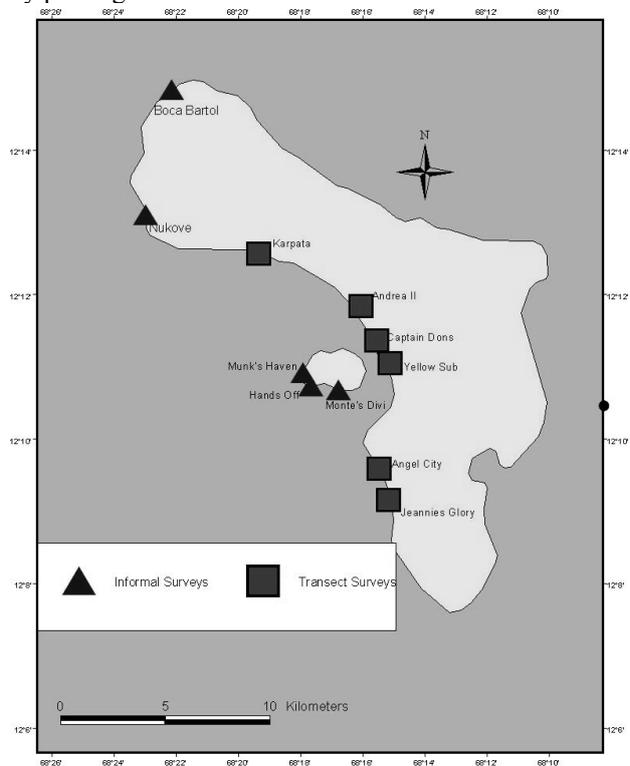
## METHODS

### QUANTITATIVE TRANSECT SURVEYS

In order to investigate sites with a variety of environmental conditions, I chose six sites along the leeward shore of the island (Figure 1).

Site A: Karpata is a high energy site to the north and down stream from BOPEC, an oil storage site on the island.

Site B: Captain Don's reef Current velocity may be mitigated by the presence of Klien Bonaire and influence BBD prevalence. The location may subject the reef to nutrient runoff from resort sewage treatment or from nearby parking lots.



**Figure 1:** An overview of all dive sites sampled during this study by quantitative transect and informal surveys

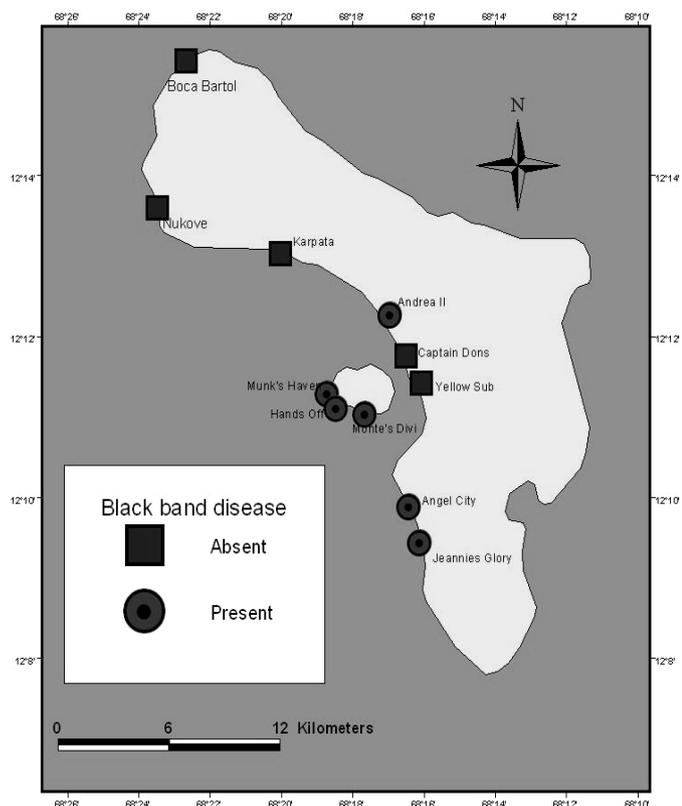
Site C: Andrea II is just offshore of a new housing development. Dense coral cover begins in relatively shallow water. I observed low turbidity on several visits to the site which may contribute to water clarity, increasing the amount of sunlight available to coral.

Site D: The Yellow Submarine reef is in front of Kralendijk, the capital of Bonaire and beneath boat traffic; it is across from Klien Bonaire which may contribute to its low energy water movement and possibly slower currents.

Site E: Angel City reef lies downstream of the salt pier. It appears to be a popular dive site. High diver frequency may influence coral stress and thus BBD incidence.

Site F: Jeannie's Glory is directly downstream from the pier where the salt from Cargill Salt Company is loaded onto transporting ships. I hypothesized that this, or overflow from salt production, may cause and increase in salinity at this site.

During random preliminary observations, I found BBD at both 15 and 30 feet, therefore for each transect site, I sampled three 10 m<sup>2</sup> belt transects at each of these two depths. Comparison of BBD incidence at multiple depths will provide insight into the relationship between depth and BBD incidence. On each transect I counted the presence



**Figure 2:** An overview of sites sampled by both quantitative transect and informal surveys. The presence or absence of BBD is shown.

and frequency of BBD within 1 m of the transect line, noting specific coral species on which it occurred. I measured the temperature (ERT600) three times per depth at each site. Three bottles of water were collected at each depth at each site at tested for salinity (YSI 85D meter), pH (Exstik EC500), nitrogen levels (LaMotte Nitrate-Nitrogen kit in ppm) and phosphate levels (CHEMets Phosphate kit in ppm). I also conducted haphazard swimming surveys at to establish the presence or absence of BBD off-transect.

#### INFORMAL SURVEYS

I conducted informal surveys for BBD at five additional sites (Monk's Haven, Hand's Off, and Monte's Divi off Klein Bonaire and Boca Bartol and Nukove in the northwest off the main island. I swam haphazardly around the reefs looking for BBD incidence. When encountered BBD, I recorded the depth at which it occurred and noted surrounding coral density. If I did not record BBD at a particular site, BBD occurrence at these sites cannot be absolutely disregarded due to the haphazard nature of the sampling.

#### STATISTICAL ANALYSIS

I used a two-way ANOVA (Systat v.11) to test for differences in the mean number of BBD incidents between sites and the two sampling depths. Co-factors for temperature, salinity, pH, phosphate and nitrogen were also tested.

#### MAPPING CURRENTS

In addition to mapping sampling sites, I used ArcView 3.2 to depict the prevalent currents around Bonaire using information published by Kallie de Meyer, Bonaire National Marine Park's former manager (De Meyer 2006).

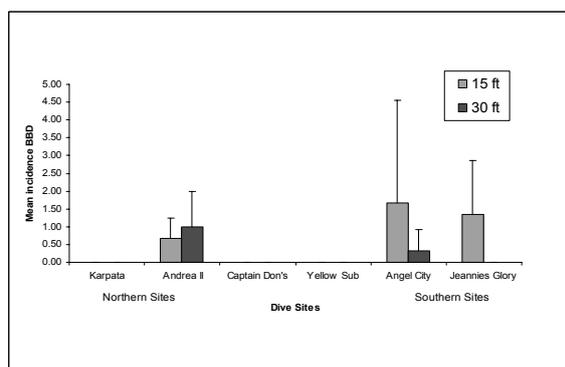
#### RESULTS

##### TRANSECT SURVEYS

I found BBD on transects at Andrea II (15 ft mean = 0.67, stdev = 0.58, 30 ft mean = 1.0, stdev = 1.0) Angel City (15 ft mean= 1.67, stdev= 2.89, 30 ft mean= 0.33, stdev= 0.58), and Jeannie's Glory (15 ft mean= 1.33, stdev= 1.53) (Figure 2, 3). BBD occurred exclusively on *Montastrea annularis* at Andrea II, and Angel City and on both *M. annularis* and *Diploria spp.* at Jeannie's Glory There was no BBD seen at Karpata, Captain Don's, or Yellow Submarine (Figure 2, 3).

Temperatures ranged from 26.4 °C at Angel City (30 ft) to 28.4 °C at Andrea II (15 ft) (Figure 4). Salinity ranged from 31.4 ppt at Karpata (30 ft) to 35.1 ppt at Andrea II (15 ft). The lowest pH reading was 8.0 recorded at Captain Don's (15 ft) with a high of 8.2 Andrea II (15 ft). A maximum nitrogen

level of 1.00 ppm was recorded at Andrea II (both depths), Jeannie's Glory (15 ft), and Karpata (30 ft). The lowest concentrations of nitrogen (0.33 ppm) were recorded from Captain Don's (both depths), Yellow Submarine (both depths), Angel City (30 ft), and Jeannie's Glory (30 ft). No phosphate was found in the water at Andrea II (15 ft), Yellow Submarine (both depths), Captain Don's (30 ft), Angel City (30 ft), and Jeannie's Glory (30 ft). A high of 3.33 ppm was recorded at Karpata (15 ft).



**Figure 3:** Mean incidence of BBD per 10 m<sup>2</sup> at 15 and 30 feet for dive sites where quantitative transects were conducted. Error bars = standard deviation, n=3.

#### STATISTICAL ANALYSIS

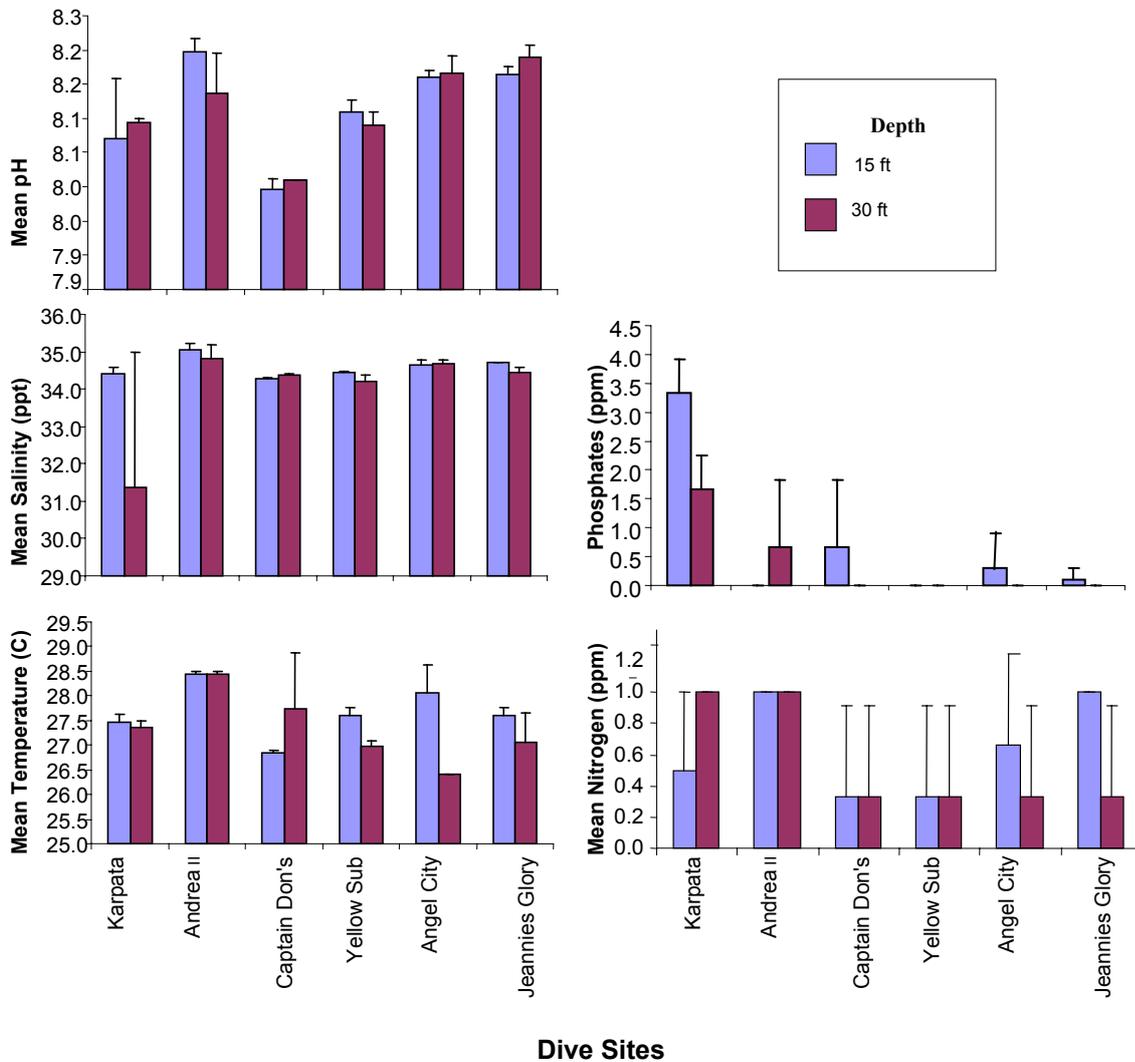
There were no statistically significant differences between sites or depths and BBD incidence (Table 1). There were also no significant interactions in the means for the physical parameters I measured (Table 2).

**Table 1:** 2-way ANOVA results for a test of mean BBD incidence between sites (6 transect locations), depths (15 and 30 ft), the interaction between site and depth ( $\alpha = p < 0.05$ ).

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
Site	5.274	5	1.055	1.008	0.44
Depth (ft)	0.051	1	0.051	0.049	0.83
Site*Depth(ft)	3.581	5	0.716	0.684	0.64

**Table 2:** A 2-way ANOVA was used to determine possible interactions between environmental parameters and the incidence of BBD. There were no significant differences among any of the variables ( $\alpha = p < 0.05$ ).

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
Site	5.274	5	1.055	1.008	0.44
Depth (ft)	0.051	1	0.051	0.049	0.83
Site*Depth(ft)	3.581	5	0.716	0.684	0.64
Temperature(C)	0.11	1	0.11	0.105	0.75
Salinity (ppt)	0.33	1	0.33	0.315	0.58
pH	2.959	1	2.959	2.827	0.11
Nitrogen (ppm)	0.632	1	0.632	0.604	0.45
Phosphate (ppm)	3.561	1	3.561	3.402	0.08
Error	19.89	19	1.047		



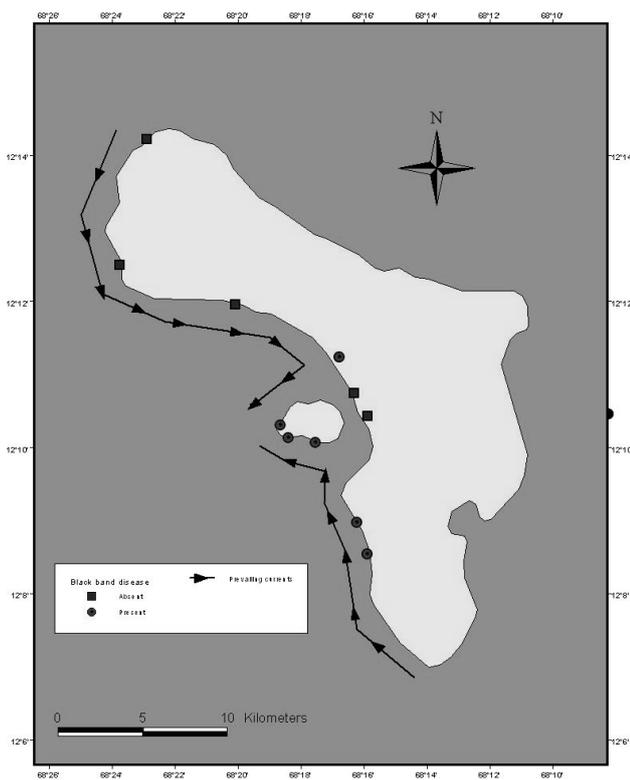
**Figure 4.** Means and standard deviations (error bars) for physical parameters measured in water samples ( $n = 3$  at each transect site).

### INFORMAL SURVEYS

BBD was found on *Copophyllia natans* and *Diploria spp* at Monk's Haven, Hand's Off, and Monte's Divi off Klein Bonaire at depths of roughly 30 feet. *Montastrea spp* was found at these sites, but none were found with BBD. No BBD was observed at Boca Bartol and Nukove.

### MAPPING CURRENTS

Bonaire's currents are mild, rarely exceeding 0.5 m/s (De Meyer 2006). Predominate currents, however, flow northward along the leeward side of the island (De Meyer 2006). Prevalent currents also follow the pattern of the easterly trade winds (from 70-110 degrees) (De Meyer 2006). These winds prevail 97.2% of the time, but may reverse due to passing hurricanes (De Meyer 2006). My observations of the prevalent currents around the island followed this fairly predictable wind pattern. Around the southern end of Bonaire and Klein Bonaire, BBD distribution falls along the current path suggesting currents as possible vector for the transport of the pathogen (Figure 5)



**Figure 5.** Distribution of BBD in relation to prevailing current flow for surveyed dive sites. Current flow around the southern tip of the island follows BBD distribution patterns from southern dive sites to sites along Klein Bonaire. This suggests currents as a possible vector for pathogen transport along the reef.

### DISCUSSION

#### DEPTH AND INCIDENCE OF BBD

According to a study done by Richardson and Kuta in the Florida Keys, no BBD cases were found at depths over 6.6 m (21.6 ft) (2002b). In my study, fourteen cases were found at greater than or equal to thirty feet during both transect and informal surveys. Untested factors concerning reef slope, turbidity, temperature, etc. may affect BBD occurrence at deeper depths on Bonaire. Varying light levels affect the bacterial composition of the band (Richardson 2002b). The sulfide-oxidizing bacteria, *Beggiatoa*, often more concentrated in disease in aerobic environments with moderate to high light levels, whereas *P. corallyticum* migrates to the band surface in low light environments (Richardson 2002b). This adaptation allows BBD to flourish under a range of light levels. Further examination of other differences between shallow and deep depths may provide scientists with information concerning the nature of BBD infection and propagation, such as sulfide and oxygen concentration or overall coral health at various depths.

My observation at these particular sites was that at 15 feet coral density was markedly less than that at 30 feet. Sand flats with small coral recruits were often present at the shallower sampling stations. In this study, BBD cases occurred most frequently in depths less than 20 feet, but in some cases only a few coral heads were found along transects at 15 ft. The likelihood that BBD will occur along a particular transect is much greater for transects done at 30 feet due to the density of corals at that depth and the frequency of occurrence within the observed area as compared with areas at 15 feet. If coral densities were higher at 15 ft, I would expect there to be a statistically significant relationship found between depth and BBD incidence.

If the pathogen is transported in the water column, a greater density of corals may yield a higher frequency of infection. More corals in closer proximity would therefore enhance the spread of the disease although results from a previous study suggest that BBD transmission is not affected by coral proximity (Richardson 2002). Higher coral densities at 30 ft would lead one to infer that there would be a greater frequency of BBD; however differences in environmental parameters such as levels of sunlight reaching coral, water visibility, or temperature may make BBD more prevalent at shallower depths. Although I found more BBD cases at 15 ft, BBD incidence at 15 and 30 ft were not found to have a statistically significant relationship.

#### TEMPERATURE AND INCIDENCE OF BBD

BBD often occurs during months of the year when temperatures exceed 28°C (Richardson 2002a). The maximum temperature recorded during this study was 28.4°C, with an average of 27.6°C. Richardson and Kuta found *P. corallyticum* photosynthesis to be dependent upon higher temperatures finding maximum photosynthesis rates at temperatures exceeding 30°C (2002a). Very low

photosynthesis was detected at temperatures below 20°C (Richardson 2002). Their study found substantial bacterial photosynthetic rates between 20 and 30°C (2002a). The temperatures recorded in this study fall within this range, but if temperatures rise due to global warming an increase in BBD may very likely follow.

No conclusions can be made about the relationship between temperature and BBD incidence from this study, because water temperature may be ephemeral, and my temperatures were taken at different times of day. A more conclusive method would entail temperature readings at the same time on the same day for all the sites. Multiple readings over a specified length of time would yield better information about the actual temperature at various sites over time.

#### SALINITY AND INCIDENCE OF BBD

Bonaire's salt production industry on the southern end may periodically alter the salinity of the marine environment. Although salinity readings for southern sites (Angel City and Jeannie's Glory) were not above average, salt transportation may expose coral to small fluctuations that may occasionally stress corals, making them susceptible to BBD infection.

#### PH AND INCIDENCE OF BBD

The recorded pH levels for sampled dive sites fell at or near 8.0, the normal ocean pH (Harrabin 2005). The September 2003 issue of New Scientist magazine reported that ocean pH has already fallen from 8.3 after the last ice age due to increased CO<sub>2</sub> emissions after the industrial era (Hecht 2003). If atmospheric CO<sub>2</sub> continues to rise, surface pH will drop below 7.4 by 2300 (Hecht 2003). If ocean acidity increases as predicted, coral health will undergo further stress. Increased stress levels may result in an increase in BBD infection.

#### NUTRIENT LEVELS AND INCIDENCE OF BBD

In my investigation, no conclusive evidence was found to suggest a relationship between nutrient levels and BBD incidence. Because nutrient levels may fluctuate over short periods of time, water samples taken at different times throughout an entire year would be more conclusive as to the actual nutrient concentrations at a particular reef. These fluctuations in nutrient levels over a length of time may alter the health of the reef making it more susceptible to disease.

Several studies have found a significant relationship between nutrient levels and BBD incidence (Bruckner 2002, Miller 2006, Richardson 2002b). Although nutrient levels were found to be significantly higher in areas with BBD, BBD occurrence in remote areas suggests that high nutrient levels are not a requirement for BBD infection (Richardson 2002). Richardson argues that perhaps BBD microbial activity itself may result in nitrite elevation (2002).

The nitrogen and phosphate kits that I used had low resolution. Color matching was used to determine nutrient levels and rendered results somewhat subjective. Using higher quality testing methods might yield better results and may have possibly shown a relationship between nutrient levels and BBD incidence.

#### BBD DISTRIBUTION

In many observed BBD cases, the disease may have infected a set of neighboring corals, however there was not an obvious pattern of infection along transects. At Angel City, one transect at 15 feet had five separate cases of BBD, yet the other two transects did not have any BBD cases.

In a few incidences at Jeannie's Glory, corals displayed a very light black band of roughly 1 mm thickness. The corals displayed a pattern of polyp death similar to that of BBD. Perhaps these corals were previously infected by the disease, and have begun to heal. A sample of the band would need to be taken in order to determine the composition of the band and determine its origins. During a three year long study by Borger and Steiner, 25 percent of all disease infected coral BBD, white plague, and dark spots syndrome were reinfected the following year (2005). Perhaps the initial attack on colony's health weakened it making it more susceptible the following year.

#### CURRENTS AS A PATHOGEN VECTOR

The distribution of BBD along the southern coast of Bonaire and the reef along Klein Bonaire seem to follow the prevailing south to northwest current flow around the island (Figure 5). The sites on the southern end of Bonaire and Klein Bonarie both included BBD infected brain corals, *Diploria spp.* and *Copophyllia natans*. Frias-Lopez et al. did not find the pathogen to be species specific, but it is interesting that the only brain corals infected by BBD were along the southern route where prevailing currents run northward (2004). Richardson and Kuta suggest currents as a transporter of the bacterium *P. corallyticum* (2002a). To test this theory of current pathway microbial analysis of the bacterial mat among the BBD bands would need to be analyzed. Perhaps there is a genetic marker that can positively link the cases together.

#### CONCLUSION

The question remains: how did the BBD pathogen reach Bonaire? Is it simply a pathogen that infects the colonies or are there environmental factors that allow a colony to be susceptible to a constant pathogen? Continued data collection in the Caribbean with regard to environmental parameters may determine the extent to which environmental stresses determine infection rates. Evidence from this study may suggest that for Bonaire, the distribution of a pathogen from a southern source might determine BBD incidence, but further research needs to be done in order to determine exact cause.

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Dive Shop donated boat dives to Klein Bonaire for data collection. Ramon de Leon let me use STINAPA's salinity meter for my water samples and provided me with information concerning Bonaire's reefs. Special thanks to Patrice Rannou for feeding me so that I had the energy to complete the project.

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# PARROTFISH AS A POSSIBLE VECTOR FOR ZOOXANTHELLAE DISPERSAL ON CORAL REEFS

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## ABSTRACT

The stoplight parrotfish, *Sparisoma viride*, is one of the dominant herbivores on the reefs of Bonaire. The effects of macroalgae herbivory have been well documented but the potential of *S. viride* to act as a shuttle for zooxanthellae remains unknown. Although coral is not considered a food item of *S. viride* they occasionally bite living tissue off of colonies of the scleractinians *Montastrea annularis* and *Colpophyllia natans*. Coral tissues contain large amounts of symbiotic dinoflagellates of the genus *Symbiodinium*, commonly referred to as zooxanthellae. *Symbiodinium* may be the key primary producer of the reef ecosystem and are found almost exclusively in symbiotic relationships with cnidarians. It is the aim of this article to examine the potential role of *S. viride* as a vector for transport of *Symbiodinium* throughout the reef environment as a result of parrotfish white spot biting. The purpose of coral biting is not known but territoriality is suspected in focused biting. Depending on the effect of parrotfish ingestion on the *Symbiodinium* cells, parrotfish white spot biting behavior could result in transport of *Symbiodinium* throughout the reef environment, increasing the genetic diversity of zooxanthellae populations.

## INTRODUCTION

Grazing fish are typical of healthy tropical reef environments (Smith and Paulson 1974). With the significant Caribbean-wide loss of the sea urchin grazer *Diadema antillarum* in 1983 coral reefs have become more reliant on the activities of teleost grazers such as *Sparisoma viride* (Mumby 2006). Scarid grazing is one of the most important factors influencing whether a tropical marine system is coral dominated or algal dominated (Mumby 2006). Herbivores can alter both the trajectory and rate of succession in marine environments (Hixon and Brostoff 1996). According to recent models this is primarily due to the constant grazing of algae that provides open substrates on which coral larvae may settle (Mumby 2006).

*S. viride*, a member of the scarid family and commonly known as the stoplight parrotfish, is an herbivorous reef fish found in the Caribbean. *S. viride* are sequential hermaphrodites, the initial phase individual can be either male or female (Fig. 1) while the brightly colored, terminal phase, individual is male (Fig. 2). *S. viride* account for 22% of the total herbivore biomass, 32% of the scarid population, and 20% of carbon intake on the shallow reefs of Bonaire, Netherlands Antilles (Van Rooij *et al.* 1998). *S. viride* can be found in the shallow reef front or on the reef crest to depths of approximately 25 meters (Humann and DeLoach 1989).

*S. viride* feed by scraping macroalgae off of reef substrates, often dead coral skeletons, leaving small divots in the surface (0.7 X 1.0 cm<sup>2</sup>) (Frydl and Stearn 1978). The skeleton fragments and plant matter are then ground to pulp in the pharyngeal mill before passing through the digestive system (Van Rooij *et al.* 1998). Viewed over time, this process liberates relatively large amounts of small CaCO<sub>3</sub> rubble and is a



Figure 1. Initial phase *S. viride* (photograph by L. Kuhnz).



Figure 2. Terminal phase *S. viride* (photograph by J. Brandon)

major contributor to sand formation. Van Rooij *et al.* (1998) noted that much organic matter passes undigested through the parrotfish digestive system and is available to microfaunal and meiofaunal organisms. The relative abundance of undigested materials in *S. viride* (Van Rooij *et al.* 1998) feces could be important

for *Symbiodinium* survival and possible transportation in coral reefs.

Unicellular algae from the genus *Symbiodinium* are dinoflagellates commonly found in obligate symbiotic relationships with scleractinian corals and other cnidarians (Muller Parker 1984). The exchange of material between symbiont and host facilitates increased tissue growth and calcification rates (Houlbreque et al. 2004). Corals excrete nutrients, such as nitrogen and phosphorus, and provide a safe, productive environment for zooxanthellae that in turn provide the coral host with photosynthetically fixed carbon (Schwarz et al. 1999). Zooxanthellae are ubiquitous within tropical reef assemblages, found in various cnidarian tissues in densities that may be as high as  $1 \times 10^8$  algal cells  $\cdot$  cm<sup>-2</sup> in healthy reefs (Baker 2003) but consistently range from  $1 \times 10^6$  to  $2 \times 10^6$  cells cm<sup>-2</sup> (Fagonee et al. 1999).

There are currently thought to be 5 different clades, *A*, *B*, *C*, *D*, and *F* of zooxanthellae found in symbiosis with scleractinian corals (Baker 2003). Corals exhibit a flexible specificity for particular strains of *Symbiodinium* (Baker 2003, Muller Parker 1984). Kinzie and Chee (1984) were able to demonstrate that aposymbiotic hosts grew at different rates when re-infected by zooxanthellae cultured from different hosts. It is believed that different species or clades of zooxanthellae offer a competitive advantage in specific environmental conditions and corals preferentially establish relationships with symbionts to maximize the energy gains from their specific environment (Baker 2003).

Most species of scleractinian corals are broadcast spawners, meaning that eggs and sperm are released into the water column where fertilization occurs (Hughes and Tanner 2000, Schwarz et al. 1999). Approximately 85% of symbiotic cnidarians extract zooxanthellae from the environment (Pasternack et al. 2006), often while feeding, and incorporate the alga into their tissues (Schwarz et al. 1999). The coral *Fungia scutaria*, a broadcast spawner, can be infected by zooxanthellae during the free swimming planula larva stage or as a settled polyp (Schwarz et al. 1999). However, because there are relatively few zooxanthellae in the water column (Baker 2003) it may be more likely that they are infected by a specific vector once the larvae have settled on a substrate. Some species of coral may only be receptive to zooxanthellae infection after settlement (Schwarz et al. 1999).

Little is known of the ecology of free-living zooxanthellae and only one instance where *Symbiodinium* was isolated from the water column has been published (Pasternack et al. 2006). Free-living zooxanthellae are flagellated and Pasternack et al. (2006) have shown that they can direct their motion

towards likely hosts. A “host attractant” released by aposymbiotic corals aids in focusing zooxanthellae movement towards the host. Zooxanthellae must be within close proximity because they can only detect the host attractant if they are within centimeters to decimeters of the source (Pasternack et al. 2006).

It is my hypothesis that *S. viride* that bite live coral tissue transport and disperse zooxanthellae across the reef environment found on Bonaire, Netherlands Antilles. There are three fundamental questions that need to be answered in the testing of this hypothesis:

1. Do zooxanthellae enter the digestive tract of *S. viride*?
2. Can zooxanthellae survive the passage through the intestinal tract of *S. viride*?
3. Can the zooxanthellae found in *S. viride* feces re-infect aposymbiotic corals?

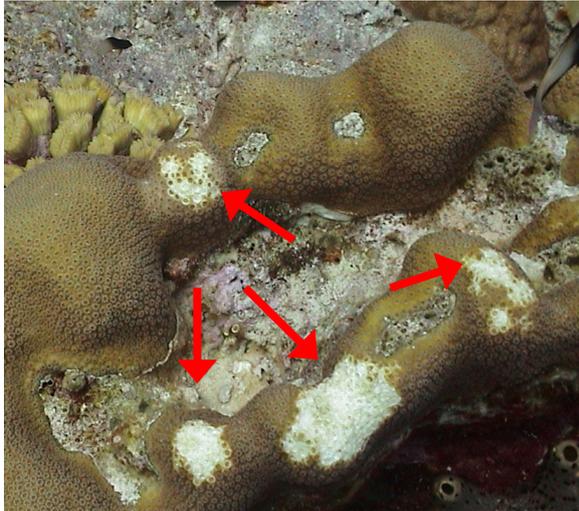
#### **DO ZOOXANTHELLAE ENTER THE DIGESTIVE TRACT OF *S. VIRIDE*?**

In 1996, a new coral disease called rapid-wasting disease (RWD) was identified on Bonaire. The disease progressed at rates as high as  $7.5 \text{ cm} \cdot \text{day}^{-1}$  and was associated with damage to or removal of the coral skeleton as well as the loss of coral tissue (Bruckner and Bruckner 1998). Bruckner and Bruckner (1998) determined through observations on Bonaire that RWD was actually the result of initial and terminal phase *S. viride* removing live tissue from coral heads. RWD was not a disease but rather the result of *S. viride* biting and the condition is now known as parrotfish white spot biting (PWSB). PWSB has been observed in Bonaire, Curaçao, and the US Virgin Islands (Bruckner and Bruckner 1998) and is not pathogenic in nature. However, Cervino et al. (1998) have documented a disease that appears to be opportunistically associated with PWSB called rapid wasting disease (RWS), where an uncharacterized fungus is found living on coral tissue and exposed skeleton.

Initial phase and terminal phase *S. viride* have been observed biting scleractinian corals and it has been hypothesized that this is a form of territoriality (Bruckner and Bruckner 1998). *S. viride* primarily bite *Montastrea annularis* and *Colpophyllia natans* (Bruckner and Bruckner 2006). *S. viride* have been observed repeatedly biting previously PWSB affected coral heads (Bruckner and Bruckner 1998, Cervino et al. 1998). Terminal phase males have been reported to bite coral heads as frequently as nine out of 100 bites and one coral head received 17 bites during a 70 minute observation dive (Bruckner and Bruckner 1998). No published research has yet suggested that PWSB is a form of feeding or in any way a nutritionally significant portion of the parrotfish diet.

PWSB can be identified with two key characteristics; the presence of shallow excavations approximately one

cm<sup>2</sup> in area and often a sharp boundary between exposed coral skeleton and healthy tissue (personal observation 2006). There are two kinds of PWSB, focused biting and spot biting. Focused bite marks (Fig. 3) result from repetitive, scouring bites in the same area by one or more individuals (Bruckner 2006). Spot bite marks occur when parrotfish take small, often numerous but spatially varied bites off of a coral head (Bruckner 2006). Bruckner and Bruckner (1998) hypothesize that PWSB does not appear to occur uniformly throughout the waters of Bonaire but may be related to *S. viride* density.



**Figure 3.** Arrows indicate focused biting on *M. annularis* (photograph by L. Kuhnz).

Preliminary research was conducted in the fall of 2006 to investigate Bruckner and Bruckner's (1998) hypothesis. Haphazardly placed transects were placed along the reef crest at five sites on Bonaire to measure stoplight parrotfish density and PWSB occurrence. The depth of the reef crest varied from seven to 12 meters and each transect measured 30 meters in length ( $n=13$ ). The results suggested a positive correlation between combined initial and terminal phase *S. viride* density and occurrence of PWSB. More robust research is needed to confirm or reject this hypothesis.

#### **CAN ZOOXANTHELLAE SURVIVE THE PASSAGE THROUGH THE INTESTINAL TRACT OF *S. VIRIDE*?**

A side effect of PWSB is the ingestion of zooxanthellae present in the coral tissue. Zooxanthellae have been identified in the feces of several marine species; *Clinocottus globiceps*, *Chaetodon auriga*, *C. unimaculatus*, and *Arothron meleagris*, which prey on coral polyps and anemones (Augustine and Muller Parker 1998, Muller Parker 1984). The chemical and physical environment in *S. viride*'s intestinal tract may be non-lethal to zooxanthellae because 1) the stomach pH is nearly neutral, 2) the enzyme, cellulase that breaks down plant cell walls, is not present, and 3) the pharyngeal jaws are ineffective on such small cells.

The gut pHs of several fish families were analyzed by Lobel (1981). He found that the stomach pH of *C. vagabundus* was 4.3. While not the same species as that used by Muller Parker (1984), it was the only available value of the stomach pH of a *Chaetodon*. If we assume this is similar to the pH of *C. auriga* or *C. unimaculatus* where zooxanthellae survived the digestive process in large numbers, it may be likely that zooxanthellae can withstand the less acidic values published for Atlantic parrotfishes. The pH in an Atlantic parrotfish, *Scarus jonesi*, was found to be between 6.4 and 8.2, not low enough for the acidity alone to break down plant cell walls (Lobel 1981, Smith and Paulson 1984). Muller Parker (1984) has also hypothesized that the high nutrient levels found within teleost digestive systems may increase the growth rate of zooxanthellae as they pass through.

Parrotfish lack the enzymatic capability to digest the cellulose cell walls of algal cells (Van Rooij *et al.* 1998) and thus it seems must rely on other means to access the contents of the cell. It is believed that physical disruption of the cell wall in the pharyngeal mill is the primary method of releasing algal cell contents in scarids (Lobel 1981). Muller Parker (1984) used a tissue homogenizer to liberate zooxanthellae from fecal pellets. He was able to isolate approximately the same density of zooxanthellae from predator feces as was found in prey species. Zooxanthellae are very small, on the order of eight to 12  $\mu$ m in diameter (personal observations of zooxanthellae collected from *Condylactis gigantean* 2006) and thus may be able to pass through the pharyngeal mill wholly intact. Without either the acidity or enzymatic activity necessary to break down the algal cell walls it is likely that many zooxanthellae survive passage through *S. viride*'s digestive tract.

Preliminary analysis of *S. viride* intestinal contents yielded a visual identification of zooxanthellae in one specimen ( $n=4$ ). Photographic equipment was not available at the time of collection to document the results however the sample has been preserved for future study. Chemical or genetic analysis will be necessary to achieve an acceptable level of confidence in the identification of future samples. In future experiments I would like to capture live *S. viride* and place them in holding tanks until they defecate. Smith and Paulson (1974) examined the stomach contents of *Scarus jonesi* and found that specimens captured during the early afternoon reliably had full stomachs. They were able to infer that the gut transit time for *S. jonesi* was approximately four to six hours. The maximum holding time should be six hours, and only fish captured during the early afternoon would be used. Muller Parker (1984) has outlined a method to successfully collect and analyze the fecal material of captive reef fishes that could be adapted, according to future circumstances, for use in experiments on Bonaire.

### CAN ZOOXANTHELLAE FROM FISH FECES RE-INFECT APOSYMBIOTIC ORGANISMS?

Muller Parker (1984) was able to infect aposymbiotic anemones with zooxanthellae by placing feces with live zooxanthellae cells in the same tank. He also found that when fecal pellets were placed on the oral disc both aposymbiotic and symbiotic anemones ingested them. Similar behavior could be the way coral polyps become infected with zooxanthellae. This could be tested using methods similar to Muller Parker's (1984). Bruckner (2006) has documented *S. viride* feces are directly released on corals in Bonaire.

### CONCLUSION

Zooxanthellae dispersal by predators of their host has been documented in several families, however to date no evidence has suggested *S. viride* could play a role. This line of inquiry could yield valuable contributions to the field of knowledge concerned with zooxanthellae ecology. There is little understanding of the means by which zooxanthellae are dispersed when dealing with distances on scales larger than centimeters. Pasternack *et al.*'s (2006) research suggests that if placed within close proximity to aposymbiotic corals zooxanthellae can locate and move towards the host. If *S. viride*, along with other coral predators, "seeded" local areas with zooxanthellae laden fecal matter it may have a significant effect on the genetic diversity of symbionts to which corals are exposed.

Some zooxanthellae are better adapted to higher temperatures and it has been suggested that coral bleaching during thermal stress may be a way to acquire heat tolerant strains of zooxanthellae (Sotka and

Thatcher 2005). Buddemeier and Fautin (1993) hypothesized that less heat adapted zooxanthellae provided corals with a competitive advantage when compared with more heat adapted strains. These corals would be more prone to bleaching during heat stress and could benefit greatly from a zooxanthellae "shuttle" service provided by corallivores and *S. viride*. Corals could also benefit merely from the exposure to new strains of zooxanthellae. Kinzie and Chee (1984) were able to demonstrate that aposymbiotic hosts grew at different rates when re-infected by zooxanthellae cultured from different hosts. This implies that zooxanthellae from one species of coral could potentially infect an entirely different species of coral if given the opportunity. Zooxanthellae transporters could facilitate and expedite the introduction of new zooxanthellae to different reef ecosystems.

Stoplight parrotfish are already known to have a major influence on coral reef dynamics (Mumby 2006) and therefore are worthy candidates for protection. However, if they are partially responsible for the introduction of genetic diversity to the zooxanthellae population of a particular reef there is even greater justification for their protection. With current global warming trends the coral reefs of the Caribbean Sea are at increasing risk from bleaching events. The presence of even one diversity "shuttle" such as *S. viride* could have important repercussions for the future health of our reef ecosystems. Further research is necessary, both to the understanding of zooxanthellae ecology and to investigate the ever increasing web of interconnection that is found in tropical waters.

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# DIADEMA ANTILLARUM POPULATIONS IN BONAIRE: IS THERE EVIDENCE OF OVER- OR UNDERPOPULATION?

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## ABSTRACT:

The sea urchin *Diadema antillarum* is an important herbivore in coral reef ecosystems of the Caribbean. The Caribbean is still recovering from a 1983 mass mortality event that decimated *D. antillarum* throughout the Caribbean, reducing populations to <3% of former levels (Lessios et al. 2001). By feeding on algae, *D. antillarum* helps prevent excessive algal growth and is beneficial to juvenile corals (Edmunds and Carpenter 2001). The urchin die off may have precipitated a phase shift in coral reef communities in the Caribbean from coral to algal dominated ecosystems. However, at high densities *D. antillarum* can have a negative effect, reducing the number of coral recruits (Sammarco 1980; Mumby et al. 2006).

In light of the potential of ecosystem level consequences of *D. antillarum* population; the purpose of this study was to document the densities in Bonaire to determine if they are over or underpopulated. The range of *D. antillarum* expected in an area at equilibrium was found to be equal to or greater than 1 m<sup>-2</sup> and less than 16 m<sup>-2</sup> (Mumby et al. 2006). Using transects, the densities of *D. antillarum* were counted on the leeward side of Bonaire, Netherlands Antilles at 20 sites. Urchins were found to be extremely patchy and underpopulated (< 1 urchin m<sup>-2</sup>) for all but one site. Karpata's population of *D. antillarum* was within the normal parameters (1 < x < 16 urchins m<sup>-2</sup>). No sites sampled had densities that would indicate overpopulation of *D. antillarum* (> 16 urchins m<sup>-2</sup>).

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## INTRODUCTION:

*Diadema antillarum* is a sea urchin that feeds on algae (Figure 1). Through grazing *D. antillarum* prevents excessive growth of algae, however, in high densities it has been shown to reduce the number of new coral colonies (Sammarco 1980). Today many areas of the Caribbean have not recovered from a disease which killed more than 97% of *D. antillarum* in 1983 (Lessios et al. 2001). While the urchins produce millions of eggs when they spawn, population numbers since 1983 have been variable (Lessios, 1988) and recovery has been slow.

Detrimental effects to corals such as algal overgrowth have been observed in locations where *D. antillarum* urchins are greatly underpopulated (Sammarco 1980). Studies have also shown negative effects of overpopulation to corals of *D. antillarum*, resulting in loss of coral recruits (Sammarco 1980). The purpose of this study is to determine the present densities of *D. antillarum* in Bonaire and to place the current densities in the context of previous studies in Bonaire and elsewhere in the Caribbean. The density information will provide a basis for analyzing the potential positive or negative effects that urchins might be having on the coral reef ecosystem in Bonaire.

## BACKGROUND:

The sea urchin, *D. antillarum*, is a keystone species in the Caribbean (Mumby et al. 2006). Therefore, over- or underpopulation of this species may have detrimental effects on corals and the reef ecosystem as a whole. In 1983 disease caused a mass mortality event, killing over 97% of *D. antillarum* throughout the tropical western

Atlantic (Lessios et al. 2001). It was the most extensive die-off ever reported for a marine animal (Lessios 1988). No increase was seen in the number of other urchin species to compensate for the losses. Some studies did show an increase in the amount of grazing fish (Mumby et al. 2006). After the mass mortality event, data from the Virgin Islands showed a decrease in the biomass of algae removed by reef grazers of more than 50% (Mumby et al. 2006).

Under normal conditions, the grazing of *D. antillarum* prevents excessive algal growth, aiding the health of coral reefs (Mumby et al. 2006). Urchins are very effective grazers even at low densities (Mumby et al. 2006) and studies in the Caribbean have attributed about 40% of grazing on shallow reefs to *D. antillarum* (Mumby et al. 2006). The foraging range for an urchin is 0.5-4.0 m<sup>2</sup> (Mumby et al. 2006). They can re-graze every 3-6 days, and may maintain the same area for over a year (Mumby et al. 2006). Prior to the mass mortality event the reported densities exceeded 1 m<sup>-2</sup> at 5-10m depth on relatively unfished reefs in the Caribbean (Mumby et al. 2006). Density of *D. antillarum* in Curacao and Bonaire was reported to be 8.5 m<sup>-2</sup> before the die-off (Mumby et al. 2006, and reference within).

Although *D. antillarum* is an important herbivore on coral reefs, overpopulation can have negative effects on corals as well as reef fish populations through competition for food (Sammarco 1980). An experiment conducted by the Australian Institute of Marine Science found that the highest coral recruitment and diversity occurred at the lowest *D. antillarum* densities, indicating that the abrasive

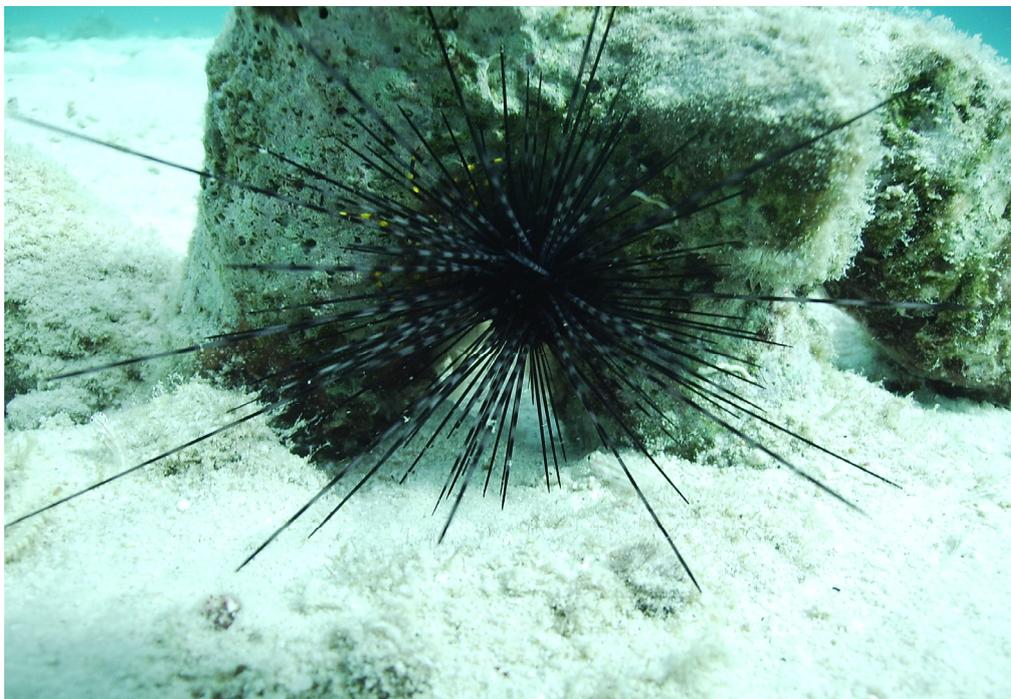
grazing was fatal to coral spat (Sammarco 1980). In another study, *D. antillarum* densities exceeding 16 m<sup>-2</sup> were shown to cause a significant reduction in coral recruits (Mumby et al. 2006).

There are 34 species of fish known to eat *D. antillarum* in the Caribbean (Smith and Malek 2005). The predators include balisted, sparid, large labrid, and batricoided fishes (Carpenter 1997). Fishing of predators may result in higher numbers of urchins. Fishing of scarids and exploitation of parrotfishes would reduce the competition for food which could also result in higher densities of urchins (Mumby et al. 2006).

In a study exploring the ability of *D. antillarum* populations to recover from the 1983 mass mortality event, varying results were seen at different locations. While scientists in Curacao were still documenting *D. antillarum* recruits five months later, no *D. antillarum* recruits were observed in Barbados for 14 months (Lessios 1988). Following the initial die-off there was a decline in *D. antillarum* population in Curacao while a significant increase was seen in Barbados. Because *D. antillarum* is a prolific spawner, it would be possible for only a few individuals to revive a population. However, population growth since 1983, perhaps due to overly dispersed individuals, has been unpredictable (Lessios, 1988).

In the Florida Keys seasonal recruits of *D. antillarum* had been observed in rubble zones from June to September, but not in other reef habitats (Chiappone et al. 2002). While this location provided ample protection from predators, the juvenile urchins were not surviving toppling from winter storms. A translocation experiment was conducted to move these recruits to patch reefs at 7.5-9 m. About 700 juvenile *D. antillarum* were translocated to two patch reefs with two control reefs (Chiappone et al. 2002). One year later, urchins had experienced 70% mortality, resulting in an ending density of about 1 m<sup>-2</sup>. There was decreased algal cover on experimental reefs, as well as more coral recruits and more species of coral. Coral cover did not change significantly over the one year study. Control reefs experienced an increase in algae and a slight decrease in coral species (Chiappone et al. 2002).

Unlike many other regions of the Caribbean, Bonaire had not experienced a significant phase shift to macroalgal species and macroalgae cover is quite low (Smith and Malek 2005). While many areas are still recovering from the die-off, marine park management on Bonaire suggested that *D. antillarum* may be overpopulated in the northern region of the island. The purpose of this study was to document the present densities of *D. antillarum* along the leeward coast of Bonaire and to use the densities reported



**Figure 1.** *Diadema antillarum* on coral rubble. Photograph by Emily McGrath.

in previous studies to classify the sites suggested that *D. antillarum* may be overpopulated in the northern region of

the island. The purpose of this study the die-off, marine park management on Bonaire was to document the present densities of *D. antillarum* as normal, over- or underpopulated.

**METHODS:**

Sites for data collection were chosen on the basis of the locations and depths where the most likely to show population recovery of *D. antillarum* was most likely to occur. The leeward side of the island was chosen based on a habitat preference of *D. antillarum* documented in a study conducted in Dominica (Steiner and Williams 2006). Depth was chosen based on the personal observation that *D. antillarum* were rare at depths of 15 ft and greater. My observations were supported by Smith and Malek (2005) who found *D. antillarum* to be rare at 5-10 m and below and suggested that population recovery was most likely to occur in shallow coastal zones on Bonaire (Smith and Malek 2005).

At each site the site name, longitude, and latitude were recorded. *D. antillarum* were counted using transects that were placed at a depth of 1-1.5 m at each site. A weight was attached to the end of a transect line to keep it in place. Each 10 m transect was carefully laid across the reef and three replicate transects were examined at each site. A one meter piece of PVC pipe was cut and the middle was clearly marked off to measure ½ m on either side of the transect, while counting all urchins along the 10 m<sup>2</sup> transect line. In addition, dive sites were searched by snorkeling for a minimum of 10 minutes to record the presence or absence of *D. antillarum* and *Echinometra lucunter* at each site.

Densities of urchins were compared to values from the literature that indicated under- or overpopulation of *D. antillarum*. A density of < 1 m<sup>-2</sup> indicated underpopulation (Lessios et al. 2001). Normal populations ranged between 1 and 16 m<sup>-2</sup>. Densities that were ≥ 16 m<sup>-2</sup> were considered overpopulated (Mumby et al. 2006).

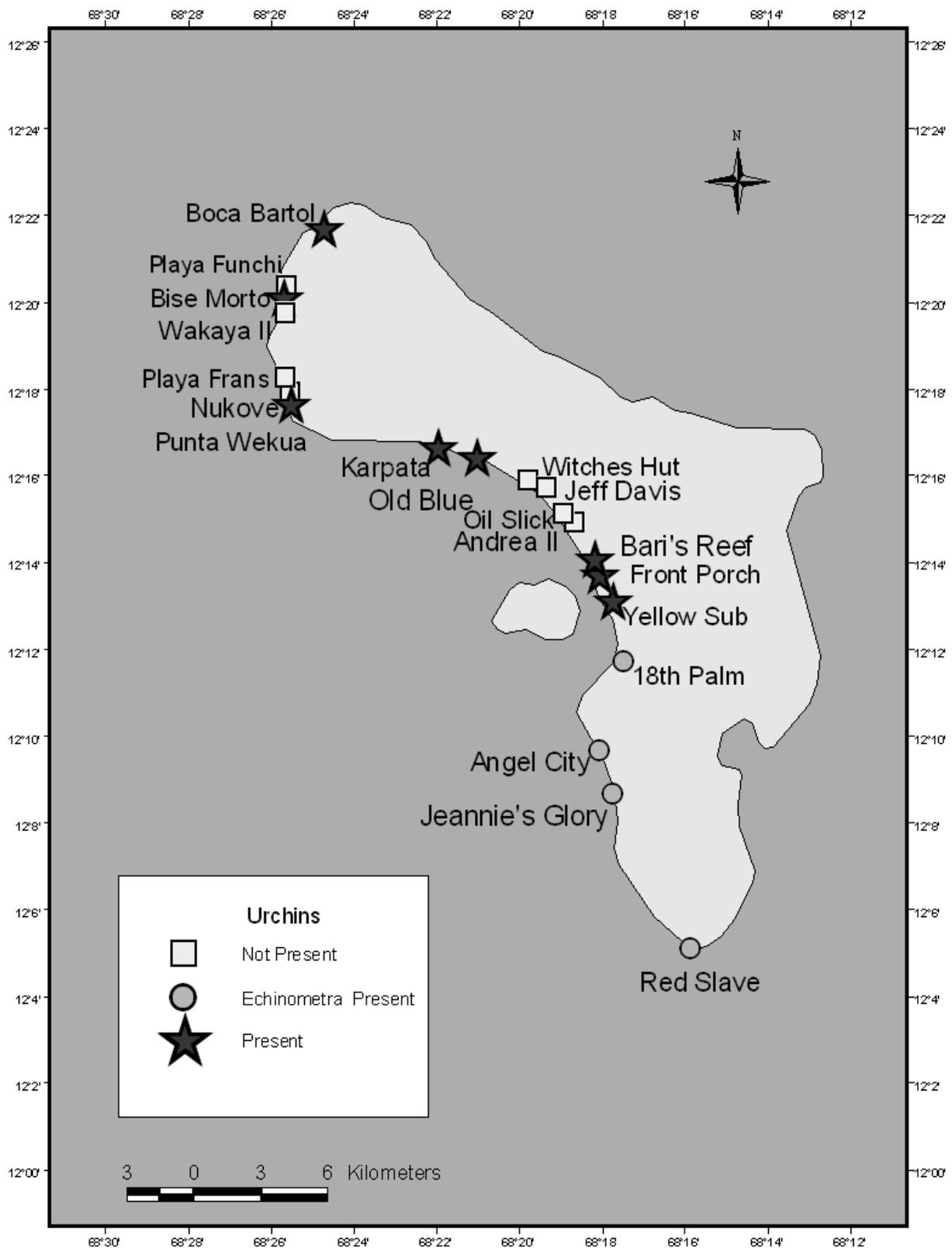
**RESULTS:**

Densities of *D. antillarum* ranged from zero, at 16 sites, to 1.83 m<sup>-2</sup> at Karpata. Of the locations sampled, Karpata had the highest mean number of *D. antillarum*, at 1.83 m<sup>-2</sup>, followed by Yellow Sub (0.37 m<sup>-2</sup>), Front Porch (0.17 m<sup>-2</sup>) and Bari's Reef (0.03 m<sup>-2</sup>). Comparing the current densities to urchin densities determined to indicate over- and underpopulation, ≥ 16 m<sup>-2</sup> and < 1 m<sup>-2</sup> respectively, all sites were found to be underpopulated with the exception of Karpata, which is within the normal density expected based on literature.

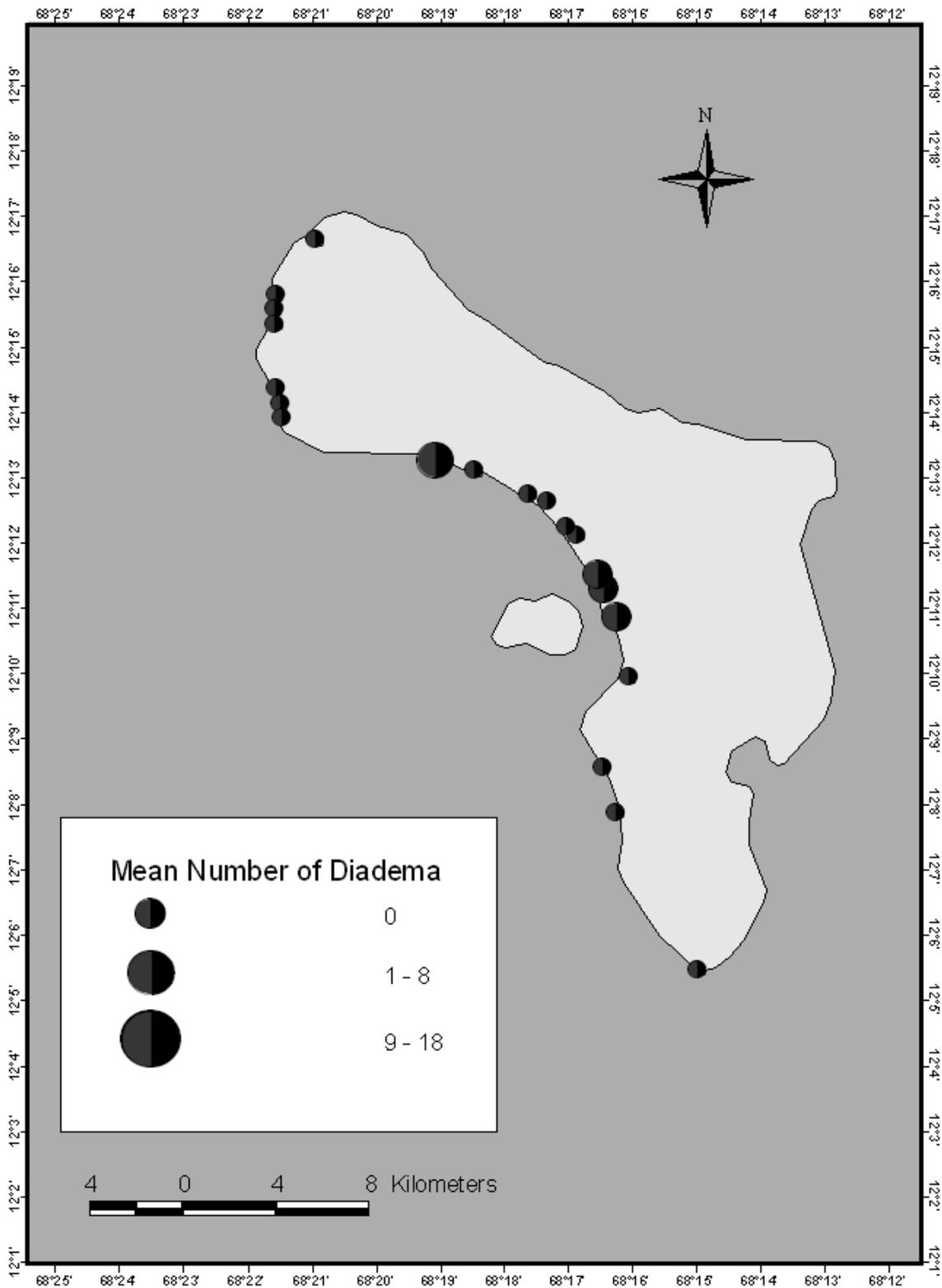
Presence and absence of *D. antillarum* and *E. lucunter* are displayed in Figure 2 and 3. Outside the transects *D. antillarum* were found at 4 sites, Boca Bartol, Bise Morto, Punt Wekua, and Old Blue. *D. antillarum* were found at 4 sites along the southern coastline, 18<sup>th</sup> Palm, Angel City, Jeannie's Glory, and Red Slave.

**Table 1.** Results of 3 replicate 10 m<sup>2</sup> transects to determine densities of *D. antillarum* at 20 sites along the leeward coast of Bonaire (\* = sites where *D. antillarum* were present outside of transects even though none were found within transects; \*\* = sites where *E. lucunter* were present).

Location	Transect 1	Transect 2	Transect 3	Mean (urchins 10 m <sup>-2</sup> )	Standard Deviation	Density (urchins m <sup>-2</sup> )
Karpata	39	13	3	18.33	18.58	1.83
Playa Funchi	0	0	0	0	0	0
Wakaya II	0	0	0	0	0	0
Boca Bartol*	0	0	0	0	0	0
Nukove	0	0	0	0	0	0
Bise Morto*	0	0	0	0	0	0
Playa Frans	0	0	0	0	0	0
Punt Wekua*	0	0	0	0	0	0
Andrea II	0	0	0	0	0	0
18 Palm**	0	0	0	0	0	0
Old Blue*	0	0	0	0	0	0
Witcheshut	0	0	0	0	0	0
Yellow Sub.	8	3	0	3.67	4.04	0.37
Jeff Davis	0	0	0	0	0	0
Oil Slick	0	0	0	0	0	0
Bari's Reef	0	0	1	0.33	0.58	0.03
Front Porch	0	5	0	1.67	2.89	0.17
Red Slave**	0	0	0	0	0	0
Jeannie's Glory**	0	0	0	0	0	0
Angel City**	0	0	0	0	0	0



**Figure 2.** Presence (star) or absence (square) of *D. antillarum* at dive sites as documented via transects or observations while snorkeling at each site. Circles indicate the absence of *D. antillarum* with the presence of *E. lucunter*.



**Figure 3.** The mean number of *D. antillarum* per 10 m<sup>2</sup> found at each dive site within 3 transects placed at a depth of 1-1.5m.

## DISCUSSION:

Before the 1983 mass mortality, population densities of *D. antillarum* in Bonaire were recorded to be 8.5 m<sup>-2</sup> (Mumby et al. 2005). In this study, the range in density of *D. antillarum* was 0-1.83 m<sup>-2</sup>, well below the density documented before the die-off. *D. antillarum* were underpopulated (< 1 m<sup>-2</sup>) at 19 sites along the west coast of Bonaire. Only one dive site, Karpata, had a normal density of urchins, 1.83 m<sup>-2</sup>. Perhaps there is potential for recovery as the population at Karpata may spread to other areas.

Would translocation of *D. antillarum* be of value to Bonaire's reefs? This may be an option to keep in mind for the future but further while monitoring the effects of the translocation study that is in progress on the Florida Keys. Based on one year's results in the Florida Keys, there seems to be a positive outlook for this technique. Of the translocated urchins 30% survived. There was also a decrease in algal cover and an increase in coral recruits. However, more time is needed to assess the impact of this population manipulation. It would also be necessary to consider the differences between the Florida Keys and Bonaire's reefs.

At many sites where data was collected, the majority of the substrate consisted of sand, which is not a suitable habitat for *D. antillarum*. Without refuges in which to hide, specimens would almost certainly fall prey to one of the urchin's many predators. If an attempt was made to repopulate by releasing raised *D. antillarum*, availability of microhabitats at sites would have to be considered. As in any scenario, the risk of human intervention in this ecosystem should be considered carefully before any action is taken. In comparison to other Caribbean regions, Bonaire has not experienced a significant phase shift from scleractinian corals to macroalgae (Smith and Malek 2005) and due to adequate populations of herbivorous fishes, it does not seem that such drastic measures as releasing lab raised *D. antillarum* are required at this time.

For future studies on the densities of *D. antillarum* in Bonaire, it would be more effective to conduct transects over a much larger area as many times urchins were observed at sites but did not fall within the transects. There were sites where the observed density of urchins is zero even though some *D. antillarum* were observed at the site. Another reason to include a larger area in future transects is that *D. antillarum* have very patchy distribution and inspecting a larger area could lead to more accurate densities. At several of the sites where zero *D. antillarum* were counted in the transects, some individuals were found at greater depths or along a particular substrate such as a cliff. However, based on my observations, high densities of *D. antillarum* were not present at any site with the noted exception of Karpata.

Smith and Malek indicated that *D. antillarum* are preyed upon in much higher frequencies when they are found on sand compared with those found on rock. In the majority of the sites tested, the shallow waters where transects were conducted consisted mainly of sand with a patchy distribution of rock and coral. If crossing the sand presents a significant risk to *D. antillarum*, it may partly account for their patchy distribution as no individual observed at any site or depth was found on sand. Therefore, areas that are surveyed should include shallow rocky environments.

A recent study which measured population densities of *D. antillarum* found dense populations at the sites observed and suggested that the population was showing signs of recovery throughout the Caribbean (Carpenter and Edmunds 2006). While the study did include Bonaire, the results found in this study did not support their hypothesis. One possible reason for this may be that only a small region in the northwest was included in their study. After measuring densities in the shallow coastal zone along the leeward side of the island, it is clear that *D. antillarum* is still underpopulated in Bonaire, although there are areas that seem to show some promise for future population growth.

At the southern sites where no *D. antillarum* were found, *E. lucunter* were consistently found in moderate densities. *E. lucunter* does not significantly contribute to reduction of algal cover and is a known bioeroder. Therefore in areas with low algal cover and low *D. antillarum* densities on Bonaire it is likely that grazing should be attributed mainly to a healthy population of grazing fish species (Smith and Malek 2005).

Future monitoring of *D. antillarum* populations along the east coast of Bonaire will be important to follow the recovery. Populations are still well below what they were before the die-off, yet there has been no switch from coral-dominated to algal-dominated reefs. The condition of reefs in Bonaire appears to differ from the reefs elsewhere in the Caribbean. To date, the only explanation offered is that herbivorous fish have helped to maintain Bonaire's reefs in the absence of *D. antillarum*. There are still many questions to answer regarding how Bonaire's coral reefs may be different from other reefs in the Caribbean and why there was no phase shift in coral reef community following the die-off. Will populations of *D. antillarum* reach densities that were typical in Bonaire before the die-off? And if so, when?

## ACKNOWLEDGEMENTS:

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# CORAL BLEACHING AND A PROPOSED MONITORING PROGRAM FOR BONAIRE, NETHERLANDS ANTILLES

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## ABSTRACT

Coral bleaching occurs when corals expel their symbiotic algae, called zooxanthellae, or when zooxanthellae expel their photosynthetic pigments during times of high environmental stress. The exact reason why corals bleach has not yet been determined, but it is theorized that a combination of multiple environmental stress factors is the cause. It is also possible that coral bleaching serves as an adaptive mechanism by allowing different types of zooxanthellae, which may be more stress-resistant than the original zooxanthellae, to colonize the coral. Temperature, salinity, over-sedimentation, anoxia, presence of pollutants, and high amounts of UV irradiation are all factors thought to contribute to bleaching. Extensive coral bleaching research has been conducted since the mass bleaching event of 1998, but there is no data on the frequency of coral bleaching on Bonaire, Netherlands Antilles. This paper proposes a monitoring program that may be implemented to collect coral bleaching and recovery data on Bonaire's reefs.

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## INTRODUCTION

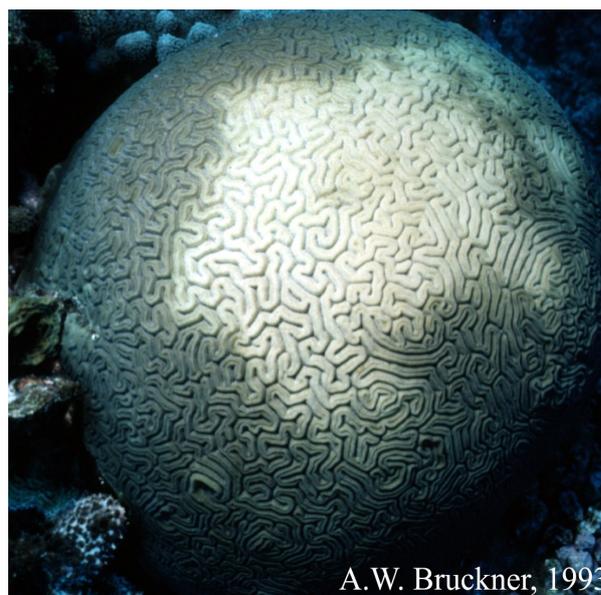
Coral reef ecosystems are one of the most biodiverse ecosystems in the world (Marshall and Schuttenburg 2006). Corals form the structural basis of the ecosystem and are dependent on an obligate mutualistic symbiosis between photosynthetic dinoflagellates, called zooxanthellae, and hermatypic, or reef-building, corals. During times of high environmental stress, coral bleaching occurs. Extensive coral bleaching research has been conducted since the mass bleaching event of 1998, but there is no data on the frequency of coral bleaching on Bonaire, Netherlands Antilles. The purpose of this paper is to provide information on coral bleaching and to propose a monitoring program that may be implemented to collect coral bleaching and recovery data on Bonaire's reefs.

## BACKGROUND

Corals have vacuoles in their gastrodermis where the zooxanthellae live and photosynthesize. The zooxanthellae photosynthetically fix carbon to create glycerol and other simple sugars that can be passed on to the coral to meet its nutritional requirements (Coffroth and Santos 2005, Pasternak *et al.* 2006). Between 50 and 95% of all the energy a hermatypic coral requires is obtained from its zooxanthellae. The presence of zooxanthellae within hermatypic corals significantly enhances the rate of calcification of their calcium carbonate skeletons. It also allows for the fixation and conservation of nitrogen, which is a limiting resource in coral reef ecosystems (Coffroth and Santos 2005).

Corals are constantly expelling and re-colonizing their zooxanthellae based on the environmental conditions that are present (Fitt *et al.* 2000). Coral bleaching occurs when corals expel large numbers of zooxanthellae, or when zooxanthellae expel their photosynthetic pigments in excessive amounts during times of high environmental stress (Buddemeier and Fautin 1993, Fitt and Warner 1995, Porter *et al.* 1989).

When this occurs corals appear white, as if they were "bleached", thus the term coral bleaching. Reduced salinity, over-sedimentation, anoxic water, and disease can all cause either a reduction in zooxanthellae or its chlorophyll per algal cell (Porter *et al.* 1989). High exposure to UV radiation can also cause bleaching (Porter *et al.* 1989, Fitt and Warner 1995), as can temperature anomalies (Goreau *et al.* 2000, Buddemeier and Fautin 1993). While all these factors have been shown to increase the risk of bleaching, the exact cause of bleaching is still unknown. Possibly, a combination of two or more environmental stressors is responsible. For example, increased water temperatures affect the bonding of hydrogen ions to carbon during photosynthetic reactions within zooxanthellae which triggers bleaching because it creates oxygen free radicals (Salm and Coles 2001). Water temperatures are



A.W. Bruckner, 1993

**Figure 1.** A bleached colony of *Diploria labyrinthiformis*. (Photo by Andy Bruckner).

considered above average when they exceed long term annual maxima by  $>1^{\circ}\text{C}$  for a week (Salm and Coles 2001). Intense light exposure also influences the severity and length of the bleaching events (Marshall and Schuttenburg 2006, Fitt and Warner 1995, Reaser *et al.* 2000, Salm and Coles 2001).

Buddemeier and Fautin (1993) have proposed that corals expel their zooxanthellae to allow re-colonization by more stress-resistant algae that are more suitable to the current environmental conditions. In addition, they suggest that it is not the individual coral or zooxanthellae that determine the tolerance limits to stress, but rather the coral-algal combination. Therefore, since there are multiple species of zooxanthellae-hosting corals and zooxanthellae, there must be multiple combinations that can be formed, with some interactions being more stress-resistant than others. Bleaching may be used to facilitate the shifting of this host-algae relationship for increased resistance. However, it is hypothesized that as the environmental stress subsides, the original coral-zooxanthellae relationship is naturally favored and the newly colonized zooxanthellae will be replaced by the original species of zooxanthellae (Buddemeier and Fautin 1993).

The world's oceans have warmed an estimated  $0.5^{\circ}\text{C}$  in the last century, bringing coral reef ecosystems within  $1\text{-}2^{\circ}\text{C}$  of their physiological upper thermal limits during the summer months (Salm and Coles 2001, Fitt and Warner 1995). There have been numerous incidences in the last 30 years where water temperatures have risen by more than  $3^{\circ}\text{C}$  over their annual maximum which were followed by mass coral bleaching events (Salm and Coles 2001). The combination of corals living near their physiological temperature limits and global events where water temperatures are sustained above these limits does not sponsor a positive forecast for the future of coral reefs. In 1983, coral reefs in all of the southern hemisphere were greatly affected by the El Niño Southern Oscillation (ENSO), causing 97% coral mortality due to coral bleaching in some reef systems (Fitt and Warner 1995). In 1997-98, mass coral bleaching occurred worldwide because of a global El Niño event, which killed nearly 16% of reef-building corals in the world (Marshall and Schuttenburg 2006). As global warming causes temperatures to increase, the frequency of coral bleaching events will also increase (Reaser *et al.* 2000).

Bonaire, Netherlands Antilles is an island in the Southern Caribbean, located approximately 85 kilometers north of Venezuela. Bonaire is home to one of the healthiest coral reefs in the Caribbean and its economy is dependent on ecotourism. Although maintaining a healthy reef system is top priority, there has been no published research performed concerning the frequency and magnitude of coral bleaching events

on Bonaire nor are there plans to start a coral bleaching monitoring program. Therefore, I present a proposal for a coral bleaching monitoring program in Bonaire. The monitoring program may be implemented by anyone who has the resources required, which are minimal in cost, and the ability to correctly identify coral bleaching while underwater.

#### **MONITORING PROGRAM PROPOSAL**

Permanent transects should be established at five dive sites along the western side of Bonaire with one located on Klein Bonaire. Dive sites should be chosen based on different geographic locations to represent an array of environmental conditions. Five possible sites are Red Slave, Angel City, Ebo's Special, Karpata, and Playa Funchi (Figure 2). Sites range from the southern tip of Bonaire to the north in Washington-Slagbaai National Park, as well as one site centrally located on Klein Bonaire. Permanent transects should be created so that data can be collected along the same area each time, allowing for observations of bleached coral heads for an extended period of time and for monitoring of the recovery or death of individual corals from bleaching.

Transects should be established randomly at three depths: 2 meters, 10 meters, and 25 meters. Transects performed at a depth of two meters could provide valuable data about bleaching effects on coral recruits. Coral recruitment is occurring at shallow depths in some areas along the coastline in Bonaire, and recruitment and survival of coral colonies is vital to the recovery of Bonaire's shallow reefs that have been devastated over the past 25 years by disease and the effects of recent hurricanes.

The depths of 10 and 25 meters were chosen because there is a large amount of coral coverage at each depth, yet corals at these two depths may be subject to different environmental stresses (UV radiation, water temperature). Another difference between depths is in the make-up of the coral-algal symbiosis. In 2001, Baker transplanted shallow and deep water corals into their reciprocal environments and noticed that the relocated deep water corals became bleached and re-colonized with shallow water zooxanthellae, but the transplanted shallow water corals kept the same zooxanthellae in their new environment and exhibited less survivorship. This experiment not only supported the theory that bleaching is an adaptive mechanism, but it shows the necessity for different types of zooxanthellae at different depths. Thus, corals at different depths could have different amounts of bleaching because of the differences in zooxanthellae/coral relationships. Also, different currents could transmit disease or bacteria through the water column to and from different areas along the reef. By collecting data on coral bleaching during the dive, researchers will be able to closely examine each coral head to identify coral bleaching and to determine the

species of coral that is bleached. When positive identification of coral bleaching is made, the entire coral head should be photographed to document the eventual effects of bleaching on the colony. Since bleaching is best determined by examining corals closely, videography should not be used as a means of identifying and diagnosing coral bleaching. Identification using video footage is unreliable because it involves interpretation of what is seen without the possibility of closer examination. This problem is exacerbated by the fact that video cameras automatically change light fields, creating variability in lighting that can cause corals to appear bleached when they are not. There are other diseases and phenomena that occur within the reef, such as white plague and parrotfish biting, that can closely resemble coral bleaching and would be extremely difficult to differentiate when viewing a video.

Monitoring should begin in August and continue through January. Sites should be sampled about once every 6 weeks to maximize the amount of data collected while maintaining practical feasibility and low costs. Data collection should commence in early August because bleaching is not normally present at this time. If bleaching is present in August, its presence could serve as an indicator of the presence of high environmental stress, as was the case in the El Niño event of 1998 (Reaser *et al.* 2000). In Bonaire, bleaching typically is present during the months of October, November, and December (C. Eckrich, pers. comm. 2006). By the end of January, the affected corals should have either recovered or died and the final data can be collected and compared with previous transect data to determine the percent recovery or death of each coral colony.

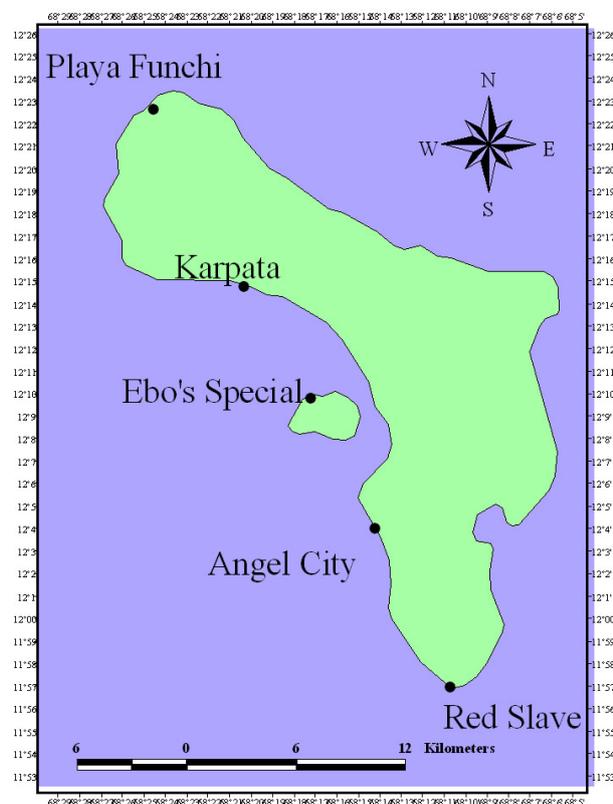
Using this proposed monitoring program, the data collected on bleaching frequency and magnitude could be used to estimate the amount of bleached coral coverage on Bonaire's reef at each specific depth. It could also be used to compare with data from other areas of the Caribbean to see how Bonaire's reefs compare with the rest of the Caribbean region.

#### SUMMARY

Although the exact causes of coral bleaching have not been proven, it is known that bleaching occurs during times of high environmental stress. Research on coral bleaching has been conducted throughout the Caribbean but there is no data available on bleaching periodicity or extent on the reefs in Bonaire. Knowledge about coral bleaching within Bonaire's surrounding reefs would provide a valuable baseline of information about the current effects of bleaching. Establishing a coral bleaching monitoring program or promoting student research with the purpose of providing data on coral bleaching will allow Bonaire to compare the reefs here with reefs around the Caribbean and the world.

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**Figure 2.** Recommended Dive Sites for Proposed Coral Bleaching Monitoring Program

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**WHEN EIGHT DARING AMERICAN STUDENTS TRAVEL TO A SMALL DESERT ISLAND TO PARTICIPATE IN A NEW PROGRAM ABOUT CORAL REEFS AND MARINE PARK MANAGEMENT, THEY HAD NO IDEA WHAT THEY WERE GETTING THEMSELVES INTO...**

They spent four months studying the behaviors and interactions of marine creatures, environmental policy, how to conserve marine resources by creating marine protected areas, and how to perform underwater research. With these concepts in mind, each student also conducted scientific research to help enhance what is known about the marine ecosystem surrounding Bonaire, Netherlands Antilles. This journal is the culmination of that research, containing all of the collected data and its importance to Bonaire in the form of 8 scientific papers.

**"IN THE END WE WILL CONSERVE ONLY WHAT WE LOVE; WE WILL LOVE ONLY WHAT WE UNDERSTAND; AND WE WILL UNDERSTAND ONLY WHAT WE HAVE BEEN TAUGHT."**

Baba Dioum, Senegalese Poet and Conservationist

**"TILL NOW MAN HAS BEEN UP AGAINST NATURE, FROM NOW ON HE WILL BE UP AGAINST HIS OWN NATURE"**

Dennis Gabor, Nobel Prize winning physicist

**"THE LEAST MOVEMENT IS OF IMPORTANCE TO ALL NATURE. THE ENTIRE OCEAN IS AFFECTED BY A PEBBLE."**

Blaise Pascal, French mathematician, physicist, and philosopher

