Managing Coral Reefs in the Face of Global Climate Change: Developing a Coral Resilience Framework

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MANAGING CORAL REEFS IN THE FACE OF GLOBAL CLIMATE CHANGE:
DEVELOPING A CORAL RESILIENCE FRAMEWORK

By
Megan Porter

A THESIS

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Managing Coral Reefs in the Face of Global Climate Change: Developing a Coral Resilience Framework

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Two experiments were performed to determine the effect of ocean acidification on *Montastraea faveolata* vertical skeletal growth and lesion healing. The first experiment used three different CO₂ concentrations: present day atmospheric pCO₂, 380 µatm, and the atmospheric pCO₂ expected by the years 2050, 560 µatm, and 2100, 800 µatm. The second experiment used 380 and 560 µatm. In the second experiment where the influence of parent colony was analyzed, *M. faveolata* fragments from one coral colony had significantly slower skeletal growth rates and less healed lesion area than other colonies. Corals that calcify and regenerate tissue slower may have less resilience to ocean acidification. The experiments demonstrated that the corals in 800 µatm grew significantly slower than corals in 380 or 560 µatm. Increased CO₂ concentrations increased *M. faveolata* skeletal growth rates and healed lesion area until a threshold was reached, 560 µatm, then growth rates and healed lesion area decreased. Less than 1% of the variability in healing rates could be explained by CO₂.

The Nature Conservancy Resilience Model was used as a framework to identify current management strategies of wider Caribbean MPAs that may increase coral reef resilience to climate change. Seven out of the 8 MPAs had representation, critical areas, connectivity, and effective management as determined by each MPA’s management plan.
Three management plans had specific climate management strategies. Each management plan had actions to build coral reef resilience, but institutional incapacities and other barriers can decrease the ability to increase reef resilience. Because of the weaknesses of the Resilience Model, revised resilience guidelines were developed with the Florida Keys National Marine Sanctuary (FKNMS) as a case study. The coral lesion experiment results and interviews with FKNMS managers and the FKNMS’s Sanctuary Advisory Council helped design the revised resilience guidelines. The revised climate-based coral reef resilience guidelines are to 1) incorporate more no-take zones and hedge the risks against ocean acidification, 2) identify resilient coral reefs and perform more climate change research, 3) reduce local stressors, 4) enhance coral reef recovery, and 5) increase public awareness and education on climate change impacts to coral reefs.
ACKNOWLEDGEMENTS

Thank you to all the Florida Keys National Marine Sanctuary staff and the Ecosystem Restoration Working Group members for all your time, information, and ideas. Permit FKNMS-2007-009 was provided by the Florida Keys National Marine Sanctuary for the collection of the *Montastraea faveolata* colonies used in this study. This project was funded in part by Conservation International. Guidance of this thesis by Liana McManus, Chris Langdon, and Kenny Broad was greatly appreciated. Thank you to my family, fiancé, and friends for your support.
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CHAPTER 1
INTRODUCTION

Goals and objectives

The negative effects of global climate change to coral reefs include increasing sea surface temperatures and ocean acidification from increasing CO₂ concentrations, but also rising sea levels and the possibility of an increasing number and/or intensity of hurricanes. Coral reefs will be especially affected due to these multiple stressors (IPCCb 2007). Caldeira and Wickett (2003) articulate that there needs to be a better understanding of the effects of increasing CO₂ in the ocean to marine biota. This study was performed to understand the effects of ocean acidification on the prevalent reef building coral *Montastraea faveolata* and to explore coral reef management options in the face of climate change. The goals of this study are to

1. Determine the effect of increasing carbon dioxide concentrations on *Montastraea faveolata* skeletal growth and lesion regeneration,

2. Identify and evaluate current management practices existing in wider Caribbean coral reef MPAs that reduce negative global climate change effects using the Nature Conservancy’s Resilience Model as a framework,

3. Assess the management implications of the experiment investigated in goal 1, and

4. Develop climate-based coral reef resilience guidelines using information from goals 2 and 3 specifically for the Florida Keys National Marine Sanctuary (FKNMS) that can also apply to wider Caribbean MPAs.
The scope of this thesis will include both a natural science and a social science study. The natural science study will analyze the effects of ocean acidification on a major reef building coral in the western Atlantic/Caribbean region, *Montastraea faveolata*. Intentionally inflicted coral lesions and coral vertical skeletal growth will be used as resilience indicators to predict the rates of *M. faveolata* calcification and tissue regeneration that can be expected in the next fifty to 100 years. Keller et al. (2009) states that more research is needed regarding the effects of ocean acidification and how it can be managed.

The Nature Conservancy Resilience Model will be used to measure the current success of wider Caribbean MPAs’ ability to manage the effects of global climate change. This model was chosen because it provides a framework to increase coral reef resilience inside MPAs in order to reduce the negative impacts of climate change. The study sites include wider Caribbean MPAs. Additionally, FKNMS managers, and their Sanctuary Advisory Council (SAC), specifically the Ecosystem Restoration Working Group, will be asked to identify management implications and actions based on the new information learned from the above *M. faveolata* lesion experiment. These responses and my own analysis of the experiment results will be used to develop revised climate-based coral reef resilience guidelines that aim to help coral reef MPA managers reduce negative climate change effects, based on new information from the coral lesion experiment and considered in the context of the FKNMS institutional capacities.
Literature review on global climate change

The effects of climate change are unmistakable with increasing temperatures in the air and ocean, melting of snow and ice, continuing rises in global sea level, and increasing extreme weather events (IPCCa 2007). Even if all greenhouse gas concentrations were stabilized, the effects of global climate change could still be felt for centuries because of the committed heating (IPCCb 2007). Much of the CO$_2$ entering the ocean from the atmosphere is from anthropogenic burning of fossil fuels and land-use change (Caldeira and Wickett 2003 and IPCCa 2007). Approximately one-third of atmospheric CO$_2$ ends up in the ocean (Doney et al. 2008). The future predictions of the magnitude and rate of change of atmospheric CO$_2$ and ocean pH are greater than any conditions experienced in the last twenty-four million years (Kleypas and Langdon 2000).

Ocean acidification

Ocean acidification is simply a decrease in the ocean’s pH. The pH of the ocean has already decreased by 0.1 units, 8.21 to 8.1 units, since pre-industrial times, and a 0.14-0.35 unit decrease is projected through the twenty-first century (IPCCb 2007). The pH is currently decreasing at a rate of 0.02 units/decade (Figure 1.1).

The concentrations of CO$_2$, CO$_3^{2-}$ (carbonate ion), HCO$_3^-$ (bicarbonate ion), and H$_2$CO$_3$ (carbonic acid) all will be modified because of ocean acidification, and all affect calcification directly or indirectly (Kleypas and Yates 2007). Increasing CO$_2$ in the ocean causes a shift in the equilibrium between bicarbonate ion (HCO$_3^-$), increases, and carbonate ion (CO$_3^{2-}$), decreases; corals need carbonate ion for skeleton growth to form calcium carbonate (Mueller 2008).
Figure 1.1: The projected global atmospheric CO\(_2\) and pH under the various SRES scenarios with respect to aragonite in the Southern Ocean. From IPCC 2007

\[
\text{CO}_2(\text{atmos}) \leftrightarrow \text{CO}_2(\text{aq}) + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{CO}_3 \leftrightarrow \text{H}^+ + \text{HCO}_3^- \leftrightarrow 2\text{H}^+ + \text{CO}_3^{2-}
\]

Langdon et al. (2000), in a coral reef mesocosm experiment at the BIOSPHERE-2, demonstrate by changing calcium and carbonate ion concentrations that coral calcification correlates with aragonite saturation state. Calcification rates decrease with decreasing carbonate ion concentration from increasing CO\(_2\) concentrations (Langdon et al. 2003, 2000, and Kleypas and Langdon 2000). There is a 30% decrease in carbonate ions with a doubling of atmospheric CO\(_2\) (Kleypas and Langdon 2000).

Gattuso et al. (1998) also predicts a decrease in coral calcification as a result of increasing CO\(_2\) concentrations. A review of studies by Langdon and Atkinson (2005) found that experimentally changing the carbonate chemistry to simulate a doubling of the pre-anthropogenic atmospheric pCO\(_2\) (i.e. 560 ppm) resulted in a 40-80% decrease in calcification of some coral species and 1-18% decrease in others. Jokiel et al. (2008) displayed a 15-20% decrease in coral calcification from a doubling of pre-anthropogenic
atmospheric CO$_2$ for a period of ten months. A range of studies reviewed by Langdon et al. (2003) illustrate an 11-40% decrease in coral calcification from doubling pre-anthropogenic atmospheric CO$_2$ in studies lasting three hours to two years. Albright et al. (2008) found that a pCO$_2$ of 560 ppm caused a 50% decline in the early post-settlement growth of coral spat.

Evidence from the Great Barrier Reef demonstrates that there has already been a 14% decrease in massive *Porites* calcification from 1990 to 2005, and the specific cause of the decline may be from ocean acidification, temperature, or both (De’ath et al. 2009). Hoegh-Guldberg et al. (2007) highlight that studies (Kleypas et al. 1999 and Kleypas and Langdon 2006) project that carbonate accretion may approach zero when the aragonite saturation state equals 3.3 or less; this will occur when atmospheric CO$_2$ equals 480 ppm. By 2050, when atmospheric CO$_2$ concentrations may reach 560 ppm, Silverman et al. (2009) projects corals to have greater dissolution than production. Studies show that juvenile corals can still form aragonite skeletons under extremely low aragonite saturation states, but the skeletons are not healthy as the morphology, organization, and packing is very different than skeletons accreted under higher aragonite saturation states (Cohen and Holcomb 2009). A coral’s energy budget for calcification may be limited, and under lower aragonite saturation states coral may have to work harder to form calcium carbonate (Cohen and Holcomb 2009). Nutritionally replete corals, however, may be able to maintain normal levels of skeleton formation in lower aragonite saturation states (Cohen and Holcomb 2009).
Increasing temperature

Ocean acidification, however, does not act alone to negatively affect corals. Tropical sea surface temperatures are expected to increase by as little as 1.1°C and as much as 6.4°C by the end of the twenty-first century (IPCCb 2007). Many studies demonstrate that increasing sea temperatures trigger coral bleaching (Hoegh-Guldberg 1999 and Rowan 2004). Jones et al. (1998) asserts that higher than average sea surface temperatures and high solar radiation are the chief causes of coral bleaching. Coral bleaching is, therefore, expected to increase in the future.

Coral bleaching is defined as the loss of corals’ symbionts, symbiodinium, and/or corals’ pigments as a result of environmental stress (Fitt et al. 2001). Bleaching can occur from short-term exposures to temperatures greater than normal highs or by long-term exposures to normal maximum temperatures (Jokiel and Coles 1990). Because corals lose their symbionts during bleaching, bleaching can lead to coral mortality and degradation (Baker 2001). The most recent widespread bleaching event was in 1997-1998, and there was massive global mortality (Fitt et al. 2001). This bleaching event was caused by a strong El Niño Southern Oscillation (ENSO) that led to ocean warming (Goreau et al. 2000). In the Caribbean actual sea surface temperatures did not exceed normal maximum temperatures, but the high temperatures were sustained for longer than usual. In Japan, after the 1997-1998 bleaching event, coral species richness decreased by 61%, coral cover decreased by 85%, and local coral extinctions were experienced (Loya et al. 2001). A phase shift in coral community structure was documented at the aforementioned Japan site with finely branched corals being more susceptible to mortality after bleaching, while massive and encrusting type corals were less susceptible.
Corals may be able to acclimatize or adapt to increasing sea surface temperatures. Different clades of corals’ symbiodinium exist, and clade D is known to be a high temperature specialist (Rowan 2004). Berkelmans and van Oppen (2006) showed that clade D provides heat protection with temperatures up to 1-1.5ºC greater than other clades. By recombining their symbionts, corals may be able to mitigate the increasing sea temperatures predicted with climate change (Rowan 2004). *Acropora millepora* was demonstrated to increase its thermal tolerance when changing symbiodinium clade C to D (Berkelmans and van Oppen 2006). It is unclear if this change is from symbiont shuffling or obtaining new symbionts from the environment. Corals that host multiple symbiodinium clades may be better able to respond to increasing thermal stress (Berkelmans and van Oppen 2006).

The adaptive bleaching hypothesis states that bleaching allows corals to be repopulated with a different type of symbiodinium that are better suited for the new conditions (Buddemeier and Fautin 1993). A study by Baker (2001), which experimentally transplanted corals upward and downward in depth, found that the corals transplanted downward had less bleaching but increased mortality, while the opposite was true for corals transplanted upward. Baker (2001) concludes that bleaching makes possible the replacement of new symbiotic algae that are better adapted to the changed conditions.

**Interacting effects of climate change**

Ocean acidification and temperature will act synergistically. In Hoegh-Guldberg’s et al. (2007) coral reef scenario B (CRS-B), there is an increase in 2ºC from present values, CO$_2$ concentrations greater than 500 ppm, and an aragonite saturation
state below 3.3. In this CRS-B coral reef ecosystems will decrease with a decline in
density and diversity of corals and will have a collapsing reef structure.

From the year 1961 through 2003, the global average sea level has been rising at a
rate of 1.8 mm/year, and this rise was quicker from 1993 through 2003 (IPCCa 2007).
Overall in the twentieth century, sea level rise was 0.17 m, and sea level rise is projected
to increase another 0.18 – 0.59 m by the end of the twenty-first century based on the
SRES scenarios. Sea level rise is attributed to a variety of factors including ice sheet and
snow melting along with thermal expansion of the ocean waters. Because corals are
predicted to experience decreased growth rates from ocean acidification and will be
stressed by increasing temperature, corals may not have enough vertical accretion to keep
up with sea level rise in the coming centuries.

Coral disease and mortality will also increase because of global climate change
(Hoegh-Guldberg et al. 2007). Whether the intensity or frequency of tropical storms will
be altered due to climate change is controversial, but theory and high-resolution
dynamical models continue to show an increase of tropical storms along with an increase
in frequency of the stronger storms (Knutson et al. 2010). This may intensify the damage
tropical storms cause to coral reefs leading to longer recovery periods, although the
interaction is not so simple as hurricanes can also bring colder water to coral reefs during
of high temperature stress (Goreau et al. 2000). All the predicted climate changes can act
synergistically to affect coral reefs.
Coral reef resilience

Although carbon dioxide levels have been much higher in the past 300 million years, up to 7,500 ppm (Caldeira and Wickett 2003), the past is an imperfect analog for the present. Scleractinian corals evolved around 250 million years ago in the Triassic (Doney et al. 2008). Corals residing over 300 million years ago were calcite-forming corals; calcite is less soluble than the aragonite that present day corals produce. Also, the rate of change of atmospheric CO$_2$ today is happening faster than before. The ocean chemistry is more sensitive to pH changes when they happen on shorter time scales because on longer time scales, the ocean is buffered by a number of processes, including dissolution of seafloor carbonate sediments, seafloor spreading, volcanism, and continental weathering, to list a few (Caldeira and Wickett 2003 and Doney et al. 2008). The highest CO$_2$ levels over the past 300 million years developed over millions of years, and the resulting reduction in pH and saturation state was much attenuated (Caldeira and Wickett 2003). The CO$_2$ concentrations expected in the next centuries will force larger and faster changes in pH and saturation state and, therefore, crucial to be addressed by policy and management of coral reefs.

Coral reef resilience factors

Resilience will be defined throughout as the recovery rate of corals or coral reefs following a stressor and/or the ability to not be undermined by stressors. Many factors play into determining the level of coral and coral reef resilience including the number and extent of environmental stressors, genetic variability, species diversity, functional group abundance, connectivity among reefs, and the amount and extent of anthropogenic stressors (Nyström et al. 2000 and McClanahan et al. 2002). Disturbances can interact in
a compounding way, where effects are greater than they would be from only one disturbance. Connectivity is important in maintaining coral reef resilience, but it can also diminish resilience (McClanahan et al. 2002). Currents can bring fish and coral larvae but also pollution and invasive species. McClanahan et al. (2002) advocates that connectivity is needed for reef recovery.

Species diversity and functional group abundance are related when studying the resilience of a coral reef. Many suggest that there needs to be high diversity within and among functional groups to ensure redundancy of functional groups for a coral reef to be resilient (Nyström et al. 2000, McClanahan et al. 2002, and Folke et al. 2007). Species more sensitive to disturbances can be replaced by those species less sensitive to maintain ecosystem functioning. Ecosystem functioning is changed when a functional group, like herbivores, is removed (Jackson et al. 2001) or when entire trophic levels are removed (Folke et al. 2004). Coral reefs in the wider Caribbean have less diversity than Indo-Pacific reefs, and Caribbean reefs have been demonstrated to have slower recovery rates (Connell 1997), although these slower rates may be due to the Caribbean’s disturbance history (McClanahan et al. 2002).

Local anthropogenic impacts that decrease coral reef resilience include increasing coastal development, sewage discharge, nutrient loading and eutrophication from agriculture, sedimentation, coral mining, overfishing, and destructive fishing practices (Nyström et al. 2000 and Carpenter et al. 2008). In addition, global climate change is an anthropogenic threat because the majority of climate change is caused by human fossil fuel use, agriculture, and land use changes (IPCCb 2007). Many of these factors stem from an increasing human population, especially on coasts. One major anthropogenic
activity that reduces coral reef resilience is overfishing, which can cause a reduction in herbivores (Hughes et al. 2003). The reduction of herbivores can start a downward spiral leading to less coral cover and more algae cover (Mumby et al. 2007). When corals die, algae can increase in cover due to more space being available. The increase in algae may be too much for an overfished herbivore population to keep in control, thus allowing more algae to grow. Overall, some state that local anthropogenic effects will reduce the resilience of corals to a point where coral reefs cannot survive global climate change (Carpenter et al. 2008).

**Scientists’ perceptions of coral reef threats**

From a survey of scientists attending the 10th International Coral Reef Symposium almost one-third of scientists thought that global climate change threats are the largest problem facing the future of coral reefs worldwide, and two-thirds said direct human impacts are the largest threat to coral reefs (Kleypas and Eakin 2003). However, climate change threats are infrequently ranked high in individual regions. The average, weighted by region, top threats perceived by scientists to the coral reef region they are most familiar with are laws/enforcement, human population growth, overfishing, coastal development, unnatural sedimentation, a lack of education, and algal competition (Kleypas and Eakin 2004). All these threats, though, serve to decrease coral reef resilience.

**Reasons to increase coral reef resilience**

Coral reefs have been around for millions of years and can be thought of as one of the most perpetual ecosystems (Veron 1995). Resilience of coral reefs is a key goal of many marine conservation activities (McClanahan et al. 2002, Hughes et al. 2003,
Wooldridge and Marshall 2005, Hughes et al. 2005, Folke et al. 2007, and Hughes et al. 2007). To increase the resilience of coral reefs, the disturbances and stressors that are negatively affecting coral reefs outside the range of natural variation because of anthropogenic influences need to be removed. According to Hughes et al. (2003) reducing pollution, maintaining food webs, and protecting key functional groups will increase reef resilience. Conversely, Aronson and Precht (2006) say that even coral reefs isolated from human impacts still show similar signs of damage to those reefs in proximity to human pressures. Resilience in coral reefs, but also resilience in social-ecological systems, is needed to allow both humans and ecosystems to adapt to global climate change (Tompkins and Adger 2004).

Corals reefs are vital to humans for many reasons; almost 500 million people depend on reefs (Wilkinson 2004). People's livelihoods depend on coral reef resources by making a living through extractive (commercial fishing, aquarium trade, charter fishing operators) and non-extractive activities (scuba diving and snorkeling operators). Many use coral reefs for subsistence to provide food for themselves and family. People also enjoy reefs recreationally through recreational fishing, scuba diving, and snorkeling. Coral reefs provide physical protection to coastlines from storms. Also, coral reefs provide opportunities for scientific and pharmaceutical research. Coral reefs have non-use values too: option, bequest, and existence (Cesar 2000). People give value to coral reefs just from knowing they exist and from knowing they can leave them to following generations.
CHAPTER 2

THE EFFECTS OF INCREASING CARBON DIOXIDE CONCENTRATIONS ON MONTASTREA FAVEOLATA SKELETAL GROWTH AND LESION REGENERATION: USING CORAL SKELETAL GROWTH AND LESION HEALING AS INDICATORS OF CORAL RESILIENCE

Background

Coral lesions represent partial coral mortality. Lesion regeneration requires energy and starts with the formation of new tissue from surrounding tissue and the coenenchyme (Meesters et al. 1994). New polyps, which develop from the thecal walls and basal plate, form after two weeks. Next, the radial septa form. Corals that regenerate lesions quickly may have closure of the lesion with new tissue without polyps forming; conversely, coral lesions that heal slowly may have polyps and new tissue seeming to appear together (Meesters et al. 1994 and Meesters and Bak 1995). Alternatively, van Woesik (1998) concludes that lesion regeneration occurs through the extension of surrounding polyps and extratentacular budding.

Many different factors can influence lesion regeneration in corals: colony size, coral species, sea-surface temperature, water depth, lesion location, lesion size, lesion perimeter, lesion shape, and other factors such as previous experienced stressors and the initial cause of the lesion (Bak and Steward-Van Es 1980, Bak et al. 1994, Meesters et al. 1994, Meesters et al. 1997, Oren et al. 1997, van Woesik 1998, and Lirman 2000). A simple exponential regression, commonly used to describe lesion healing, assumes an exponential decrease in lesion size to zero, but Meesters et al. (1994) provide a modified model as the simple regression does not account for lesions that do not fully close. An
asymptote is introduced into the regression, and Meesters et al. (1994) demonstrate that the new exponential regression describes lesion healing more accurately.

The study performed by Oren et al. (1997), where they inflicted lesions of different sizes and shapes on *Favia favus*, illustrates that even though lesions may be of similar sizes they do not always have similar tissue regeneration rates. One reason for the difference in regeneration rates was that the lesion perimeter/area ratios were different. The authors deduce that lesions with larger perimeter/area ratios will regenerate faster because lesions with long perimeters have more energy for regeneration. Very small lesions (single polyp lesions on *F. favus*) were in contrast to this perimeter-length hypothesis. The very small lesions healed faster even if they had lower lesion perimeter/area ratios. Meesters et al. (1994) suggest that lesion regeneration is powered by a limited energy source provided by polyps and tissue around the lesion since small and large coral lesions in their experiment stopped regenerating at the same time. The authors also conclude that lesion area regeneration per lesion perimeter would be the same in small or large lesions; this was demonstrated by Bak and Steward-van Es (1980) and Meesters et al. (1997). Meesters et al. (1997) also hypothesize that lesion regeneration is dependent on lesion perimeter, and due to that, lesion shape is more vital when studying lesion regeneration. In general, size and the lesion perimeter/area ratio both play a role in determining lesion regeneration rates, and lesion size may have a stronger effect as the size of the lesion decreases.

The effects of lesion regeneration on coral growth are well studied (Bak 1983, Lester and Bak 1985, and Meesters et al. 1994) as are the effects of ocean acidification on coral calcification (see Chapter 1, Langdon et al. 2003, Langdon and Atkinson 2005,
Albright et al. 2008, and Jokiel et al. 2008), but the effects of ocean acidification on lesion healing and coral growth have not been well studied. The experiment by Meesters et al. (1994) demonstrates that growth was decreased in *Montastraea annularis* after lesion infliction and even after lesion regeneration stopped. A lesion of 8.8% of the coral colony surface decreased growth by 32% after fifty-six days. On the other hand, Lester and Bak (1985) comparing coral (*M. annularis*) growth and lesion regeneration in two environmental conditions, found no correlation between coral growth and lesion regeneration rates. Between colonies there can be a large variation in growth, with or without lesions, and Meesters et al. (1994) find significant differences in coral skeletal growth between colonies even without lesions.

Coral lesions can be used as indicators of coral health and environmental conditions (Meesters et al. 1994, Williams 1994, and Fisher et al. 2007). According to Fisher et al. (2007), because lesion regeneration rates reflect the ability of the coral to repair injuries, lesions represent useful indicators of coral health and/or environmental conditions. Also, other factors that contribute to coral lesions being useful indicators are that coral lesions are a widespread response to an array of different stressors, and coral lesions can be monitored easily and inexpensively (Williams 1994). Fisher et al. (2007) illustrate that *Montastraea* spp. complex colonies experiencing different environmental conditions, at the same depth, in South Florida had significantly different lesion regeneration rates. The sites include a coral reef in Biscayne National Park near the city of Miami and a nuclear power plant, a coral reef in Key Largo off its most urbanized coastline, and two sites in John Pennekamp Coral Reef State Park. One of the coral reefs in John Pennekamp Coral Reef State Park had a significantly higher live coral cover,
significantly higher lesion regeneration rates, and significantly more healed lesions. In general, corals experiencing more favorable environmental conditions will have higher lesion regeneration rates, a high percentage of healed lesions, and lesion sizes will more closely follow an exponentially decreasing model through time. The Coral Resilience Assay program is designed to assess coral resilience quickly and inexpensively by studying lesion healing on *M. faveolata* (Mueller 2008). A coral with a faster healing lesion has greater resilience than a coral with a slower healing lesion. Resilience can also be used as an indicator of stress.

The lesions in this experiment are simulated fish bites from corallivorous and herbivorous fishes. With the ensuing threats of global climate change, it is important that corals are able to survive and heal from everyday stressors, like fish bites. For example, the stoplight parrotfish (*Sparisoma viride*) is known to bite live coral, including *Montastraea* among other genera (Bruckner and Bruckner 1998). These fish bites can be 2-5 cm in width and greater than 50 cm long. *S. viride* bite and remove coral tissue and skeleton (Bruckner et al. 2000). *M. annularis* even appears to be stimulated to regenerate tissue faster when there is skeletal damage (Bak et al. 1994).

Two experiments were performed, one in Summer 2009 and one in Fall 2009. In these experiments, *M. faveolata* fragments received intentional lesions to study and to understand lesion regeneration and skeletal growth resulting from different carbon dioxide concentrations, the present and future acidification scenarios, and inter-colony variability. The control condition was 26°C and 380 µatm, which is the current atmospheric CO₂ concentration. If CO₂ emissions continue along the current trajectory, predicted CO₂ concentrations will be 560 µatm in 2050 and 800 µatm in 2100 (IPCCa...
Using the predicted CO₂ concentrations, treatment conditions in the experiment are 26°C and 560 µatm and 800 µatm. In Fall 2009, only the predicted atmospheric CO₂ concentration by 2050 was used as the treatment condition, 26°C and 560 µatm.

The null hypothesis was that there will be no difference in lesion regeneration or skeletal growth rates in corals experiencing different CO₂ concentrations. The alternative hypothesis was that there will be slower lesion regeneration and skeletal growth rates as the CO₂ concentrations increase, while a second alternative hypothesis was that elevated pCO₂ might promote tissue regeneration and skeletal growth. Also, the differences in lesion regeneration or skeletal growth rates may be due to inter-colony variability, which may take a more vital role than the effects of increasing pCO₂. The results of the experiment will be able to predict *M. faveolata* resilience in the next fifty to 100 years, if the CO₂ concentrations reach their projected values.

**Methods**

The coral species, *Montastraea faveolata*, was used to study lesion regeneration and skeletal growth rates in three different carbon dioxide levels. *M. faveolata* colonies, originally collected from a Key West sea wall, were obtained in May 2007 (Permit FKNMS-2007-009). The corals were kept in a mesocosm at RSMAS receiving natural sunlight and ocean water from Bear Cut, Miami, filtered through glass media depth filters to remove particles greater than 25 µm.

On May 28\textsuperscript{th} for the Summer 2009 experiment, a drill press was used to core eighteen 1.5 inch diameter fragments, and on September 8\textsuperscript{th}, 2009, the drill press was used to core eight 1.5 inch diameter fragments from each of 4 *M. faveolata* colonies, for a
total of 32 fragments for the fall experiment. A tile saw was used to file off the bottom of
the coral fragments to roughly make them the same height and to make the bottom flat.
The coral fragments were kept in a 20 gallon tank at 26°C and with a pCO$_2$ of 380 µatm,
receiving natural sunlight and filtered ocean water from Bear Cut, Miami, also filtered to
remove particles greater than 25 µm.

A two part epoxy, All Game parts A and B, was used to cement down 2 fragments
to each of 9 PVC ‘sleds’ on June 5, 2009 for the summer experiment, and 16 PVC ‘sleds’
on September 25, 2009 for the fall experiment (Figure 2.1). Only fragments from the
same parent colony were placed together on a sled during the fall experiment. The
fragments were also fed these days with Zeigler shrimp larval diet (AP100 larval food
supplement, microparticle size <100 µm). Throughout both experiments the coral
fragments were fed twice a week. Two feeding days during the fall experiment, October
23$^{rd}$ and 27$^{th}$, a larger size diet had to be used (250-450 µm) because the smaller size diet
ran out temporarily. The larger size diet did not seem to stay in the water column and
just sank to the bottom, possibly inhibiting coral feeding.

![Figure 2.1: Each PVC ‘sled’ had two coral fragments cemented on it. The fragments are known to be from
the same parent colony in the fall experiment.](image)

The drill press, with a grinding stone (1/4” in the summer and 5/16” in the fall),
was implemented to make small circular lesions in the centers of the fragments. The
average initial lesion size was $0.68 \pm 0.06 \text{ cm}^2$ and $0.95 \pm 0.10 \text{ cm}^2$ for the Summer and
Fall 2009 experiments, respectively. On June 8\textsuperscript{th}, the 18 coral fragments were lesioned, and the summer experiment ended July 27\textsuperscript{th}, 49 days later. For the fall experiment the lesions were inflicted starting on October 7\textsuperscript{th}, but the drill press broke after only 6 fragments received lesions. Once the drill press piece was replaced on October 9\textsuperscript{th}, the rest of the fragments were lesioned, and the previously lesioned fragments were slightly re-lesioned in case any healing had occurred. The fall experiment began on October 9\textsuperscript{th} and ran until December 16\textsuperscript{th}, 69 days later.

Three ‘sleds’, 9 coral fragments, each randomly went into either the control tank or one of the pCO\textsubscript{2} treatment tanks, 560 µatm or 800 µatm during the summer experiment. In the fall experiment, the coral fragments were randomly assigned to four different tanks making sure that each tank had two fragments from each parent colony. There were a total of 8 fragments, 4 sleds, in each tank with 2 fragments from each of the 4 parent colonies in each tank. There were 2 tanks with control conditions of 26°C and a pCO\textsubscript{2} of 380 µatm and 2 tanks with experimental conditions of 26°C and a pCO\textsubscript{2} of 560 µatm. The tanks were the same size as described above and received natural sunlight and filtered water as described above. The pCO\textsubscript{2} measured in µatm in the treatment tanks was increased by bubbling the tanks with CO\textsubscript{2} enriched air. Streams of dried outside air and pure CO\textsubscript{2} gas from a cylinder was mixed using mass flow controllers to prepare the enriched air.

Once a week, photographs were taken of the coral fragment lesions with a Canon PowerShot SD1000 Digital Elph in the Canon WP-DC13 underwater housing using the macro setting. A transparent ruler was attached to the underwater housing so that the ruler was placed next to the right side of each coral fragment, showing the scale in every
picture (Figure 2.2). Pictures were done slightly different during the summer experiment. From these photographs, the freeware ImageJ (http://rsbweb.nih.gov/ij/) was used to find the area and perimeter of each fragment’s lesion through time.

Figure 2.2: The underwater camera case with bent ruler attached so that the ruler would show up next to each coral fragment photograph as a scale to be used in ImageJ.

Also, laser micrometer measurements were performed once a week. The laser micrometer uses a laser that is directly vertical above the coral fragment, along the PVC sled’s centerline. Every 64 µm the height of the coral fragment under the laser is recorded, creating a vertical profile of the fragments, which is used to calculate the daily growth rate (µm/d) of the coral fragments.

There are two lesions on the coral fragment: the initial lesion from making the 3.81 cm (1.5 inch) diameter corals from the coral colonies and the small circular lesions in the center of each fragment. The diameter of the coral fragments subtracting the lesion was divided into 6 parts, each roughly 4 mm (Figure 2.3). The growth rate was then calculated for the areas (parts 1, 3, 4, and 6) within 4 mm of the center lesion or the edges and then for the middle areas (parts 2 and 5) along the coral’s centerline.
Figure 2.3: *M. faveolata* coral fragment divided into 6 sections. Sections 1, 3, 4, and 6, on the coral’s centerline, are roughly within 4 mm of a lesion, either the center lesion or the outside edge. Sections 2 and 5, on the coral’s centerline, are the sections farther than 4 mm from a lesion.

About every two weeks the tanks were cleaned to remove macroalgae on the tanks’ walls. At least twice a week the coral lesions were lightly flushed with a small plastic pipette to remove any colonizing algae. This action removed loose algae that would naturally be removed in the ocean by wave action. Also, lightly flushing the lesion helped to obtain more accurate pictures for lesion measurements.

Water samples from each of the tanks were obtained about every week, between 12:00-1:00 p.m., to analyze the water chemistry for total alkalinity (TA, µmol/kg seawater), total CO$_2$ (µmol/kg seawater), pCO$_2$ (µatm), and the aragonite saturation state ($\Omega_{\text{arg}}$), as well as salinity. The total alkalinity was analyzed using the open-cell Gran titration method as explained in SOP3B of the *Best Practices Guide to the Analysis of Seawater Carbonate Chemistry* (Dickson et al. 2007).

**Statistical Analysis**

A one-way analysis of variance (ANOVA) was performed to analyze the skeletal growth rate and percent healed lesion area for the summer experiment. To analyze the skeletal growth rates within 4 mm of a coral’s lesions or greater than 4 mm from a coral’s
lesions the U-Mann Whitney test was used for all data pooled together and by each CO₂ concentration. For the fall experiment, a two-way analysis of variance (ANOVA) was used to test for the significance of the CO₂ treatment, the parent coral colony, and the interaction between CO₂ and the parent colony on skeletal growth rates the full 69 days of the experiment. The U-Mann Whitney test was used to analyze the percent healed area in the fall by CO₂ concentration, and the Kruskal-Wallis test was used to analyze the percent healed area in the fall by parent colony. To analyze the skeletal growth rates within 4 mm to a coral’s lesions or greater than 4 mm from a coral’s lesions for the fall, the U-Mann Whitney test was used for all data pooled together and by each CO₂ concentration and parent colony.

A one-way ANOVA, with Sum of Squares Type II, was used for comparing skeletal growth rate by CO₂ concentration with all data from the summer and fall (used data only up to 49 or 48 days, respectively) pooled together. A two-way ANOVA, with Sum of Squares Type III, was used to calculate the effect of season, CO₂ concentration, and their interaction between the summer and fall data for 380 and 560 µatm. The same tests were performed for the standardized healed area.

All data used in the ANOVAs for summer and fall was evaluated for normal distribution and equal variances. When data did not meet the assumption of normal distribution and/or equal variances even after transformations the non-parametric tests, U-Mann Whitney or Kruskal-Wallis were implemented. Following the ANOVAs, the Tukey-Kramer Honestly Significant Difference (HSD) test was used, and after the Kruskal-Wallis test pair wise comparisons were performed.
SigmaPlot was used to perform a nonlinear least-squares regression of lesion size through time to an exponential decay model, \( f = y_0 + a \cdot \exp(-b \cdot x) \), to the data for both the summer and fall for each CO\(_2\) concentration and for each parent colony in the fall.

The first derivative, \( df/dx = -ab \cdot \exp(-b \cdot x) \), of the exponential decay model equation was calculated to find the lesion healing rate by CO\(_2\) concentration. The Kruskal-Wallis test was used to analyze lesion healing rates for the summer, and the U-Mann Whitney test was used to analyze lesion healing rates for the fall. Lesion healing rates were also calculated by \( \Delta T/P \). \( \Delta T \) is the percent healed lesion area*initial lesion size/length of experiment. \( P \) is the initial perimeter. A two-way ANOVA, with Sums of Squares Type III, was used to analyze the \( \Delta T/P \) healing rates at 380 and 560 \( \mu \)atm between seasons, and a one-way ANOVA, with Sums of Squares Type III, between the three CO\(_2\) concentrations with summer and fall data combined. A linear regression was performed on summer and fall healing rates (\( \Delta T/P \)) by CO\(_2\) concentration.

**Results**

**Summer 2009 experiment**

The average total alkalinity (TA, \( \mu \)mol/kg seawater), total CO\(_2\) (\( \mu \)mol/kg seawater), pCO\(_2\) (\( \mu \)atm), and the aragonite saturation state (\( \Omega_{arg} \)), as well as temperature and salinity for each tank for the length of the experiment show expected trends (Table 2.1). The analyzed water chemistry showed that the aragonite saturation states and pH decreased as the pCO\(_2\) increased. The pCO\(_2\) in each tank were close to the nominal pCO\(_2\) values.
Table 2.1: The temperature, salinity, nominal pCO$_2$ (partial pressure of CO$_2$), TA (total alkalinity), TCO$_2$ (total CO$_2$), pH, pCO$_2$, and $\Omega_{arg}$ (aragonite saturation state) for each tank in the summer. Means ± SD

<table>
<thead>
<tr>
<th>Tank</th>
<th>Temperature</th>
<th>Salinity</th>
<th>Nominal pCO$_2$</th>
<th>TA (µmol/kg gSW)</th>
<th>TCO$_2$ (µmol/kg gSW)</th>
<th>pH$_{26}$</th>
<th>pCO$_2$ out (µatm)</th>
<th>$\Omega_{arg}$ @26C</th>
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</thead>
<tbody>
<tr>
<td>10</td>
<td>25.9 ± 0.2</td>
<td>34.1</td>
<td>800</td>
<td>2296 ± 51</td>
<td>2145 ± 51</td>
<td>7.75 ± 0.02</td>
<td>900 ± 38</td>
<td>2.0 ± 0.1</td>
</tr>
<tr>
<td>11</td>
<td>25.9 ± 0.2</td>
<td>33.8 ± 0.9</td>
<td>380</td>
<td>2274 ± 60</td>
<td>1969 ± 46</td>
<td>8.06 ± 0.05</td>
<td>384 ± 49</td>
<td>3.5 ± 0.3</td>
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<tr>
<td>12</td>
<td>26.00 ± 0.2</td>
<td>34.3 ± 0.8</td>
<td>560</td>
<td>2282 ± 69</td>
<td>2040 ± 58</td>
<td>7.94 ± 0.02</td>
<td>534 ± 24</td>
<td>2.8 ± 0.2</td>
</tr>
</tbody>
</table>

The average skeletal growth rate for corals was highest in the mid, 560 µatm, pCO$_2$ treatment, 4.0 ± 0.5 µm/day (means ± SE), followed by corals in the control, 380 µatm, conditions, 3.3 ± 0.6 µm/day, and the corals in the high, 800 µatm, CO$_2$ concentration had a skeletal growth rate of 1.6 ± 0.3 µm/day (Figure 2.4). pCO$_2$ had a significant affect on the skeletal growth (ANOVA, $F_{2,17} = 6.90$, $p < 0.05$). The corals at a pCO$_2$ of 560 µatm grew significantly faster than corals experiencing a pCO$_2$ of 800 µatm (Tukey-Kramer HSD, $p < 0.05$).

Coral polyps within 4 mm to the coral fragment’s lesion and outside edges grew significantly slower, 2.70 ± 0.21 µm/day (means ± SE), than coral polyps more than 4 mm from the coral fragment’s lesion and outside edges, 3.75 ± 0.32 µm/day (U-Mann Whitney, $U = 1,479.5$, df = 1, $p < 0.05$) when all data, regardless of CO$_2$ concentration, was pooled together, but not when analyzed separately by CO$_2$ concentration.
The average initial lesion size for all coral fragments at the beginning of the experiment was $0.68 \pm 0.01 \text{ cm}^2$ (means ± SE). CO$_2$ concentration exhibited a significant effect on the percent of healed lesion tissue (ANOVA, $F_{2,17} = 2.84$, $p < 0.1$). In the control tank, an individual lesion was on average $68 \pm 5\%$ (means ± SE) healed, with these corals healing the least. The corals in the mid CO$_2$ treatment healed on average $88 \pm 5\%$ of their lesion area. The corals in the high CO$_2$ treatment healed on average $72 \pm 9\%$ of their lesion area. Only one coral lesion completely healed during the time of the experiment; that coral was experiencing a pCO$_2$ of 560 µatm. Corals in a pCO$_2$ of 560 µatm had significantly more lesion tissue re-grown than corals at 380 µatm (Tukey-Kramer HSD, $p < 0.1$).
Lesion size through time was fit to an exponential decay model, $f = y_0 + a \times \exp(-b \times x)$ (Table 2.2 and Figure 2.6). This again showed that corals in a pCO$_2$ of 560 µatm healed more than corals in either 380 µatm or 800 µatm, and lesion size decreases through time and appears to begin to asymptote before the lesions fully close. The regression was significant for all three CO$_2$ concentrations (380 µatm: $F_{2,47} = 98.49$, $p < 0.05$, 560 µatm: $F_{2,7} = 122.48$, $p < 0.05$, 800 µatm: $F_{2,7} = 30.82$, $p < 0.05$). The exponential decay model explained 81%, 84%, and 58% of the variability in the lesion size through time for 380 µatm, 560 µatm, and 800 µatm CO$_2$ concentrations, respectively (380 µatm: $R^2 = 0.81$, 560 µatm: $R^2 = 0.84$, 800 µatm: $R^2 = 0.58$). The
average lesion healing rate was the fastest in a pCO$_2$ of 560 µatm, followed by 800 µatm, and the slowest healing rate was in 380 µatm (Table 2.3). There was no significant effect of CO$_2$ concentration on lesion healing rates.

Table 2.2: Equation coefficients, $f = y_0 + a \cdot \exp(-b \cdot x)$, and the standard error for each CO$_2$ concentration in the summer. ‘$y_0$’ is the asymptotic percentage of lesion area still present at infinity. ‘$a$’ is the initial lesion area minus ‘$y_0$’, and ‘$b$’ is the exponential healing rate factor.

<table>
<thead>
<tr>
<th></th>
<th>380µatm</th>
<th>560µatm</th>
<th>800µatm</th>
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</thead>
<tbody>
<tr>
<td>$y_0$</td>
<td>0.22 SE = 0.02</td>
<td>0.07 SE = 0.02</td>
<td>0.20 SE = 0.02</td>
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<td>$a$</td>
<td>0.48 SE = 0.02</td>
<td>0.64 SE = 0.02</td>
<td>0.51 SE = 0.03</td>
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<tr>
<td>$b$</td>
<td>0.067 SE = 0.008</td>
<td>0.060 SE = 0.006</td>
<td>0.08 SE = 0.01</td>
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</table>

Table 2.3: Average *M. faveolata* healing rates (mm$^2$/day) in the summer calculated by the first derivative of the equation $f = y_0 + a \cdot \exp(-b \cdot x)$, $df/dx = -a \cdot b \cdot \exp(-b \cdot x)$. Means ± SE, $p > 0.05$, n = 6 for each CO$_2$ concentration.

<table>
<thead>
<tr>
<th></th>
<th>380 µatm</th>
<th>560 µatm</th>
<th>800 µatm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.9 ± 0.1</td>
<td>1.21 ± 0.1</td>
<td>1.0 ± 0.1</td>
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</tbody>
</table>
**Fall 2009 experiment**

The average total alkalinity (TA, µmol/kg seawater), total CO$_2$ (µmol/kg seawater), pCO$_2$ (µatm), and the aragonite saturation state ($\Omega_{arg}$), as well as temperature and salinity for each tank for the length of the experiment showed expected trends (Table 2.4). The analyzed water chemistry showed that the aragonite saturation states and pH were lower in the higher pCO$_2$. The pCO$_2$ in each tank were close to the nominal pCO$_2$ values. There was one downward temperature spike lasting a few hours in each tank 7 and 9 leading to their lower average temperatures and higher standard deviations.

Table 2.4: The temperature, salinity, nominal pCO$_2$ (partial pressure of CO$_2$), TA (total alkalinity), TCO$_2$ (total CO$_2$), pH, pCO$_2$, and $\Omega_{arg}$ (aragonite saturation state) for each tank in the summer. Means ± SD

<table>
<thead>
<tr>
<th>Tank</th>
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<th>Salinity</th>
<th>Nominal pCO$_2$</th>
<th>TA (µmol/kg/SW)</th>
<th>TCO$_2$ (µmol/kg/SW)</th>
<th>pH$_T$ @26C</th>
<th>pCO$_2$ out (µatm)</th>
<th>$\Omega_{arg}$ @26 C</th>
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<tr>
<td>1</td>
<td>26.0 ± 0.2</td>
<td>36 ± 1</td>
<td>560</td>
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<tr>
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<td>380</td>
<td>2251 ± 184</td>
<td>1940.9 ± 159</td>
<td>8.04 ± 0.05</td>
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<tr>
<td>9</td>
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<td>2377 ± 77</td>
<td>2103.1 ± 55.3</td>
<td>7.96 ± 0.04</td>
<td>522 ± 45</td>
<td>3.1 ± 0.3</td>
</tr>
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</table>

There was a significant effect on skeletal growth rate by parent colony ($F_{3,31} = 5.84, p < 0.05$) and by the interaction of parent colony and CO$_2$ concentration ($F_{3,31} = 3.51, p < 0.05$). Corals from parent colony 3 grew significantly slower than the corals from colonies 1 and 2 (Tukey-Kramer HSD, $p < 0.05$) (Figure 2.7a). The corals from parent colony 3 had a skeletal growth rate of 3.4 ± 0.6 µm/day (means ± SE), while the growth rates of corals from colony 1 and 2 were 5.5 ± 0.5 µm/day and 6.1 ± 0.7 µm/day, respectively. Skeletal growth rates from colony 3 in a pCO$_2$ of 560 µatm were
significantly slower than skeletal growth rates from colonies 1 and 2 also in 560 µatm (Tukey-Kramer HSD, p < 0.05) (Figure 2.7b). When corals from parent colony 3 were removed, there was an effect of pCO$_2$ ($F_{1,23} = 3.37$, p < 0.10); corals in 560 µatm grew faster than corals in 380 µatm, 5.9 ± 0.5 µm/day and 4.9 ± 0.4 µm/day (means ± SE), respectively. Corals from colonies 1 and 2 had increased skeletal growth rates when growing in a pCO$_2$ of 560 µatm, while corals from colonies 3 and 4 had decreased skeletal growth rate in the higher CO$_2$ tanks. There was no significant difference between skeletal growth within 4 mm of the coral’s lesions or greater than 4 mm from the coral’s lesions with the data pooled or separately by parent colony and CO$_2$ concentration.

Figure 2.7a: Average *M. faveolata* vertical skeletal growth rate (µm/d) for the fall by parent colony. Mean ± SE, p < 0.05, means with different letters are significantly different, n = 8 for each parent colony
Figure 2.7b: Average *M. faveolata* vertical skeletal growth rate in the fall by CO\(_2\) concentration and parent colony. Mean ± SE, p < 0.05, means with different letters are significantly different, n = 8 for each parent colony.

The initial lesion size at the beginning of the experiment was 0.95 ± 0.02 cm\(^2\) (means ± SE). No lesions fully closed during the time frame of the experiment. There was a significant effect of parent colony on percent healed lesion area (Kruskal-Wallis, \(H = 11.15\), df =3, p < 0.05) but not by CO\(_2\) concentration (Figure 2.8). Corals from colony 4 healed a significantly larger percentage of their lesion area than corals from colony 1 (U-Mann Whitney, \(U = 10\), df =1, p < 0.05) and colony 3 (U-Mann Whitney, \(U = 4\), df =1, p < 0.05), 94 ± 3 % (means ± SE) versus 80 ± 5 % and 71 ± 5 % of tissue healed, respectively.
Figure 2.8: Average lesion area of *M. faveolata* healed in the fall by parent colony. The closer the bars are to 100% the more healed the lesions were at the end of the experiment. Mean ± SE, *p* < 0.05, means with different letters are significantly different, *n* = 8 for each parent colony.

The lesion size through time was fit to an exponential decay model, \( f = y_0 + a \cdot \exp(-b \cdot x) \) (Figure 2.9 and Table 2.5). Lesion size decreases through time and asymptotes before the lesion fully closes. The logistic regression was significant for each CO\(_2\) concentration (380 µatm: \( F_{2,175} = 330.07, \ p < 0.05 \), 560 µatm: \( F_{2,175} = 270.33, \ p < 0.05 \)). The function explained 79% and 76% of the variability in lesion size through time for a pCO\(_2\) of 380 and 560, respectively. The logistic regression was also significant for all four parent colonies (Parent Colony 1: \( F_{2,87} = 130.28, \ p < 0.05 \), Parent Colony 2: \( F_{2,87} = 391.63, \ p < 0.05 \), Parent Colony 3: \( F_{2,87} = 158.60, \ p < 0.05 \), Parent Colony 4: \( F_{2,87} = 374.76, \ p < 0.05 \)). The exponential decay model explained 75%, 90%, 79%, and 90% of the variability in parent colonies 1, 2, 3, and 4, respectively. Because the data fit better when divided by parent colony, those equation coefficients were used to calculate the
lesion healing rate. While the lesion healing rates were not significantly different from each other, the average lesion healing rate was fastest in colony 4, followed by colonies 2 and 1, and colony 3 had the slowest lesion healing rate (Table 2.6).

Table 2.5a: Equation coefficients, \( f = y_0 + a \exp(-b \cdot x) \), and the standard error for each CO\(_2\) concentration in the fall. ‘\( y_0 \)’ is the asymptotic percentage of lesion area still present at infinity. ‘\( a \)’ is the initial lesion area minus ‘\( y_0 \)’, and ‘\( b \)’ is the exponential healing rate factor

<table>
<thead>
<tr>
<th></th>
<th>380 μatm</th>
<th>560 μatm</th>
</tr>
</thead>
<tbody>
<tr>
<td>( y_0 )</td>
<td>0.13 SE = 0.01</td>
<td>0.15 SE = 0.02</td>
</tr>
<tr>
<td>( a )</td>
<td>0.85 SE = 0.03</td>
<td>0.83 SE = 0.04</td>
</tr>
<tr>
<td>( b )</td>
<td>0.046 SE = 0.002</td>
<td>0.044 SE = 0.003</td>
</tr>
</tbody>
</table>

Table 2.5b. Equation coefficients, \( f = y_0 + a \exp(-b \cdot x) \), and the standard error for each parent colony in the fall. ‘\( y_0 \)’ is the asymptotic percentage of lesion area still present at infinity. ‘\( a \)’ is the initial lesion area minus ‘\( y_0 \)’, and ‘\( b \)’ is the exponential healing rate factor

<table>
<thead>
<tr>
<th>Parent Colony</th>
<th>( y_0 )</th>
<th>SE</th>
<th>( a )</th>
<th>SE</th>
<th>( b )</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.16</td>
<td>0.06</td>
<td>0.78</td>
<td>0.06</td>
<td>0.038</td>
<td>0.008</td>
</tr>
<tr>
<td>2</td>
<td>0.11</td>
<td>0.02</td>
<td>0.88</td>
<td>0.03</td>
<td>0.057</td>
<td>0.006</td>
</tr>
<tr>
<td>3</td>
<td>0.25</td>
<td>0.05</td>
<td>0.71</td>
<td>0.05</td>
<td>0.037</td>
<td>0.007</td>
</tr>
<tr>
<td>4</td>
<td>0.02</td>
<td>0.04</td>
<td>1.01</td>
<td>0.04</td>
<td>0.045</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Figure 2.9a: Average \( M. faveolata \) lesion size through time by CO\(_2\) concentration using the exponential decay model \( f = y_0 + a \exp(-b \cdot x) \). Mean ± SE, 380 μatm: \( R^2 = 0.79 \), 560 μatm: \( R^2 = 0.76 \), \( p < 0.05 \) for both CO\(_2\) concentrations, \( n = 16 \) for each CO\(_2\) concentration at each point
Figure 2.9b: Average *M. faveolata* lesion size through time for the fall by parent colony using the exponential decay model \( f = y_0 + a \cdot \exp(-b \cdot x) \). Mean ± S.E., Parent Colony 1: \( R^2 = 0.75 \), Parent Colony 2: \( R^2 = 0.90 \), Parent Colony 3: \( R^2 = 0.79 \), Parent Colony 4: \( R^2 = 0.90 \) \( p < 0.05 \) for all parent colonies, \( n = 8 \) for each parent colony at each point

Table 2.6: Average *M. faveolata* healing rates (mm²/day) in the fall calculated by the first derivative of the equation \( f = y_0 + a \cdot \exp(-b \cdot x) \), \( \frac{df}{dx} = -a \cdot b \cdot \exp(-b \cdot x) \). Means ± SE, \( p > 0.05 \), \( n = 8 \) for each parent colony

<table>
<thead>
<tr>
<th>Parent Colony 1</th>
<th>Parent Colony 2</th>
<th>Parent Colony 3</th>
<th>Parent Colony 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.03 ± 0.09</td>
<td>1.2 ± 0.1</td>
<td>0.94 ± 0.08</td>
<td>1.4 ± 0.1</td>
</tr>
</tbody>
</table>

**Summer 2009 and Fall 2009**

There was a significant effect of season on vertical skeletal growth rate (not including the summer data for the corals in 800 μatm and data from the fall is only used from the first 48 days of the experiment) (ANOVA, \( F_{1,43} = 5.28 \), \( p < 0.05 \)) but not CO\( \text{₂} \) concentration or the interaction of season and CO\( \text{₂} \) concentration (Table 2.7). Individual *M. faveolata* fragment vertical skeletal growth ranged from 0.9 – 5.7 in the summer and from 1.4 – 7.4 μm/day in the fall after 48 days. With all data from the summer and fall
experiments pooled together there was a significant effect of CO$_2$ concentration on skeletal growth rates (data from the fall experiment is only from the first 48 days of the experiment, ANOVA, $F_{3,49} = 10.97, p < 0.05$) (Figure 2.12). The corals in 800 µatm grew significantly slower, 1.6 ± 0.3 µm/day than corals in either 380 and 560 µatm, 4.2 ± 0.3 µm/day and 4.7 ± 0.3 µm/day, respectively (Tukey-Kramer HSD, p < 0.05).

Table 2.7: Average *M. faveolata* vertical skeletal growth rate (µm/day) for the summer and fall. Means ± SE, p > 0.05 means with different letters are significantly different, n = 12 for the summer and n = 32 for the fall

<table>
<thead>
<tr>
<th>Summer</th>
<th>Fall</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0 ± 0.4 A</td>
<td>4.8 ± 0.3 B</td>
</tr>
</tbody>
</table>

Lesion healing standardized to the lesion’s initial perimeter, as the initial lesion sizes were different, was also compared for the first 48 d of the fall experiment and the full 49 d of the summer experiment. While the summer experiment demonstrated that the
corals in 560 µatm healed more area than those in 380 µatm; the fall experiment showed the opposite trend (Figure 2.11). There was no significant difference in lesion area healed standardized to initial perimeter by season, CO₂ concentration, or their interaction (the values from 800 µatm were removed). The data from both the summer and fall combined shows a trend, while not significant, of corals healing more in 560 µatm, followed by 380 µatm, and lastly by 800 µatm (Figure 2.12).

![Figure 2.11: Average M. faveolata lesion area healed standardized by initial lesion perimeter by season and CO₂ concentration. Means ± SE, p > 0.05, n = 6 for each CO₂ concentration for the summer and n = 16 for each CO₂ concentration for the fall](image)

Healing rates were compared between summer and fall standardized by initial lesion perimeter, ΔT/P. There was no significant difference between healing rates pooled by CO₂ concentration or CO₂ concentrations compared between fall and summer (Table
A linear regression was performed on the data in Table 2.7 (Figure 2.13). The slope is not significantly different from 0, and only 0.53% of the variability in healing rates (cm/d) can be explained by CO₂ concentration.

Figure 2:12: Average *M. faveolata* lesion area healed standardized by initial lesion perimeter by CO₂ concentration for the pooled summer and fall data. Means ± SE, p > 0.05, n = 22 for 380 and 560 µatm and n = 6 for 800 µatm

Table 2.8: The average healing rates, ∆T/P (cm/d) and standard errors for the summer and fall experiments by CO₂ concentration. ∆T = percent healed lesion area * initial lesion size/length of experiment, P = initial lesion size, length of experiment is 49 days for the summer and 48 days for the fall, p > 0.05, n = 6 for each CO₂ concentration in the summer and 16 for each CO₂ concentration in the fall

<table>
<thead>
<tr>
<th>Season</th>
<th>pCO₂ (µatm)</th>
<th>∆T/P (cm/d)</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>380</td>
<td>0.0034</td>
<td>0.0003</td>
</tr>
<tr>
<td>Fall</td>
<td>380</td>
<td>0.0039</td>
<td>0.0002</td>
</tr>
<tr>
<td>Summer</td>
<td>560</td>
<td>0.0045</td>
<td>0.0003</td>
</tr>
<tr>
<td>Fall</td>
<td>560</td>
<td>0.0038</td>
<td>0.0002</td>
</tr>
<tr>
<td>Summer</td>
<td>800</td>
<td>0.0036</td>
<td>0.0005</td>
</tr>
</tbody>
</table>
Figure 2.13: A linear regression of $\Delta T/P$ and CO$_2$ concentration for the pooled summer and fall data. $\Delta T/P$ is defined in Table 2.8, means ± SE, $p > 0.05$, $R^2 = 0.0053$

**Discussion**

**Summer 2009**

In the summer coral lesion experiment, one trend was evident through all aspects analyzed. Corals experiencing a pCO$_2$ of 560 µatm had better skeletal growth and healed more lesion tissue and faster. There are two explanations I will offer for corals growing and healing better at higher CO$_2$ concentrations; the experiment was short-term and in the long run this trend would not exist or that increased CO$_2$ to a certain level is beneficial to corals because it is advantageous to their photosynthetic symbionts, symbiodinium. The results demonstrated that increasing pCO$_2$ to at least 560 µatm can be beneficial to coral
skeleton growth and lesion healing to some extent, but the benefits decrease as the CO$_2$ concentration increases to 800 µatm where lesion healing benefited relative to the control but skeletal growth was significantly attenuated.

There are many theories as to what role symbiodinium play in enhancing calcification. Symbiodinium may increase the amount of photosynthates transferred to the coral, they might be able to raise the pH and provide more carbonate ions, they could remove inhibiting substances, and they may manufacture organic matrix precursors (Muller-Parker and D’Elia 1997). At a pCO$_2$ of 560 µatm the symbiodinium will have increased photosynthesis because there is more CO$_2$, as long as other factors, like nutrients, are not limiting. With increased photosynthesis, the possible positive interactions between symbiodinium and coral calcification could increase. These factors could lead to the enhanced skeletal growth rate and faster lesion healing seen at 560 µatm in this experiment. Since growth and tissue healing at 800 µatm was decreased compared to the corals in 560 µatm, the positive benefits from an increase in photosynthesis must be overcome by negative effects as CO$_2$ concentrations continue to increase. At higher CO$_2$ concentrations, like 800 µatm, the corals may lose control over their symbionts, the symbionts’ photosynthesis becomes limited by other factors, the pH of the water/calcifying fluid is too low forcing corals to slow down their calcification, and/or the pH negatively affects coral metabolism and other physiological processes. However, corals in a pCO$_2$ of 800 µatm did show faster healing rates, although not significant, than the corals in 380 µatm in the summer. The relationship between corals and their symbionts is very complex and requires further work into how symbiodinium can influence calcification and healing.
**Fall 2009**

While CO$_2$ had a significant effect on coral skeletal growth and lesion healing in the summer, there was less of an effect from CO$_2$ when accounting for variability between for parent colonies. Corals from colony 3 grew significantly slower than the colonies 1 and 2. The skeletal growth rate of colony 3 was slower in a pCO$_2$ of 560 µatm than 380 µatm. Because corals from colony 4 also grew slower in the higher pCO$_2$ treatment while corals from colonies 1 and 2 grew faster in the higher pCO$_2$ treatment, it seems to demonstrate that colonies 1 and 2 are more resilient than colonies 3 and 4.

Also, corals from colony 3 had the least amount of healed tissue and the slowest healing rates. Because of that colony 3 may have lower resilience compared to all other colonies in the study. Colony 3 was more sensitive to the increased CO$_2$ concentration and simulated ocean acidification. While corals from colony 4 showed a slight decrease in skeletal growth rate between the current and expected CO$_2$ increase by 2050, corals from colony 4 healed their lesions significantly faster than corals from colonies 1 and 3 but also faster colony 2. Colony 4 appears to have put more energy into healing versus calcifying, while colonies 1 and 2 appear to have put more energy into calcifying than healing.

**Summer 2009 and Fall 2009**

Coral skeletal growth rates were faster during the fall experiment than the summer experiment. The difference in growth may be due to seasonal growth changes as the corals would have experienced different amounts of sunlight. Another possible reason was that there were different amounts of recovery between making the initial coral fragment and the small circular lesions for the summer, 10 days, and the fall, 30 days.
There was a threshold effect on *M. faveolata* skeletal growth and CO$_2$ concentration, meaning that *M. faveolata* skeletal growth increased with increasing CO$_2$ concentrations until it reached a threshold CO$_2$ concentration, where thereafter skeletal growth decreased. The results of this study are contradictory to many other experiments demonstrating a decrease in calcification with a doubling of pre-anthropogenic atmospheric pCO$_2$ to 560 µatm (see Langdon et al. 2003, Langdon and Atkinson 2005, and Jokiel et al. 2008). Yet, McNeil et al. (2004), using a climate model, predict an increase in coral calcification from future aragonite saturation states and SST. This study found an average of 22% calcification increase when grown in 560 µatm in the summer after 49 d and a 6% increase in the fall after 69 d. Silverman’s (2009) prediction that coral reefs will be in a state of dissolution when pCO$_2$ reaches 560 µatm is not reflected for *M. faveolata* in this experiment. Lesion healing is known to decrease growth (Bak 1983 and Meesters et al. 1994), so the skeletal growth rates of *M. faveolata* observed in the summer and fall experiments may be even higher when they are not healing lesions, but see Lester and Bak (1985).

At 48 d or 49 for the fall and summer experiments, there are different trends for total lesion area healed. In the summer corals experiencing 560 µatm had more healing than at a pCO$_2$ of 380 µatm, but not in the fall experiment at 48 d. Although in the fall experiment at 69 d, corals in a pCO$_2$ of 560 µatm had more healing than 380 µatm. I suspect that different trends may be present depending on the length of the experiment. One trend present after one month may not be the same trend present after two months and so on.
Many agree that lesion perimeter is an important determinant of lesion healing (Bak and Steward-van Es 1980, Meesters et al. 1994, 1997, and Oren et al. 1997). The energy to heal the coral lesion comes from the surrounding polyps, so a lesion with a longer perimeter will have more polyps to draw energy from to grow tissue to heal the lesion. However Bak and Steward-van Es (1980) hypothesized that lesion regeneration per lesion perimeter would be the same regardless of lesion size. In the current experiments lesion regeneration per lesion perimeter was not the same regardless of size as summer and fall corals did not heal the same amount of tissue even when standardized to lesion perimeter, but the differences were not significant. Many factors could affect this: parent colony, CO$_2$ concentration, season, genetics, previous stressors, different recovery periods, unaccounted for error, or a combination of some or all. The data did show trends with faster skeletal growth farther away from lesions than next to lesions in the summer, but not in the fall. Meesters et al. (1994) calculate the area that supplies energy for lesion regeneration is only about the width of two polyps, or 6 mm, surrounding the lesion. A smaller width was used when calculating the skeletal growth rates near a coral’s lesions and away from a coral’s lesion in this study because the coral fragment was too small to have wider width sections for determining skeletal growth near and far from lesions.

Both summer and fall experiments demonstrated that lesion size decreases through time exponentially but asymptotes before fully closing the lesion as first shown by Meesters et al. (1994). The healing rates ($\Delta T/P$) from the summer and fall experiment were similar to the healing rates reported by Fisher et al. (2007). Short-term regeneration rates (45 to 154 d) in the Fisher et al. (2007) field study ranged from -0.0040 to 0.0065
cm/d, with an average of 0.0013 cm/d. The current study found that healing rates ranged from 0.0019 to 0.0055 cm/d for 49 d, with an average of 0.0034 cm/d and 0.0039 cm/d at a pCO$_2$ of 380 µatm for the summer and fall experiments respectively. For 69 d, the healing rates ranged from 0.0018 to 0.0040 cm/d, with an average of 0.0030 cm/d at a pCO$_2$ of 380 µatm. The ranges of the rates in the Fisher et al. (2007) and the present coral lesion studies are similar, although the Fisher et al. (2007) study has negative healing rates, which did not occur in the present coral lesion study.

From personal observation, it appeared that the lesions healed by extension of surrounding polyps. Polyps that were cut in half when lesioned re-grew into full polyps first, followed by extratentacular and intratentacular budding. In the summer experiment, which ran for 49 days, only one coral lesion completely healed. In the fall experiment, which lasted slightly longer at 69 days, no coral lesions completely healed. The study by Fisher et al. (2007) found that in the field many coral lesions require greater than 200 days to fully close. This explains why there was low incidence of complete lesion closure in the summer and fall experiments.

Because of the differences seen between the experiments with the same treatment and control conditions, the studies show that other factors besides CO$_2$ concentrations are affecting coral calcification and tissue regeneration, possibly colony variability, season, or recovery period between stressors among other factors. The linear regression of lesion healing rates and CO$_2$ concentrations demonstrated that CO$_2$ concentrations only had a small impact on determining lesion healing rates. The exponential models of lesion size through time also showed that other factors beside CO$_2$ concentration are affecting lesion healing. This could make it difficult to use coral lesion healing as an indicator of
environmental conditions since there is great variability seen in coral lesion healing rates. Instead, coral lesion healing and calcification should be used as indicators of resilience with those corals growing faster and healing faster being more resilient than those growing and healing slower. Some corals have more inherent resilience than others. Two of the same coral species, different colonies living next to each other, will not react the same to all stressors. The corals from colony 3 in the fall experiment had decreased resilience as they grew and healed significantly less than other colonies. Colony 3 was more impacted by the increased CO₂ concentration. In the next fifty years one can expect a wide variety of positive and negative effects on coral growth and lesion healing; those with high resilience will be positively affected with increasing skeletal growth and lesion healing rates, while those with low resilience will be negatively affected by ocean acidification, as shown by *M. faveolata*. In the next 100 years, when the pCO₂ is projected to be 800 µatm, there will be negative effects on skeletal growth, but those that are more resilient will show little change in their lesion healing capabilities, as shown by *M. faveolata*. 
CHAPTER 3

CURRENT MANAGEMENT FRAMEWORKS FOR REDUCING CLIMATE-INDUCED CHANGES ON CORAL REEFS BY ENSURING CORAL RESILIENCY

Background

There are many options used and discussed by both scientists and managers to conserve coral reefs. MPAs, no-take zones, ecosystem based management, and coastal zone management are all broad options that can have a variety of more specific actions within them. Examples of these more specific actions include reducing local anthropogenic stressors, increasing marine stewardship and education, reef monitoring, various research, and herbivore management. There are also strategies to enhance coral reefs: coral nurseries, artificial reefs, and electrochemical stimulation among other actions. Reef shading, polyp feeding, symbiont stimulation, and wave-powered artificial upwelling are all techniques used to reduce temperature stress and bleaching. The most common solutions suggested in the Kleypas and Eakin (2004) survey of scientists’ perceptions of coral reef threats are decreasing greenhouse gas emissions and human population growth, along with increasing education and communication. All these strategies boil down to increasing coral reef resilience directly or indirectly by reducing coral reef stressors.

MPAs and marine reserves are commonly the tools of managers to protect coral reefs (Allison et al. 1998, Halpern 2003, and Mumby and Steneck 2008). An extensive review of the success of marine reserves (no-take areas) by Halpern (2003) reveals that marine reserves promote a significantly increased diversity, biomass, density, and size of functional groups, except invertebrate biomass and size. There are, however, three
screen doors through which stressors can enter MPAs and prevent MPA success: land, ocean, and atmosphere (Jameson et al. 2002). MPA managers are limited in what external local anthropogenic stressors can be removed because they do not have authority over threats coming from outside MPA boundaries. According to Jameson et al. (2002), MPAs should be placed in locations where the threats are more controllable so that MPAs have a better chance of being effective.

While Aronson and Precht (2006) agree that MPAs can be successful, they also state that large-scale disturbances like climate change must be tackled or coral reefs will continue to decline. Mumby and Steneck (2008) agree that management at local scales, working to reduce local physical and biological stress, is most advantageous since there is no direct local solution or immediate management solution for climate change. West and Salm (2003) suggest that protecting coral reefs resilient and resistant to bleaching in order to protect coral reef biodiversity is a priority. Although the establishment of marine reserves is definitely a step in the right direction, reserves alone may not be enough to combat declining coral reefs (Mumby and Steneck 2008).

Keller et al. (2009) suggest that most coral reef MPA management plans do not have climate change management strategies. Institutional incapacities limit the integration of climate change into MPA management actions. Again, MPA managers do not have authority over all activities that affect their MPA (Jones 2002). It would be impossible for MPA managers to implement the global action of reducing greenhouse gas emissions. There is a spatial difference in the scale between MPAs, which are local, and climate change, which is global. MPA managers alone cannot manage climate change at the suitable scale (Mumby and Steneck 2008). There is little capacity to assist
policymakers in developing climate change adaptation planning processes (Heller and Zavalata 2009). Keller et al. (2009) articulate that there are no concrete management strategies specifically for ocean acidification. Also hindering the incorporation of climate change into management plans is the uncertainty about management outcomes, because climate change impacts are hard to separate from other stressors (Keller et al. 2009).

Doney et al. (2008) encourage more research on the effects of climate change to coral reefs so that policymakers can make informed management decisions. The role of science in management institutions can be contentious. There are those that do not believe scientific details are necessary for effective management and those that do think scientific details are necessary; a middle ground is essential to incorporate science into the management of MPAs (Halpern et al. 2008). Scientific research can lessen uncertainty, but resources (financial, human, and technical) are often lacking (Ehler et al. 1997). Scientific research can also divert resources away from other management actions. There are many barriers to the effective incorporation of science into management. Scientists and policymakers have different objectives, information needs, motivations, timelines, and core questions (Reaser et al. 2000). The goal is to overcome the differences to allow effective communication between scientists and policymakers (Reaser et al. 2000).

The Nature Conservancy’s Resilience Model was developed to increase coral reef resilience to climate change inside MPAs (Salm et al. 2006). The TNC Resilience Model has four principles to include in MPA design: representation and replication, critical areas, connectivity, and effective management¹. These managing principles are tools to

¹ The definitions of the Resilience Model principles are from Salm et al. (2006) and the TNC Reef Resilience online course [https://www.conservationtraining.org/]. Representation and replication means
help MPA managers build coral reef resilience. Many agree that resilience is a key component for mitigating climate change (McClanahan et al. 2002, Tompkins and Adger 2004, and Graham et al. 2008). Mueller (2008) states that corals in better health have the possibility of being more resilient to climate change, but can MPAs increase the resilience of corals? There are expectations that marine reserves can promote increased resilience from climate change, but Graham et al. (2008) found that marine reserves in the Indian Ocean demonstrated no evidence of less coral and fish declines after a bleaching event than on fished reefs. The authors conclude that bleaching recovery rates, or resilience, would probably be no different inside or outside of marine reserves. However, Selig and Bruno (2010) compared coral cover from 310 MPAs globally and demonstrated that coral cover remained constant in MPAs and declined in unprotected areas. The authors suggest that older MPAs do increase the resilience of corals.

The effects of climate change will definitely be felt at a large scale and will act outside the boundaries of present and future MPAs. Because MPAs with management actions to increase ecosystem resilience are common tools to protect coral reefs, wider Caribbean MPA management plans were used in this study to discover if it is true that most coral reef MPAs do not have climate change management strategies. This study on current climate change management strategies will further elucidate the specific institutional incapacities for incorporating climate change management that is lacking in the literature. Thus, the objective of chapter 3 is to (1) identify and evaluate current management practices existing in wider Caribbean coral reef MPAs that reduce negative

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three replicates of each coral reef community type, conditions, and linked habitats. Critical areas are biologically and ecologically significant areas, unique or vulnerable habitats, source areas, and resistant or resilient reefs. Connectivity refers to connections between adjacent habitats, distant connections through larval dispersal, and distant connections through adult movements. Effective management utilizes adaptive management and monitors for coral reef health.
global climate change effects using the TNC Resilience Model as a framework, and chapter 4 will (2) assess the management implications of the *M. faveolata* experiment, the effect of increasing CO$_2$ concentrations on coral skeletal growth and lesion regeneration, and (3) develop revised climate-based coral reef resilience management guidelines, using information from objectives 1 and 2, specifically for the FKNMS that can also apply to MPAs in the wider Caribbean.

**Methods**

**Objective 1: Assessment of Caribbean MPA management plans**

First an Internet search on wider Caribbean coral reef MPAs was performed. From those MPAs identified another Internet search was carried out to find out which MPAs had management plans available online. Nine MPA management plans were obtained: Biscayne National Park, Bonaire National Marine Park, Florida Keys National Marine Sanctuary (FKNMS), Glover’s Reef Marine Reserve World Heritage Site, Hol Chan Marine Reserve, St. Croix East End Marine Park, St. Eustatius National Marine Park, St. Maarten Marine Park, and Soufriere Marine Management Area (Figure 3.1). The Soufriere Marine Management Area has never used the management plan for guiding management, thus precluding the use of this management plan in the analysis (http://www.smma.org.lc/Background.htm). The climate related provisions in the management plans were examined using the TNC Resilience Model as a basis for identification of management actions that increase coral reef resilience.
Figure 3.1 continued
Each category of the TNC Resilience Model - representation and replication, critical area, connectivity, and effective management - was given a YES or NO for each MPA. The TNC Reef Resilience online course (https://www.conservationtraining.org/) and Salm et al. (2006) were used to develop a concise definition for each principle. Representation is defined as having representation of coral reef community types, conditions, and linked habitats. If the management plan had representation of any of the above three conditions, the MPA received a YES in that category. Three replicates of each coral reef community type, condition, and linked habitats is suggested, although the exact number of replicates will not be discussed as that information was not in the management plans.

Critical areas include biologically and ecologically significant areas (such as nursery breeding areas, sources of larvae aggregations, spawning aggregations, and migration corridors), unique or vulnerable habitats, source areas, and areas that have resistant or resilient characteristics. If the management plan demonstrated that the MPA included any critical area, the MPA was given a YES for the critical area category. Connectivity is defined as connections between adjacent habitats, distant connections through larval dispersal, and distant connections through adult movements. To receive a YES for connectivity, the management plan had to demonstrate connectivity through adjacent habitats, larval dispersal, or adult movements.

The potential for effective management was determined if the management plan had management strategies for adaptive management and for monitoring coral reef health. Adaptive management was defined as evaluating management strategies and using that information to develop and change management strategies. To receive a YES
for effective management, the management plan had to include actions to both manage for coral reef health and use adaptive management. This category, however, only takes into account managers’ intentions for adaptive management and to monitor for coral reef health and not institutional capability or metrics like enforcement or compliance. I added another category: climate change. If climate change, bleaching, or global warming was mentioned the management plan, then the MPA received a YES in that category. A short explanation is also provided to explain the reason for the YES or NO for each resilience principle for each MPA.

**Results**

Six of the eight management plans analyzed - Bonaire National Marine Park, FKNMS, Glover’s Reef Marine Reserve World Heritage Site, Hol Chan Marine Reserve, St. Eustatius National Marine Park, and St. Maarten Marine Park - received a YES in each TNC Resilience Model category and also in the climate change category (Table 3.1). Some of the management plans included the Resilience Model principles into areas with extra protection, like no-take areas. Because all the management plans identified that the MPAs either consisted of an area from the shoreline out to a certain depth or surrounded part or all of an island, the MPAs were considered representative of all available coral reef community types, conditions, and linked habitats for the area the MPA is situated in.

Nurseries and spawning areas were the most prevalent type of critical area protected and were included in the management plans of over half (5) of the MPAs analyzed. Other critical areas mentioned in management plans included fragile areas,
unique areas, high natural value areas, biologically important areas, unspoiled areas, replenishment areas, areas for genetic protection, areas of ecological significance, areas to protect fish stocks, areas with endangered organisms, areas with larval sources, and resilient and resistant reefs.

Connectivity between adjacent areas was the most common type of connectivity identified and was present in all 8 management plans as the MPAs contain area from the shoreline out to varying depths, which includes mangroves, seagrass and coral reefs. Discourse on oceanographic currents was included in many of the management plans. Whether this allowed connectivity to other MPAs was not answered, but Glover’s Reef Marine Reserve is identified as a source and sink site with other MPAs on the Belizean Barrier Reef.

All of the management plans except one had the framework for effective management since the management plans referred to the tenets of adaptive management and mentioned managing for coral reef health. It must be noted that management outcomes may or may not be effective because only the intention for effective management can be gathered from a MPA’s management plan. Biscayne National Park (BNP) received a NO for effective management because the management plan is over 25 years old and, thus, does not allow for adaptive management. The BNP management plan is the oldest plan still being used out of the 8 management plans analyzed, although it is currently being updated.
Table 3.1: Current management practices existing in wider Caribbean coral reef MPA management plans to build coral reef resilience using the TNC Resilience Model as a management framework for building resilience. Also, a climate change category was added. Criteria for why a MPA received a YES/NO are explained in the methods.


<table>
<thead>
<tr>
<th>MPA</th>
<th>MPA Establishment Date</th>
<th>Size</th>
<th>Management Plan Date</th>
<th>TNC Resilience Model Principle</th>
<th>Yes/No</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1Biscayne National Park</td>
<td>1980</td>
<td>708.20 km$^2$</td>
<td>1983</td>
<td>Representation and Replication</td>
<td>Yes</td>
<td>Protects inshore, offshore, and patch reefs on a stretch of Florida's coastline including different conditions, and adjacent habitat</td>
</tr>
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<td></td>
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<td></td>
<td>Conserving Critical Areas</td>
<td>Yes</td>
<td>Has a protected natural area and an outstanding natural feature subzone, which protects fragile, unique and ecologically significant areas</td>
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<td></td>
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<td></td>
<td>Connectivity</td>
<td>Yes</td>
<td>Connectivity between adjacent habitats</td>
</tr>
<tr>
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<td></td>
<td>Effective Management</td>
<td>No</td>
<td>BNP manages for coral reef health, but does not use adaptive management as management plan is older than 25 years</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Climate Change</td>
<td>No</td>
<td>No mention of climate change threats in the management plan</td>
</tr>
<tr>
<td>MPA</td>
<td>MPA Establishment Date</td>
<td>Size</td>
<td>Management Plan Date</td>
<td>TNC Resilience Model Principle</td>
<td>Yes/No</td>
<td>Explanation</td>
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<tr>
<td>Bonaire National Marine Park</td>
<td>1979</td>
<td>27 km²</td>
<td>2006</td>
<td>Representation and Replication</td>
<td>Yes</td>
<td>MPA surrounds the whole island from the high water mark to 60m depth, so MPA is representative of all coral reef community types, conditions, and linked habitats around the island</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>Conserving Critical Areas</td>
<td>Yes</td>
<td>Establishing (if haven't already) Fish Protected Areas to protect fish stocks so the areas can be sources of fish larvae</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td>Connectivity</td>
<td>Yes</td>
<td>The Caribbean Current passes Bonaire before entering the Gulf of Mexico Connectivity between adjacent habitats</td>
</tr>
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<td>Effective Management</td>
<td>Yes</td>
<td>Manages for coral reef health and even has a place in their management plan for additions and developments after analyzing the effectiveness of management strategies</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td>Climate Change</td>
<td>Yes</td>
<td>Management plan mentions global warming as a significant threat</td>
</tr>
<tr>
<td>MPA</td>
<td>MPA Establishment Date</td>
<td>Size</td>
<td>Management Plan Date</td>
<td>TNC Resilience Model Principle</td>
<td>Yes/No</td>
<td>Explanation</td>
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</tr>
<tr>
<td>3 Florida Keys National Marine Sanctuary</td>
<td>1997</td>
<td>9,800 km²</td>
<td>2007</td>
<td>Representation and Replication</td>
<td>Yes</td>
<td>Represents and replicates all coral reef community types, conditions, and linked habitats present along Florida's coast</td>
</tr>
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<td></td>
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<td></td>
<td>No-take zones SPA (Sanctuary Preservation Areas), SUA (Special Use Areas), and ER (ecological reserves) represent and replicate coral reef community types and linked habitats</td>
</tr>
<tr>
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<td></td>
<td>Conserving Critical Areas</td>
<td>Yes</td>
<td>Protects biologically important areas in no-take zones</td>
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<td></td>
<td></td>
<td></td>
<td>Spawning aggregation sites, permanent-residence areas, and nursery sites were taken into account when designing no-take Ecological Reserves</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td>Connectivity</td>
<td>Yes</td>
<td>Connectivity with adjacent habitats</td>
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<td></td>
<td>Connectivity was taken into account when locating no-take Ecological Reserves</td>
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<tr>
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<td></td>
<td>Effective Management</td>
<td>Yes</td>
<td>Management plan has actions to monitor coral reef health</td>
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<tr>
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<td></td>
<td>Promotes the concept of adaptive management by having an Evaluation action plan in the management plan</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Climate Change</td>
<td>Yes</td>
<td>Climate change is listed as a threat to the FKNMS in the management plan</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td>Has programs (Coral Bleaching Watch Program and Reef Ecosystem Condition (RECON)) to monitor for bleaching</td>
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<td></td>
<td>Marine Ecosystem Event Response and Assessment (MEERA) helps scientific community better understand processes like bleaching</td>
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<td></td>
<td>Monitors water temperature</td>
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<td></td>
<td>Management plan states that human-induced stressors will affect the resilience of sanctuary resources to climate change</td>
</tr>
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<td></td>
<td>Management plan says that the FKNMS is establishing a coral reef resiliency plan in response to climate change</td>
</tr>
<tr>
<td>MPA</td>
<td>MPA Establishment Date</td>
<td>Size</td>
<td>Management Plan Date</td>
<td>TNC Resilience Model Principle</td>
<td>Yes/No</td>
<td>Explanation</td>
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<tr>
<td>²Glover's Reef Marine Reserve World Heritage Site</td>
<td>1993</td>
<td>351.87 km²</td>
<td>2008</td>
<td>Representation and Replication</td>
<td>Yes</td>
<td>At Glover's Reef Atoll, coral reef community types are protected as well as linked habitats, and different conditions are represented as the MPA surrounds the entire atoll.</td>
</tr>
<tr>
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<td>Conserving Critical Areas</td>
<td>Yes</td>
<td>Has a conservation zone (subsistence fishing only) to provide a representative cross section of habitats through the atoll.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Connectivity</td>
<td>Yes</td>
<td>Seasonal closure and permanent closure in an area that is known to be a fish spawning aggregation site, specifically for Nassau grouper.</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>Effective Management</td>
<td>Yes</td>
<td>Conservation zone also protects nursery and spawning aggregations.</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td>Climate Change</td>
<td>Yes</td>
<td>Knows the location of resistant and resilient coral reefs to warming temperatures/bleaching.</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>Glover's Reef is connected as a source and sink to the other protected areas of the Belize Barrier Reef - Bacalar Chico National Park and Marine Reserve, Laughing Bird Caye National Park, Half Moon Caye National Monument, Blue Hole Natural Monument, South Water Caye Marine Reserve, and Sapodilla Cayes Marine Reserve.</td>
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<td>Connectivity between adjacent habitats.</td>
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<tr>
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<td></td>
<td>Has a monitoring program to evaluate the success of conservation strategies and integrate scientific results into management strategies, and well as goals to increase coral reef health in the management plan.</td>
</tr>
<tr>
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<td></td>
<td>Identified areas less susceptible to bleaching.</td>
</tr>
<tr>
<td>MPA</td>
<td>MPA Establishment Date</td>
<td>Size</td>
<td>Management Plan Date</td>
<td>TNC Resilience Model Principle</td>
<td>Yes/No</td>
<td>Explanation</td>
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<tr>
<td>Hol Chan Marine Reserve</td>
<td>1988</td>
<td>18.13 km²</td>
<td>2002</td>
<td>Representation and Replication</td>
<td>Yes</td>
<td>Represents coral reef community types and linked habitats, less replication as the MPA is a strip of water extending away from the island, not surrounding the entire island Zone A (no-take zone) protects a representative coral reef</td>
</tr>
<tr>
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<td></td>
<td>Conserving Critical Areas</td>
<td>Yes</td>
<td>Two areas are no-take zones to conserve critical habitat for endangered organisms and larvae sources</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td>Connectivity</td>
<td>Yes</td>
<td>Connectivity between adjacent habitats</td>
</tr>
<tr>
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<td></td>
<td>Effective Management</td>
<td>Yes</td>
<td>The research and monitoring program has a goal of providing information for the management of the reserve's resources</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td>Climate Change</td>
<td>Yes</td>
<td>The reserve monitors sea level rise through the Caribbean Planning Adaptation for Climatic Change Methodologies Closes areas during bleaching events</td>
</tr>
<tr>
<td>MPA</td>
<td>MPA Establishment Date</td>
<td>Size</td>
<td>Management Plan Date</td>
<td>TNC Resilience Model Principle</td>
<td>Yes/No</td>
<td>Explanation</td>
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<tr>
<td>6St. Croix East End Marine Park</td>
<td>2003</td>
<td>155 km²</td>
<td>2003</td>
<td>Representation and Replication</td>
<td>Yes</td>
<td>Surrounds the entire East end of the island from the shoreline to the 3-nautical mile territorial boundary, thus representing and replicating coral reef communities, conditions, and linked habitats</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>Conserving Critical Areas</td>
<td>Yes</td>
<td>Proposed no-take zones are identified so as to protect the full range of biodiversity, including different coral reef community types</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Connectivity</td>
<td>Yes</td>
<td>Connectivity between linked habitats was taken into account when locating proposed zones.</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td>Effective Management</td>
<td>Yes</td>
<td>The MPA has a monitoring program to provide managers with information to make decisions and to evaluate management success</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Climate Change</td>
<td>No</td>
<td>Climate change not mentioned in the management plan</td>
</tr>
<tr>
<td>MPA</td>
<td>MPA Establishment Date</td>
<td>Size</td>
<td>Management Plan Date</td>
<td>TNC Resilience Model Principle</td>
<td>Yes/No</td>
<td>Explanation</td>
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<tr>
<td>7 St. Eustatius National Marine Park</td>
<td>1996</td>
<td>27.5 km²</td>
<td>2007</td>
<td>Representation and Replication</td>
<td>Yes</td>
<td>The MPA surrounds the whole island from the high water line to the 30 m depth contour, thus representing with replication the island's coral reef community types, conditions, and linked habitats</td>
</tr>
<tr>
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<td></td>
<td>Conserving Critical Areas</td>
<td>Yes</td>
<td>Protects spawning and nursery grounds                                                                 bulunduz isaret</td>
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<td></td>
<td></td>
<td>Two areas are no-take zones to conserve biodiversity and protect fish stocks</td>
</tr>
<tr>
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<td></td>
<td></td>
<td>Connectivity</td>
<td>Yes</td>
<td>There is movement of water and organisms between linked habitats, but because there are shallow coastal waters there is not much water and organism exchange between deep and coastal areas</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>There are other MPAs in the Netherlands Antilles that may be connected by the Antilles Current</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Effective Management</td>
<td>Yes</td>
<td>Practices the tenets of adaptive management and manages for coral reef health</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Climate Change</td>
<td>Yes</td>
<td>Global warming is mentioned as a threat to coral reefs and the management plan even mentions the IUCN's recommendations to lessen the damage to corals from sea surface temperatures increases</td>
</tr>
<tr>
<td>MPA</td>
<td>MPA Establishment Date</td>
<td>Size</td>
<td>Management Plan Date</td>
<td>TNC Resilience Model Principle</td>
<td>Yes/No</td>
<td>Explanation</td>
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<tr>
<td>St. Maarten Marine Park</td>
<td>1997</td>
<td>51.28 km²</td>
<td>2007</td>
<td>Representation and Replication</td>
<td>Yes</td>
<td>The MPA surrounds the Dutch side of the island from the average high water mark to the 60 m depth contour, so the MPA will represent the island's coral reef communities, conditions, and linked habitats and have replication</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>Conserving Critical Areas</td>
<td>Yes</td>
<td>Protects spawning and nursery grounds</td>
</tr>
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<td></td>
<td>Has conservation zone that is no-take to protect unspoiled coral reefs with have high natural vales and that function as nursery areas</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Connectivity</td>
<td>Yes</td>
<td>There is movement of water and organisms between linked habitats, but because there are shallow coastal waters there is not much water and organism exchange between deep and coastal areas</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>There are other MPAs in the Netherlands Antilles that may be connected by the Antilles Current</td>
</tr>
<tr>
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<td></td>
<td></td>
<td>Effective Management</td>
<td>Yes</td>
<td>Promotes adaptive management and monitors for coral reef health</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Climate Change</td>
<td>Yes</td>
<td>Global warming is mentioned as a threat to coral reefs and the management plan even mentions the IUCN's recommendations to lessen damage to corals from sea surface temperatures increases</td>
</tr>
</tbody>
</table>
BNP and St. Croix East End Marine Park received a NO in the climate change category because there was no mention of climate change, bleaching, or global warming in their management plans. Bonaire National Marine Park only listed climate change as a threat. St. Eustatius National Marine Park and St. Maarten Marine Park, in the Netherlands Antilles, both mentioned the IUCN’s recommendations for decreasing damage to corals from increasing sea surface temperatures. Hol Chan Marine Reserve monitors sea level change and removes further stress during bleaching events. Glover’s Reef Marine Reserve has identified bleaching resilient corals. The FKNMS management plan is the most cognizant of climate change with multiple actions to monitor climate change and its impacts.

The organizational structure of the management plans analyzed, excluding BNP and the FKNMS, showed a lack of human resources (Table 3.2). The FKNMS has a complex organizational structure with federal and state employees, contractors, volunteers, and also has supporting groups to provide management resources through the Interagency Compact Agreement, the FKNMS Sanctuary Advisory Council (SAC), and NGOs (U.S. Department of Commerce et al. 2007). The St. Croix East End Marine Park has a group similar to the FKNMS’s SAC, the Marine Park Advisory Committee, which can assist in addressing management issues (The Nature Conservancy 2002).

All of the MPAs receive funding from multiple sources, and all management plans mentioned financial constraints to MPA management. The Bonaire National Marine Park was not actively managed for the first six years due to a lack of finances (STINAPA Bonaire National Parks Foundation 2006). MPAs need to receive funding from several sources because one source cannot provide all the necessary funding. The
St. Croix East End Marine Park has a funding deficit of $4.2 million dollars (The Nature Conservancy 2002). In the FKNMS management plan, the estimated costs for implementing all fourteen of their action plans for the five years of the management plan would be $586,435,000 or $11,968 per year per square kilometer of the FKNMS (U.S. Department of Commerce et al. 2007). Organizational structures and financial constraints limit the ability of the MPAs to manage the effects of climate change.

Discussion

Biscayne National Park (BNP) had the most NOs in the analysis of current management frameworks for reducing climate-induced changes on coral reefs by ensuring coral resiliency through BNP’s management plan, and secondary sources confirm this. There has been a loss of coral cover in BNP, possible due to dredging, turbidity, siltation, alteration of freshwater flow, nutrification, overfishing, and anthropogenic impacts (Dupont et al. 2008). BNP is very close to Miami and receives a large number of recreational boaters who can enter the park from many places (Tilmant and Schmahl 1981). Dupont et al. (2008) state that environmental conditions in BNP still need to improve. A study by Fisher et al. (2007) using lesion regeneration as an indicator of South Florida environmental conditions found that the corals in BNP have poor lesion recovery and poor environmental conditions.
Table 3.2: Organizational structures of the MPAs.


<table>
<thead>
<tr>
<th>MPA</th>
<th>Organizational Structure</th>
</tr>
</thead>
</table>
| 1 Biscayne National Park | 7 Administration  
Superintendents  
Budget  
Human Resources  
Secretary  
7 Interpretation Rangers  
7 Law Enforcement Rangers  
10 Facilities Management  
12 Resource Management  
Biologists  
Technicians |
| 2 Bonaire National Marine Park | 1 Director  
1 Manager  
1 Accountant  
1 Chief Ranger  
1 Cleaner  
1 Communications Officer  
1 Education Officer  
6 Rangers  
1 Receptionist  
6 STINAPA Bonaire staff |
| 3 Glover's Reef Marine Reserve World Heritage Site | 1 Reserve Manager  
1 Biologist  
2 Rangers |
| 4 Hol Chan Marine Reserve | 1 Manager  
1 Peace Corps Volunteer Biologist  
2 Rangers |
| 5 St. Croix East End Marine Park | 1 Marine Park Office Director  
1 Administrative Assistant  
1 Education and Outreach Coordinator  
1 Field Biologist  
1 Licensing Coordinator  
1 Maintenance Supervisor  
3 Officers: Enforcement and Interpretation  
1 Supervisor: Enforcement and Interpretation |
| 6 St. Eustatius National Marine Park | 1 Manager  
2 Administrators  
1 Education Officer  
1 MPA Chief Ranger  
1 MPA Ranger  
1 Sea Turtle Program Coordinator |
<table>
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<th>MPA</th>
<th>Organizational Structure</th>
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<tr>
<td>St. Maarten Marine Park</td>
<td>1 Marine Park Manager&lt;br&gt;1 Assistant Marine Park Manager&lt;br&gt;1 Office Manager&lt;br&gt;1 Outreach/Education Coordinator</td>
</tr>
<tr>
<td>Florida Keys National Marine Sanctuary</td>
<td>1 NMSP Southeast Regional Superintendent&lt;br&gt;1 NMSP Southeast Region Science Coordinator&lt;br&gt;1 Acting Superintendent&lt;br&gt;1 Chief of Staff for Programmatic Integration&lt;br&gt;2 Managers&lt;br&gt;1 Acting Research Coordinator&lt;br&gt;2 Administrative Assistants&lt;br&gt;1 Administrative Assistant II&lt;br&gt;1 Assistant Manager&lt;br&gt;1 Assistant Marine Operations Coordinator&lt;br&gt;1 Building Maintenance&lt;br&gt;1 Captain - Law Enforcement&lt;br&gt;1 Case Management Coordinator&lt;br&gt;1 Communication Coordinator&lt;br&gt;1 Computer Support Specialist&lt;br&gt;1 Education Coordinator&lt;br&gt;2 Education Specialists&lt;br&gt;2 Environmental Specialist II&lt;br&gt;1 EPA&lt;br&gt;2 Florida Keys Eco-Discovery Center Interpretive Specialists&lt;br&gt;1 Florida Keys Eco-Discovery Center Manager&lt;br&gt;4 Lieutenants - Law Enforcement&lt;br&gt;1 Maintenance Mechanic&lt;br&gt;1 Maintenance Operations Specialist&lt;br&gt;2 Marine Mechanic&lt;br&gt;1 Marine Services Specialist&lt;br&gt;1 Marine Services Supervisor&lt;br&gt;1 Mooring Buoy Maintenance Specialist&lt;br&gt;2 Mooring Buoy Specialists&lt;br&gt;12 Officers - Law Enforcement&lt;br&gt;1 Operations Manager&lt;br&gt;1 Permit Coordinator&lt;br&gt;1 Program Assistant&lt;br&gt;1 Program Support Specialist&lt;br&gt;1 Resource Management Specialist&lt;br&gt;1 Resource Specialist&lt;br&gt;1 SAC/Volunteer Coordinator&lt;br&gt;1 Team Leader for Damage Assessment&lt;br&gt;1 Team O.C.E.A.N Assistant&lt;br&gt;1 Team O.C.E.A.N Coordinator</td>
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Fortunately, BNP is in the process of updating their management plan from 1983. The new management plan, though, is still expected to last 20-25 years not lending well for adaptive management (http://parkplanning.nps.gov/projectHome.cfm?parkID=353&projectId=11168). There were public scoping meetings in Summer 2009 to present the idea of no-take areas inside BNP for the purpose of allowing divers and snorkelers to experience a healthier reef. Hopefully, this plan will also discuss climate change impacts and actions to reduce them. BNP also has a damage recovery program to prevent and restore damaged habitats from boaters, and a coral nursery program to provide corals from nurseries to restore damaged reefs (National Parks Conservation Association 2006). Working with the Comprehensive Ecosystem Restoration Plan (CERP), BNP will be able to demonstrate the importance of restoring traditional freshwater flow in the Everglades to Biscayne Bay (National Parks Conservation Association 2006). A Fisheries Management Plan has also been developed to provide management strategies to stop overfishing because 27 out of 35 fish species are overfished (National Parks Conservation Association 2006).

While funding is a large barrier to the FKNMS, there are other issues too. The FKNMS website (http://floridakeys.noaa.gov/le/welcome.html) lists several issues with enforcing sanctuary regulations: multiple entryways, a large area, many visitors from different places, the combination of commercial and recreational uses of the sanctuary, and a public lack of awareness. Sanctuary users have reported noncompliance (Dobrzynski and Nicholson 2001). Unrelenting opposition groups and continued cooperation of local, state, and federal agencies are always a threat to the FKNMS (Bohnsack 1997 and Suman 1997). There are five zones, with the first three being no-
take zones, in the FKNMS, Ecological Reserves, Sanctuary Preservation Areas, Special Use Areas, Wildlife Management Areas, and Existing Management Areas (Suman 1997). Around 6% of the sanctuary is no-take area. The FKNMS works to reduce local stressors, increases user education through a variety of actions, and like BNP restores coral reefs following boat damage (U.S. Department of Commerce et al. 2007). Through their management actions the FKNMS has the potential to build coral reef resilience.

The St. Croix East End Marine Park is the first move towards the U.S.V.I’s territorial marine park system (Rothenberger et al. 2008). The St. Croix East End Marine Park has issues with finances, enforcement, monitoring, education, and outreach, among others (The Nature Conservancy 2002). The management plan says that the park receives funding from multiple sources while Rothenberger et al. (2008) states that the park is funded only by federal government money. Either way, the enforcement program is ill funded and managed (Quinn 2008). St. Croix East End Marine Park is also criticized for its reliance on NGOs (Quinn 2008).

As a management strategy, St. Croix East End Marine Park has four zones (Quinn 2008). The recreation zone is for snorkelers, divers, and recreational fishers. The Turtle Wildlife Preserve protects turtle nesting. Almost 10% of the park is a no-take zone. Open Fishing is the largest zone in the park and has no fishing regulations; the only difference between this zone and unprotected areas is that coral and live rock cannot be collected. In 2008 the park’s education program was initiated (Quinn 2008). The zones and education program may help increase resilience in the park by reducing stressors. Coral reef monitoring is performed twice a year by NOAA (Rothenberger et al. 2008).
Hol Chan marine reserve has been successful in increasing resilience as commercially valuable stocks have increased (Cho 2005). Many years ago, the reserve was reported to have a higher biomass of fishes per unit area of coral reef than any other coral reef (Roberts and Polunin 1994). A review of ecological, socio-economic, and organizational features of Caribbean MPAs categorize Hol Chan Marine Reserve as having a high level of management (Geoghegan et al. 2001). This means that there are enough resources for managers to address the reserve goals, along with strong levels of compliance and knowledge among users. The Hol Chan Marine Reserve management plan, although, states there is not enough money for monitoring, environmental education, and research (Young and Bilgre 2002). Hol Chan Marine Reserve also suffers from a lack of community support and needs more relationships with NGOs (Young and Bilgre 2002). It is interesting that Hol Chan Marine Reserve has a lack of community support when local communities are the ones who lobbied for the marine reserve in the first place (Cho 2005).

Hol Chan Marine Reserve is also divided into four zones (Young and Bilgre 2002). Zones A and D are for scuba diving and snorkeling, where trained dive guides must go on every dive and no gloves are allowed to be worn. Zones B is for sportfishing. Commercial fishing occurs in zones C and part of D. Zone A and part of zone D are no-take zones. Education for divers and monitoring resources are additional management strategies for Hol Chan Marine Reserve (Young and Bilgre 2002).

Geoghegan et al. (2001) find Glover’s Reef Marine Reserve to have a moderate level of management because there may be a lack of resources. There is definitely a lack of staff, and there is also high turnover of the staff (Wildtracks/Wildlife Conservation
Society 2007). Glover’s Reef is dependent of tourism, and there are conflicts between divers and fishers (Geoghegan et al. 2001). Yet, Glover’s Reef Marine Reserve is ecologically successful as commercially important fish stocks have increased inside the reserve (Cho 2005). Resilience at some level is therefore increasing on Glover’s Reef, possibly because of the zoning strategy. Glover’s Reef Marine Reserve has four zones (Carballo and Cantun 2008). The General Use Zone allows fishing with gear restrictions. The Conservation Zone is a no-take area. The Wilderness Zone is for scientific research only, and the Special Protected Zone protects and monitors spawning aggregations. The reserve also monitors conch, lobster, turtles, fishes, and coral bleaching (Carballo and Cantun 2008).

The Bonaire National Marine Park (BNMP) management plan lists several challenges facing their MPA: difficulties with legal jurisdiction and government support, public relations, relationship of Bonaire government with NGOs, lack of enforcement, and a lack of economic benefits (STINAPA Bonaire National Parks Foundation 2006). Dixon et al. (1993) also highlight many issues that decrease BNMP management effectiveness: lack of modern sewage system, financial issues, anchor damage, human pressure, and improper waste disposal, although Geoghegan et al. (2001) state that BNMP has a moderate-high level of management. Initially BNMP was a “paper park” without money and staff because a user fee could not be implemented as not everyone was in favor of the user fee (Dixon et al. 1983 and 2000). Now a $10 fee exists and covers all salaries, operating costs, and capital depreciation (Dixon et al. 2000).

Even with all the issues, BNMP divers assert that the park contains some of the healthiest coral in the Caribbean, however there has still been coral cover decline (Dixon
et al. 2000). BNMP staff implement many management actions that could help increase resilience inside the park. Boats cannot anchor on reefs, and 38 mooring buoys were initially provided at dive sites (Dixon et al. 1993). There are many services and guides to educate park users, research and monitoring programs, and regulations on fishing in BNMP (van’t Hof 1983). In early 2008, two no-take areas were implemented due to declining fish populations (http://www.bmp.org/fpa.html). A diver carrying capacity has been calculated for the BNMP, and the park is already very near their capacity (Dixon et al. 2000). Due to the increasing number of divers, new management strategies are needed to ensure resource protection (Dixon et al. 2000).

Geoghegan et al. (2001), through their review of Caribbean MPAs, find that St. Eustatius National Marine Park has a moderate level of management. A large strain that St. Eustatius National Marine Park managers are facing is the government wanting the park staff to be responsible for its own enforcement instead of the using country’s police system (MacRae and Esteban 2007). This will be difficult for the MPA since it is lacking financial resources, and water patrols only occur a couple times a week (St. Eustatius National Parks Foundation 2008). The park is also at risk from oil spills, anchoring, and other anthropogenic impacts (McClellan 2009). The fishermen do not feel they have any meaningful participation in regards to the park’s management and that no-take areas are placed in the best fishing places (White et al. 2007). The no-take areas are meant to increase the tourism benefits of scuba diving, but these areas have created conflicts between divers and fishers (McClellan 2009). Originally fishing was not regulated, except in the no-take areas, but regulations have increased through the years (McClellan 2009).
St. Maarten Marine Park is a voluntary MPA as the government has not ratified the Marine Park Ordinance, and the Nature Foundation St. Maarten manages the park (Nature Foundation St. Maarten 2008). St. Maarten Marine Park has a moderate level of management (Geoghegan et al. 2001). There are five zones in the St. Maarten Marine Park: a conservation zone, anchoring zone, traffic zone, shipping/industry zone, and multiple use zone (Nature Foundation St. Maarten 2008). Fishing is allowed only in the traffic and multiple use zones. The St. Maarten Marine Park stakeholders list monitoring, governance, finances, and a lack of human and physical resources as management issues (St. Maarten Nature Foundation St. Maarten 2006). Even so, St. Maarten Marine Park has a moderate level of management (Geoghegan et al. 2001). Tourism is the largest industry in St. Maarten (Klomp and Kooistra 2003). Conflicts exist between managers and cruise ships, and cruise ships have even run aground on St. Maarten’s reefs (Geoghegan et al. 2001 and Klomp and Kooistra 2003). St. Maarten’s reefs are showing the negative effects from all the disturbances they are exposed to (Klomp and Kooistra 2003).

All of the management plans demonstrate management actions that have the potential to increase coral reef resilience, but local stressors and institutional incapacities can become barriers to MPAs effectively increasing reef resilience. There does not seem to be any relation between the age of the MPA or management plan and the effectiveness of management actions to build coral reef resilience, but the BNP does have the oldest management plan still being used and received more NOs than the other MPAs.

The first weakness identified in the TNC Resilience Model was that the eight management plans found for the wider Caribbean MPAs met the Resilience Model
principles out of default over actual intention to incorporate representation and replication, critical areas, and connectivity. Replication and representation of coral reef community types, conditions, and linked habitats was easy to incorporate as the management plans showed that the MPAs cover a strip of coastline from the shoreline out to a certain depth, and that many islands have a MPA surrounding the whole island, thus having all possible representation and replication for that area. The same justification also applies to incorporating critical areas and connectivity. When an MPA contains a strip of coastline from the shoreline out to a certain depth and/or surrounds an island, there will be incorporation of critical areas and connectivity of adjacent habitats.

Looking at the connectivity of source populations for MPAs could be beneficial. Coral reefs depend on larval recruitment; if the source area, either within the MPA or outside the MPA, is not protected, the MPA will most likely be unsuccessful in the long term. Just because the MPA management plans had incorporation of the Resilience Model principles does not guarantee that local stressors are still not affecting the areas. The effective management principle was too narrowly focused. Adding enforcement and compliance metrics as well as an indicator of effective reduction of local stressors could help give better indication as to whether MPAs are actually increasing coral reef resilience and being effectively managed.

Three of the MPAs had specific management actions to deal with climate change impacts. Monitoring bleaching events was a common strategy. Coral reef monitoring can be used to evaluate management actions, and real-time monitoring can distinguish different coral reef susceptibilities to bleaching (Salm et al. 2006). Maynard et al. (2008) describe a new remote sensing application, ReefTemp, to calculate daily bleaching risk.
This application can more accurately predict the severity of bleaching at smaller scales than other applications. The MPAs could use that information to remove compounding stressors from coral reefs before bleaching starts.

Another weakness relating to the TNC Resilience Model was that it may not be feasible for management plans to effectively incorporate the Resilience Model principles because of a MPA’s institutional incapacities that could impede effective management, the incorporation of climate-based coral reef resilience management actions, and even general management actions. Discussing ecological goals in relation with MPA institutional capacity could help illustrate the feasibility of the Resilience Model. All the management plans analyzed have institutional incapacities with a lack of human and/or financial resources and obstacles to effective management. The management barriers from institutional incapacities and the lack of resources faced by MPAs will definitely limit the incorporation of scientific findings into management strategies. Without the proper resources, the development and implementation of a climate change management plan will be difficult.

A third weakness of the TNC Resilience Model was that it focuses on natural science concerns. In general MPA management needs to take into account natural and social science concerns of the stakeholders in MPA design. For example, while it may be ecologically beneficial to provide protection to three replicates of each coral reef community type, social concerns of stakeholder livelihoods may prevent the ability of managers to incorporate representation and replication of coral reef community types into a MPA. The MPA management plans also have different mandates that dictate to what degree managers are able to protect resources or allow for resource use.
If management plans cannot effectively manage local stressors, they will not be able to effectively manage global stressors. The TNC Resilience Model has several weaknesses; in general the model does not incorporate possible management barriers. There was an ease of management plans incorporating the TNC Resilience Model principles without actually increasing coral reef resilience because the effective management principle in the Resilience Model is too narrowly focused and did not include enforcement and compliance metrics or an indicator of effective reduction of local stressors. There is also a lack of discourse on social issues and institutional incapacities. Because of the TNC Resilience Model weaknesses, revised climate-based coral reef resilience guidelines are needed. Chapter 4 addresses the gaps and presents a revised suite of guidelines using the FKMNS as a case study.
CHAPTER 4

REVISED CLIMATE-BASED GUIDELINES FOR CORAL REEF RESILIENCE APPLIED IN THE FKNMS

Reasons for revised resilience guidelines

Chapter two showed that while *M. faveolata* can grow and heal faster in 560 µatm, the CO₂ concentration expected in 2050, *M. faveolata* growth was significantly decreased at 800 µatm, the CO₂ concentration expected by 2100. The experiment did not account for increasing temperatures and other possible negative climate change impacts, which presumably would multiply the negative effect seen at a pCO₂ of 800 µatm. Because ocean acidification may cause negative effects to corals in the future and corals with more resilience may be less affected by ocean acidification, climate-based coral reef resilience guidelines are advocated.

The third chapter demonstrated, through an evaluation of management plans in wider Caribbean MPAs, that a few of the management plans analyzed do have climate-based management actions: commonly monitoring bleaching events. However, chapter three also demonstrates that the TNC Resilience Model has flaws. There was an ease of management plans to incorporate the TNC Resilience Model principles without the MPA necessarily increasing coral reef resilience due to the fact there was no discourse on social concerns, enforcement or compliance metrics, nor a mention of reducing local stressors in the MPA. If a management plan with goals to reduce local stressors is effectively enforced, coral reef resilience will possibly increase reducing the negative impacts of climate change to reefs.
Since there is a significant threat to corals from ocean acidification and the TNC Resilience Model does not address management barriers, revised climate-based coral reef resilience guidelines were created using management implications and actions learned from the coral lesion experiment (chapter 2) through semi-structured interviews. The guidelines were designed to incorporate management actions that could promote resilience and address the gaps in the Resilience Model. Coral reefs will definitely change in the future but hopefully not disappear. The revised climate-based coral reef resilience guidelines were developed using the FKNMS as a case study so that FKNMS management barriers can be discussed in tandem with the guidelines.

Methods

Case study – Florida Keys National Marine Sanctuary

The Florida Keys National Marine Sanctuary (FKNMS) was chosen as a case study because the *M. faveolata* corals used in the coral lesion experiment (chapter 2) originated in the FKNMS. The FKNMS contains the largest coral reef in the U.S., and coral cover has continued to decline from 12% to 6% since the creation of the FKNMS (http://floridakeys.noaa.gov/visitor_information/welcome.html and Callahan et al. 2008). From chapter 3, the FKNMS was demonstrated to have more institutional capacities and an extensive and recent management plan with more consideration for climate change than the other MPAs examined. The FKNMS is also well documented in the literature providing a plethora of sources to develop the FKNMS as a case study. It is important for the FKNMS to manage for ocean acidification as coral reefs closer to the latitudinal
limits of reef building, like the FKNMS, have greater solubility of CO₂ leading to more dramatic changes of pH (Keller et al. 2009).

A Florida congressman and U.S. senator established legislation in Congress to create the Florida Keys National Marine Sanctuary and Protection Act (FKNMSPA) (Suman 1997). The FKNMSPA was approved November 16, 1990, and the FKNMS went into effect on July 1, 1997 (Figure 4.1). This sanctuary was established after much turmoil due to a lack of community support. The establishment was triggered by ecological reasons, mainly the unique coral reef habitat, but also increasing coral disease and anthropogenic reasons (Bohnsack 1997). The FKNMS was increasingly being used by humans engaging in a range of activities causing exploitation and destruction (Bohnsack, Miller, and Haskell 1999). Three purposes of the FKNMS in the FKNMSPA are to protect the marine resources of the area, educate and interpret the resources for the public, and to manage human activities in a manner consistent with the act.

There were clear mandates that federal, state, and local authorities work together in collaboration for the development and management of the FKNMS (Suman 1997). The FKNMS is managed by both NOAA and the State of Florida, specifically, the Florida Department of Environmental Protection (U.S. Department of Commerce et al. 2007). A Sanctuary Advisory Council was formed to include stakeholder interests and expertise for the management of the FKNMS (Suman 1997). The FKNMS has federal and state employees, contractors, volunteers, and NGOs all working together to manage the FKNMS (Table 3.2) (U.S. Department of Commerce et al. 2007). Presently, there are fourteen management action plans for the FKNMS: Science Management and Administration, Research and Monitoring, Education and Outreach, Volunteer,
Figure 4.1: The Florida Keys National Marine Sanctuary boundaries and zones. From U.S. Department of Commerce et al. (2007)

**Objectives 2 and 3: Assessment of the management implications of the coral lesion experiment and development of revised resilience guidelines**

To develop revised resilience guidelines, the experiment on the effects of increasing carbon dioxide concentrations on *Montastraea faveolata* skeletal growth and lesion regeneration, using coral skeletal growth and lesion healing as indicators of coral resilience (chapter 2), was presented to FKNMS staff and the SAC’s Ecosystem Restoration Working Group (ERWG) on the following occasions: (1) using a semi-structured conference call to six FKNMS staff (1 administrative personnel, 1 education personnel, and 4 natural science personnel) on March 24, 2010; (2) a semi-structured phone interview with one FKNMS staff member (research personnel) on March 25, 2010; (3) a semi-structured phone interview with one FKNMS staff (administrative personnel) on April 2, 2010; and (4) a semi-structured webinar with four people in the ERWG (1 regulatory FKNMS personnel, 2 members from an outside regulatory agency, and 1 member from a conservation organization) on April 27, 2010. After the experiment was presented to the interviewees, they were queried about their thoughts on coral resilience based on the experimental results, what management implications the experimental results identified, and the management actions, if any, suggested by experiment’s
outcomes. Lastly, the interviewees were asked what management actions they think the FKNMS management plan should include in the future to reduce the negative impacts of climate change to coral reefs irrespective of the coral lesion experiment.

The coral resilience statements, management implications, and management actions obtained relating to the coral lesion experiment were combined into a flow chart to show the process of creating the revised climate-based coral reef resilience guidelines. The coral resilience statements were linked to the management implications. Then the management implications were linked to suggested management actions that addressed the implication. If the management implication was not linked to a management action, no management action was seen necessary for that implication. My own management implications and management actions observed from the coral lesion experiment results were added into the flow chart as well. Furthermore, the additional management actions suggested by interviewees, not directly related to the M. faveolata lesion experiment, and management strategies currently being considered by FKNMS managers to implement in the future were also added to the flow chart. Lastly, the management actions were categorized to create the climate-based coral reef resilience guidelines specifically for the FKNMS but that could also apply to other MPAs. The feasibility of each resilience guideline will be discussed specifically considering the FKNMS institutional capacity.
Results

The management actions categorized into the following revised resilience guidelines:

(1) Incorporate more no-take zones and hedge the risks against ocean acidification,
(2) identify resilient coral reefs and perform more climate change research,
(3) reduce local stressors,
(4) enhance coral reef recovery, and
(5) increase public awareness and education on climate change impacts to coral reefs.

While the revised resilience guidelines do not necessarily change coral reef management priorities, the coral lesion experiment (chapter 2) provides additional reasons for the importance of long standing recommendations. Guideline 1 indicates spreading the risk of any one area being damaged by stressors by having more no-take area inside MPAs. Guideline 2 promotes more climate change science and monitoring to facilitate decision making. Guideline 3 involves reducing any threat occurring inside the MPA and coming from surrounding land, ocean, and atmospheric sources. Guideline 4 strictly means enhancing recovery by humans placing organisms or objects onto reefs to speed up recovery. Guideline 5 aims to increase marine stewardship in MPA users. Ideally, all the guidelines will increase resilience because they remove stressors.

There was limited interaction with interviewees, and response effects could be present because of an interviewee’s political environment and intent, among other
potential bias. In the flow chart (Figure 4.2), resilience statements were linked to management implications. All the management implications were linked to management actions that addressed the implication, except for one implication. The management implication, there is still time to see a natural recovery of corals in the FKNMS (telephone interview, April 2, 2010), was not linked to a management action because no management action is required to address it as corals may have increased growth and healing without management intervention. This management implication means that while coral cover has been constant in the FKNMS, *M. faveolata* and maybe other corals might show a natural increase in growth rate because the coral lesion experiment in chapter 2 demonstrated that *M. faveolata* growth increased at the CO₂ concentration predicted to occur by 2050. Another positive implication identified was that all the previous stressors (hurricanes, bleaching, pollution, and etc) affecting coral reefs might have already selected for the more resilient and resistant corals (telephone interview, March 25, 2010). This could be one reason why, on average, the *M. faveolata* used in the coral lesion experiment grew and healed faster in the higher CO₂ concentration expected by 2050. If the existing corals in the FKNMS are already resilient to many stressors, they may also be more resilient and less sensitive to predicted climate change impacts. There could be areas that have experienced more stressors than other reefs making those corals more resilient than other areas. The *M. faveolata* used in chapter 2 were from an area that receives many stressors (telephone interview, March 24, 2010).
Figure 4.2: Flow chart linking resilience statements to management implications to management actions and finally to climate-based coral reef resilience guidelines. Statements in black are the resilience statements, management implications, and management actions suggested by the interviewees based on the coral lesion experiment results. Statements in orange are ideas suggested by me, statements in blue are activities currently being considered by FKNMS managers, and statements in green are management actions interviewees want the FKNMS managers to incorporate in the future to protect coral reefs against climate change.

2Person 2, telephone interview, March 24, 2010; 3Person 3, telephone interview, March 24, 2010; 4Person 4, telephone interview, March 25, 2010; 5Person 5, telephone interview, April 2, 2010; 6Person 6, telephone interview, April 27, 2010; 7Person 8, telephone interview, April 27, 2010
The coral lesion experiment demonstrated that *M. faveolata* corals obtained from the same seawall in the FKNMS had different growth and healing rates. Genetic make-ups and different micro environments may be giving rise to different resiliency among coral colonies (telephone interview, April 27, 2010). The coral lesion experiment from chapter 2 provides another reason why more no-take areas are beneficial leading to the creation of guideline 1 – incorporate more no-take areas and hedge the risks against ocean acidification. The experiment showed that with future predicted CO$_2$ concentrations *M. faveolata* skeletal growth was significantly decreased in the laboratory and that identifying resilient coral reefs may be difficult because *M. faveolata* corals from the same place had different inherent resilience. Additional no-take areas can provide more protection to corals, reduce compounding threats, and could contain more corals that are resilient without having to know which specific colonies are resilient. By giving extra protection to more areas (i.e. no-take zones), there is less chance of losing coral reef biodiversity and genetic diversity with climate events (telephone interview, April 27, 2010).

The coral lesion experiment (chapter 2) provides two additional factors that can be used to identify coral resilience, coral skeletal growth and lesion healing, leading to the creation of guideline 2 – identify resilient coral reefs and perform more climate change research (telephone interview, April 2, 2010). Coral skeletal growth and lesion healing measured in the field could identify individual coral colony resilience and possibly coral reef resilience. The coral lesion experiment provides a new use for coral growth and lesion healing indices, which is to identify corals resilient to ocean acidification. The flow chart displays how scientific studies, which increase the
knowledge base of managers, can lead to management implications and specific management actions for MPAs. Additional climate change coral reef impact studies could be used to help develop climate change action plans for MPAs (telephone interview, April 2, 2010).

There are management actions that are not linked to management implications because the management actions do not directly relate to the coral lesion experiment. They were either suggested by the interviewees as actions they would like to incorporate in the FKNMS’s future climate-based management or actions that are currently being considered by FKNMS managers to implement in the near future. One coral resilience statement, increasing CO$_2$ concentrations may have a negative impact on corals despite initial benefits (telephone interview, April 2, 2010 and 27, 2010), links directly to two management actions. The coral lesion experiment demonstrating that CO$_2$ concentrations predicted by the end of the century could have significant negative effects to coral calcification offers another reason for MPA managers to reduce local stressors, guideline 3. The coral lesion experiment also provides more reasons to increase public awareness and education, guideline 5, because simulated ocean acidification was shown to significantly decrease coral growth, which could affect organisms that depend on reefs and the people that depend on reefs for their livelihoods. Also, the coral lesion experiment results could hopefully further promote the importance of coral reef conservation.
Revised resilience guidelines applied to the FKNMS

The revised guidelines are meant to be suggestions for the FKNMS, taking into account its enabling and disabling conditions. The guidelines may help provide management priorities for the FKNMS. In the FKNMS’s next revised management plan, there will be a stand-alone action plan for climate change (telephone interview March 25, 2010). While the guidelines are specifically developed for the FKNMS, they could also apply to other wider Caribbean MPAs to help them identify management priorities according to their own enabling and disabling conditions. The climate-based coral resilience guidelines will highlight that reducing stressors and increasing coral reef resilience could reduce the negative effect of climate change impacts. Continuing to release CO₂ will cause an impact, and there is not much time, but there may be more time than originally thought (telephone interview, April 2, 2010).

Guideline 1 - Incorporate more no-take zones and hedge the risks against ocean acidification

This guideline stems from two management implications; previous stressors have already selected for resilient and resistant corals, but calcification may still be negatively impacted by the end of the century. Also, identifying resilient and resistant coral reefs will be difficult because the coral lesion experiment demonstrated that corals of the same species and from the same location have different inherent resilience. The management action that addresses the first implication is to 1) identify resilient areas and provide extra protection in the form of no-take areas. The FKNMS has identified areas believed to be bleaching resilient, but these reefs experienced much coral mortality in the cold weather
event this past January 2010 (telephone interview, April 2, 2010). Coral reefs resilient to one threat are not necessarily resilient to other threats. That piece of information helped lead to the formation of implication two, which was linked to a variety of management actions: 2) more zoning, 3) protect larger coral reef areas with high diversity or protect more smaller areas with high diversity, 4) spread coral reef protection across a large geographic area, and 5) incorporate a stratified random design for no-take zone locations.

One interviewee suggested having a nest of protected resilient areas using a formula based risk analysis (telephone interview, March 24, 2010). A stratified random design could also be used to locate no-take zones. The stratified random design would have random locations to protect areas managers do not know are resilient, but also stratified to include important critical areas managers know they want to include. Spawning sites, source areas, resilient reefs, resistant reefs, migration corridors, and heavily damaged reefs among other critical areas could be included in the no-take zone design, along with more randomly selected areas as back-up to hedge the risks against ocean acidification. There may also be areas managers know they do not want to include as no-take areas, like popular fishing sites gathered by examining resource use patterns.

This type of design can also be adjusted to include connectivity between the no-take zones and representation and replication of coral reef types, in other words following the TNC Resilience Model principles for a no-take zone network. The FKNMS demonstrates how the Resilience Model principles can be incorporated into a no-take zone network. There are five different zones in the FKNMS: Ecological Reserves (ER), Existing Management Areas, Sanctuary Preservation Areas (SPA), Special-Use Areas (SUA), and Wildlife Management Areas, with ERs, SPAs, and SUAs being no-take zones.
(Figure 4.1) (U.S. Department of Commerce et al. 2007). There are currently two Ecological Reserves, the Western Sambos and the Tortugas North and South (U.S. Department of Commerce et al. 2007). All together the ERs total approximately 548 km². The eighteen small SPAs protect shallow coral reefs, totaling around 22 km², but four of the SPAs are used for catch and release trolling (U.S. Department of Commerce et al. 2007). There are four SUAs, roughly 2 km², for research uses (Bohnsack 1997).

The no-take zones, SPAs, SUAs, and ERs demonstrate representation and replication of coral reef community types and linked habitats. For example, many fore-reefs are represented and replicated in no-take zones, and the Tortugas ER contains mangroves, seagrass beds, and coral reefs (telephone interview, March 24, 2010). Inside the FKNMS there are several known critical areas: larval recruitment areas, nursery sites, coral spawning, grouper and snapper spawning aggregations, and resilient areas (telephone interview, March 24, 2010). The Tortugas ER is downstream from the rest of the FKNMS and serves as a larval source for the FKNMS (telephone interview, April 27, 2010). These critical areas were taken into account when initially deciding where to locate no-take zones (telephone interview, March 24, 2010). Connectivity, eddies, gyres, and currents, was also taken into account when initially locating no-take zones (telephone interview, March 24, 2010). While the FKNMS managers did consider connectivity, critical areas, and representation and replication when locating no-take zones, they did not include more randomly selected reefs. When locating no-take zones, costs are to be minimized and socioeconomics taken into account (Dobrzynski and Nicholson 2001). There are many ways to design a network of no-take areas, and the exact method used is
not as important as making sure that the no-take areas meet ecological, social, and socioeconomic goals.

Currently, around 6% of the FKNMS’s 9,800 km² is no-take area. About 10% of the coral reefs are inside no-take zones (B. Causey, personal communication). It is, however, not easy to increase the percentage of no-take protection in the FKNMS. There are many complications of incorporating more no-take zones for the FKNMS. The FKNMS must consider input from all stakeholder groups: commercial fishers, recreational fishers, charter fishing operators, scuba diver/snorkel operators, and scuba divers/snorkels among others. When the FKNMS was first implemented, there was much uproar about the proposed no-take zones. The stakeholders caused the number and size of initial proposed no-take zones in the FKNMS to decrease (Suman 1997).

During the FKNMS establishment process, the commercial fishers and charter fishing operators felt highly alienated and believed they could not influence management decisions (Suman et al. 1999 and Shivlani et al. 2008). Views have changed since the FKNMS establishment; a survey conducted in 2000-2001 demonstrated that over half of Monroe County residents supported the idea of more no-take zones in the FKNMS (Johns et al. 2003). The median percentage of coral reefs suggested to be in no-take zones suggested by Monroe County residents is 20% (Johns et al. 2003). The Marine Zoning Action Plan, which has executed the zone monitoring program, has also seen a gain of public support for no-take zones (U.S. Department of Commerce et al. 2007). Commercial divers, though, still do not support the Western Sambos Ecological Reserve (Shivlani et al. 2008).
More or larger no-take zones could impact commercial fishers, charter fishing operators, scuba/snorkel operators, and tourism. No-take zones can lead to fisher displacement, crowding, conflicts, and having to spend more time on the water fishing. A majority of Key West charter fishing operators and a large percentage of commercial fishers do spend more time on the water since the implementation of FKNMS no-take zones (Dobrzynski and Nicholson 2001). Dive/snorkel operators had no short-term change in gross annual income and no significant changes in average personal income through 2006 (Dobrzynski and Nicholson 2001 and Shivlani et al. 2008). Dive/snorkel operators report an increase in the number of customers per week, but they do not attribute that to the implementation of no-take zones (Dobrzynski and Nicholson 2001). Another positive benefit for the dive/snorkel operators is a decrease in crowding at dive sites (Dobrzynski and Nicholson 2001). The majority of Key West charter fishing operators had increases in gross annual incomes from an increase in trip fees. While, commercial fishers may have worried about the impacts of no-take zones on their industry, the majority of Key West commercial fishers had no short-term changes in landings, fishing effort, amount of time on the water, number of crew, and gross annual income (Dobrzynski and Nicholson 2001). Besides no-take zone impacts, gear regulations, operation costs, maintenance costs, and hurricanes among other factors can also affect commercial fisher incomes (Shivlani et al. 2008).

In the near future, after the FKNMS managers finish evaluating the marine zoning plan, public meetings will be held to obtain the views of the stakeholders before any decisions about no-take zones in the FKNMS are made (telephone interview, March 24, 2010 and April 27, 2010). This will be key to show stakeholders that their opinions are
important and that the decisions about no-take zones have not already made, therefore allowing meaningful participation of stakeholders by being able to influence managers’ future decisions about the number and size of no-take zones. Explaining the possible socioeconomic benefits or at least no negative economic consequences from no-take zones could also help gain support from stakeholders. A Bohnsack et al. (2009) study shows that because of fishing, some reef fish species population densities are lower than they are without fishing in the FKNMS. This study should be presented, along with additional supporting ecological and social research, to stakeholders. The biodiversity must be preserved to conserve the economy, and a balance of equal and sustainable resource use and resource protection is desired (telephone interview, March 24, 2010 and March 25, 2010).

Guideline 2: Identify resilient coral reefs and perform more climate change research

FKNMS managers are required by Congress through the FKNMSPA to select research priorities and obtain funding for them (U.S. Department of Commerce et al. 2007). This guideline will explain the interviewees’ and my own suggested research and monitoring priorities based on the coral lesion experiment (chapter 2). The FKNMS does use peer-reviewed scientific studies when creating management actions and will even ask for additional scientific studies to be completed before making management decisions (U.S. Department of Commerce et al. 2007). The management actions that led to the creation of this guideline are to 1) measure coral growth and lesion healing rates to identify resilient corals and reefs as shown by the coral lesion experiment, 2) have more coral reef monitoring and incorporate additional CO₂ monitoring, and 3) have more
climate change/ocean acidification research. More science is needed for MPA managers and decision-makers to make appropriate decisions (telephone interview, April 2, 2010). All of the suggested research priorities below are dependent on sufficient resources, whether is it money, humans, time, or physical resources.

Much coral reef monitoring occurs in the FKNMS and continued monitoring is necessary in the FKNMS to evaluate management success and/or failures and to evaluate coral reef health. The FKNMS has volunteer programs, Marine Ecosystem Event Response and Assessment (MEERA), Bleach Watch, and Eyes on the Water, to notify FKNMS managers when they see disturbances occurring, including coral bleaching (telephone interview, March 24, 2010 and April 27, 2010). The Florida Reef Resilience Program (FRRP) and the TNC monitor changes to coral reefs from disturbances, and other long term monitoring by scientists is occurring (ex: Coral Reef Ecosystem and Monitoring Project - CREMP) (telephone interview, March 24, 2010 and April 27, 2010).

There are two areas of research that seem to be lacking. First, more research on what makes a coral more or less resilient to ocean acidification and what coral species are more resilient is lacking. There are many methods that can be used to help identify corals and coral reefs that may be more resilient to ocean acidification that MPAs can include in their coral reef monitoring programs using skeletal growth and tissue regeneration as indicators of resilience (APPENDIX 1). The Coral Reef Evaluation and Monitoring program (CREMP) surveys 41 reefs each year (Callahan et al. 2007). This program could be adapted to find corals and coral reefs possibly resilient to ocean acidification by including a coral lesion study, then FKNMS managers could provide extra protection to those areas.
Secondly, experiments increasing both temperature and CO$_2$ concentration completed on the FKNMS’s most prevalent corals, especially *M. annularis* as that species is an important framework building and is still declining inside the FKNMS (Donahue et al. 2008). Other organisms where climate change impact studies could be useful are *Diadema antillarum* and reef fish if possible. The incentive for the FKNMS to perform climate change impact studies is that the studies help elucidate how reef organisms may respond to climate change. The FKNMS managers could then use that data to develop and further refine their future climate change action plan.

There is currently one CO$_2$ sensor at Molasses Reef in the FKNMS (telephone interview, April 27, 2010). This interviewee also suggested that additional CO$_2$ sensors be incorporated at different reefs throughout South Florida to monitor CO$_2$ changes locally. This would allow the FKNMS managers to know more specifically what CO$_2$ changes are happening in sanctuary waters and how large of a threat ocean acidification may be in sanctuary waters. CO$_2$ sensors can be expensive possibly inhibiting the development of CO$_2$ monitoring in the FKNMS.

**Guideline 3: Reduce local stressors**

Local stressors can be unrelenting and sufficient enough to cause coral reefs to surrender to climate change. This guideline stems from two management actions suggested by the interviewees when asked what management actions they would like to see incorporated into the FKNMS to decrease the negative effects of climate change: 1) continue to control local stressors that can be removed, and 2) modify the boater license system. In general, it is very important for MPA managers to reduce stressors interacting
in their protected area leaving only climate change, because the coral lesion experiment showed that by the end of the century if CO$_2$ concentrations reach predicted values coral growth could be significantly decreased. If FKNMS managers are reducing local stressors to coral reefs and increasing reef resilience, they are managing for climate change impacts. Managing to reduce local stressors is a long-term priority action because of the additional global climate impacts.

If one was born before January 1, 1988 there is no required boater education course to operate a vessel in Florida (http://myfwc.com/rulesandregs/Rules_Boat.htm#PWC). Also, there is no suspension of licenses due to violations (telephone interview, April 27, 2010). There is much resistance to requiring all boaters to take a boater education course (telephone interview, April 27, 2010). It may be wasted time, energy, and money for FKNMS managers to lobby the state of Florida to change its boater regulations. The FKNMS managers may just take comfort in the fact that all new boaters, born after January 1, 1988 and operating a vessel with a motor of 10 horsepower or greater, will be required to take a boater education course due to the personal watercraft regulations (http://myfwc.com/rulesandregs/Rules_Boat.htm#PWC). Hopefully, the boater education course will decrease boat issues, such as boat groundings, in the FKNMS as boaters become more educated about navigation maps and signage. It should be noted that the FKNMS mostly depends on users voluntarily complying with the sanctuary’s regulations. Key West FKNMS users reported that out of town private recreational boaters are the most prevalent violators of FKNMS regulations (Dobrzynski and Nicholson 2001).
Dobrzynski and Nicholson (2001) suggest increased education for those boaters at boat facilities and on mooring buoys.

FKNMS managers work to decrease point sources of pollution, encourage a central sewage system in the Florida Keys, reduce nitrification, reduce sedimentation, reduce storm water runoffs, work with coastal developers to use Best Management Practices, and prevent overfishing (telephone interview, March 24, 2010). After monitoring for thirteen years, high levels of nitrogen are still entering the FKNMS (Diersing 2009). The nitrogen is probably coming from sewage traveling through groundwater and fertilizer run-off.

Reducing local stressors requires the coordination of different agencies with different jurisdictions (Sleasman 2009). The FKNMS coordinates with federal, state, and local agencies, organizations, and stakeholder groups as facilitated at the establishment of the FKNMS. For example, FKNMS managers helped Monroe County develop their Year 2010 Comprehensive Plan, specifically the Water Quality Protection Program, to help reduce nutrient loading into the ocean from sewage and wastewater (Sleasman 2009). The county is responsible for implementing the Water Quality Protection Program, not FKNMS managers, but the county lacks the funds to carry out their Comprehensive Plan. Working with other agencies can also lead to management obstacles like conflicting authorities and viewpoints (Sleasman 2009). Bohnsack (1997), though, lists several reasons why the cooperation between federal, state, and local agencies works for the FKNMS management framework: shared common goals, clear legislative mandates, commitment by participants, thorough public involvement, and consensus and compromise by participants and users.
Even if MPAs are protected against bleaching, bleaching is not the only climate change threat. The FKNMS enhances their regulations, removes additional local stressors, when they know certain areas are under temperature and bleaching stress and uses *A Reef Manager’s Guide to Coral Bleaching* (telephone interview, March 24, 2010). Bleaching and ocean acidification consequences are fundamentally different. Bleaching episodes come and go, but are predicted to increase in the future. Ocean acidification will always be continually increasing. Therefore, coral reefs will continue to be stressed by ocean acidification and management strategies could be implemented like they would be if bleaching events always occurring.

MPA managers can work diligently towards facilitating increased biodiversity. One way to do this is to reduce overfishing. Overfishing reduces important functional groups that are needed for coral reefs to be healthy, i.e. herbivores. Catch limits and fishing regulations could be strengthened to achieve this goal, as well as no-take zones. The FKNMS manages functional groups and manages to reduce overfishing, but implementing more fishing regulations will probably be contentious with stakeholders and does require cooperation with federal agencies (telephone interview, March 24, 2010).

Climate change may cause huge negative effects to the FKNMS environment and negatively impact the economy. To summarize the interviews, the ecosystem is very important to the FKNMS especially because of the tropical economy. By reducing local stressors, FKNMS managers are not only protecting the FKNMS coral reefs but also South Florida’s tropical economy. Greater than four million visitors come to the Florida Keys’ coral reefs each year (Gibson et al. 2008). In Monroe County, natural coral reefs
provide 8,000 jobs and $106 million (in 2000 dollars) in income from June 2000 through May 2001 (Johns et al. 2003). Coral reef related activities contribute $363 million (year 2000 dollars) in sales to Monroe County from June 2000 through May 2001. The FKNMS is working to reduce, bit by bit, local stressors (telephone interview, March 24, 2010).

**Guideline 4: Enhance coral reef recovery**

The three management actions put forward in the FKNMS management plan or currently being reviewed by FKNMS managers to enhance recovery are to 1) introduce artificial structures, 2) transplant corals, and 3) reintroduce *Diadema antillarum* onto coral reefs. The management actions suggested to enhance recovery require many resources (human, financial, and physical resources), and the outcomes of the actions may not be fully known or studied. Analyzing the cost and benefits of these three techniques could discover whether the reef recovery actions are worthwhile for managers to implement. Managers working to reduce local anthropogenic stressors could lessen the need to enhance recovery because having appropriate substrate available for reef organism recruitment and settlement can be accomplished by decreasing boat groundings, nitrification, and overfishing.

The FKNMS does restore coral reefs from catastrophic events. There are hundreds of vessel groundings reported in the FKNMS and many more unreported (U.S Department of Commerce et al. 2007). Also, the initial phases of transplanting corals back to reefs where the corals used to be present has been initiated (telephone interview, March 24, 2010). The corals can come from coral nurseries and/or possibly laboratory
propagated corals (telephone interview, March 24, 2010). Resilient coral species grown in nurseries and laboratories allow resilient corals to be transplanted back onto reefs. The corals need to be able to survive at the reef they are placed at, and if climate impacts or local stressors originally caused the corals to disappear, then more resilient corals have the best chance of surviving. The FKNMS does have multiple nurseries in different locations to spread the risk of any one of the nurseries being damaged by disturbances (telephone interview, March 24, 2010). Transplantation activities are often executed by partner organizations and funding can come from lawsuits to those who damaged the reef (U.S. Department of Commerce et al. 2007).

The second way to enhance recovery is to make sure appropriate substrate is available for coral recruitment and settlement. Artificial reef structures may increase the amount of area for coral recruitment and settlement. Artificial structures did provide settlement space for the *M. faveolata* used in the coral lesion experiment that naturally recruited to a man-made sea wall in the FKNMS. The use of artificial structures (i.e. intentionally sunk ships) is being researched by a FKNMS NGO partner, Reef Environmental Education Foundation (REEF) (U.S. Department of Commerce et al. 2007). The impacts on the ecosystem and longevity of these types of artificial structures in the sanctuary are not known (U.S. Department of Commerce et al. 2007). If these sunken ships do support increased fish and coral populations with negligible impacts from the actual process of sinking ships, these and other artificial structures are options for future use. Sinking ships, though, is a very expensive venture. The annual use values, recreational benefits to reef users, of residents and visitors to Monroe County for new artificial reefs is $2.14 million (Johns et al. 2003). The use values can be compared
to the cost of employing new artificial reefs to determine whether artificial reefs are a wise investment.

The FKNMS is studying the possibility of rehabilitating, replenishing, and reintroducing *Diadema antillarum* (telephone interview, March 24, 2010). For the FKNMS’s coral reefs to be healthy, all functional groups must be present. Reintroducing *D. antillarum* would increase herbivory on the coral reefs. The *D. antillarum* could remove macroalgae leaving potential space for coral recruitment (Aronson and Precht 2006).

**Guideline 5: Increase public awareness and education on climate change impacts to coral reefs**

This guideline was initiated by one interviewee’s opinion on how to mitigate FKNMS management disabling conditions. The interviewee said, “through public awareness, change can happen” (telephone interview, April 27, 2010). If people continue to be educated about coral reefs and the threats they face, hopefully they will be more willing to do what actions they can to preserve coral reefs. The same interviewee seemed to infer that stakeholders were unaware of the potential negative effects of CO₂ on coral calcification (telephone interview, April 27, 2010). Education is key for public users to understand the reasons for MPAs, thus leading to users voluntarily following MPA regulations. The majority of Key West dive/snorkel operators and charter fishing operators believe that the majority of their customers are not aware of the FKNMS no-take zones, and the operators themselves are confused about the potential impacts of no-take areas (Dobrzynski and Nicholson 2001). A majority of Key West FKNMS users
also believe that outreach efforts to inform the public about no-take zones are not sufficient (Dobrzynski and Nicholson 2001).

Many outreach strategies are used by the FKNMS (information at docks, TV, tourism, press releases, websites, public presentations, and etc.) (telephone interview, March 24, 2010). These outlets, plus other available outlets, can be geared to the different user groups to explain how climate change affects coral reefs and how each stakeholder group could more positively impact coral reefs by reducing local anthropogenic stressors. Educational and outreach management actions are also limited by appropriate funding and human resources. One action the FKNMS lists in the management plan, print marine etiquette on marine-related materials packaging, seems like a good way to get users to learn marine etiquette easily but will require cooperation with packaging companies. This activity will be implemented when funding is available (U.S. Department of Commerce et al. 2007).

People all over the world visit the FKNMS, and one management option is to increase out-of-town education and outreach. While FKNMS visitors do not live in Monroe County, their activities in the sanctuary can still contribute to local anthropogenic stressors. The use of distance learning and audio-visual technologies are both being implemented at the FKNMS. While South Florida schools definitely have an easier time incorporating coral reefs and the FKNMS into their curriculum, distance learning and audio-visual presentations could be used to reach schools in other states. These programs are dependent on available technical experts (U.S. Department of Commerce et al. 2007).
Assessing institutional capabilities of the FKNMS to address climate change through the revised resilience guidelines

There are barriers and benefits for FKNMS managers to work with local, state, and federal agencies. These barriers and benefits disable and enable the ability to incorporate climate change management actions and reduce local anthropogenic stressors. The National Marine Sanctuary Act (NMSA), responsible for executing conservation and management of marine sanctuaries including the FKNMS, must cooperate with suitable federal, state, and local agencies, organizations, and private and public interests (Suman 1997). The National Marine Sanctuary Program (NMSP) has the authority to make regulations on activities that humans can and cannot perform in sanctuaries, and the NMSP also has the authority to enforce regulations with penalties (http://sanctuaries.noaa.gov/about/legislation/). The observations of an evaluation of the NMSP are that the NMSP is improving in resource protection and management, sanctuary enforcement must be increased, and stronger collaborations are needed with partners (U.S. Department of Commerce et al. 2008). The budget for the NMSP in FY2008 is $62 million, but there will be shortfalls in funding for some of the sanctuaries (U.S. Department of Commerce et al. 2008).

The FKNMS includes federal and state waters leading to the obvious inclusion of Florida for involvement and agreement regarding the FKNMS development and management (Suman 1997). The state of Florida governor could have objected to the inclusion of state waters no more than 45 days after the enactment of the FKNMSPA (Suman 1997). The Florida governor and Florida cabinet had several provisions to ensure state sovereignty over Florida’s submerged lands inside the FKNMS (Suman 1997).
There are several examples of collaboration of agencies for the management of the FKNMS. The Interagency Group, originally formed to ensure Florida participation in the FKNMS development, consists of Florida representatives (Florida Department of Natural Resources, Florida Department of Environmental Regulation, Florida Department of Community Affairs, and the governor’s office), federal agencies (National Park Service, U.S. Fish and Wildlife Service, Environmental Protection Agency, and NOAA), local governments (Monroe County Department of Marine Resources), and the South Florida Water Management District (Suman 1997). Another example of cooperation is the Interagency Compact Agreement, which ensures coordination between agencies as part of the management process to collaborate all the federal, state, and local agencies (Sleasman 2009). Signatories included NOAA, U.S. Environmental Protection Agency, U.S. Coast Guard, governor of the state of Florida, South Florida Water Management District, Monroe County Board of County Commissioners, and Monroe County municipalities (Suman 1997).

A third example of collaboration is the SAC, which includes representatives from the boating industry, fishing industries, diving industry, education and outreach, submerged cultural resources, tourism, research and monitoring, conservation and environment industry, citizens at large, an elected county official, and FKNMS staff (FKNMS Sanctuary Advisory Council Charter). Law enforcement personnel could also be beneficial members in the SAC (U.S. Department of Commerce et al. 2008). The SAC can provide management advice to FKNMS managers but not make decisions on behalf of the FKNMS (FKNMS Sanctuary Advisory Council Charter). A benefit of collaborating with the SAC is that stakeholder opinions and knowledge can be
incorporated in management decisions hopefully leading to more satisfied users. Many more agencies also actively participate in FKNMS management plan action plans.

The obstacles to trying to coordinate numerous federal, state, and local agencies are overlapping authorities, differing objectives, and replication of resources (Suman 1997 and Sleasman 2009). Also, interestingly, regulatory changes in the FKNMS have to be approved through an act of Commerce (telephone interview, March 24, 2010). The NMSP and the National Marine Fisheries Service often conflict when trying to regulate fishing in sanctuaries (U.S Department of Commerce et al. 2008). There is also a need, due to a lack of collaboration, to better distribute research findings at the sanctuaries to the appropriate audiences (U.S. Department of Commerce et al. 2008).

Yet, coordination with many agencies helps tackle ecosystem threats outside of one agency’s authority (Suman 1997). Since FKNMS managers do not alone have jurisdiction over the stressors impacting the sanctuary, they must cooperate with appropriate local, state, and federal agencies to address sanctuary concerns. The active participation of many agencies has led to all state waters in the FKNMS becoming a no-discharge zone in 2002, and all sanctuary waters will be a no-discharge zone this year, 2010 (U.S. Department of Commerce et al. 2007 and B. Causey, personal communication).

The FKNMS receives funding from state and federal sources, partner agencies, and from other opportunities like grants (Suman 1997 and U.S. Department of Commerce et al. 2007). The FKNMS is largely financed through the NMSP (National Marine Sanctuary Program 2004). For each national marine sanctuary, the estimated funding requirement is based on a site complexity index (high for the FKNMS) and a life cycle
phase (6 – adaptive management for the FKNMS). In the FKNMS management plan, the estimated costs for implementing all fourteen of their action plans for the five years of the management plan is $586,435,000 (U.S. Department of Commerce et al. 2007). The sharing of the financial obligations reduces the financial stress on the NMSP to provide all the funding and may limit the amount of financial stress on the FKNMS (Suman 1997). Public-private partnerships are beneficial to the FKNMS. REEF has a fish survey program that it coordinates in the FKNMS using voluntary divers and snorkelers (White Water to Blue Water 2006). The data collected helps the FKNMS obtain baseline data as well as data to evaluate no-take zone effectiveness. A sense of ownership of FKNMS resources can be perceived by volunteers (White Water to Blue Water 2006).

Dive/snorkel operators, commercial fishers, and charter fishing operators have all reported seeing non-compliance to FKNMS rules (Dobrzynski and Nicholson 2001). Two disabling conditions to effective FKNMS management mentioned in one interview were the large area of the FKNMS and funding (telephone interview, April 27, 2010). These two barriers and the large number of visitors affect the effectiveness of FKNMS enforcement. Fortunately, a significant drop in violations in the past five years has occurred because of increasing education, dedicated law enforcement, and possibly less people using the sanctuary because of the economic downturn (http://floridakeys.noaa.gov/le/welcome.html). There is 1 captain, 4 lieutenants, and 12 officers providing enforcement in the park.

The enabling and disabling conditions existing for the FKNMS are the same whether the FKNMS is managing to reduce local stressors or implementing more specific climate-based management actions. This is because the FKNMS can only be
effective in reducing local stressors. A lack of funding can lead to a lack of human resources and a lack of other resources needed to implement management actions. Collaboration with local, state, and federal agencies, the SAC, and NGOs is overall an enabling condition for the FKNMS and assists in reducing the disabling conditions, like human, financial, and physical resources.
CHAPTER 5
CONCLUSION AND FUTURE WORK

Ocean acidification is already occurring, and the ocean’s pH will continue to drop as well as be impacted by other compounding climate change effects: increasing sea surface temperatures, increasing sea levels, and the possibility of an increasing number and/or intensity of tropical storms. Many demonstrate a decrease in coral calcification when simulating ocean acidification (Gattuso et al. 1998, Langdon et al. 2000, Langdon and Atkinson 2005, Albright et al. 2008, and Jokiel et al. 2008). Coral bleaching has already had devastating effects on coral reefs worldwide. However, the future may not be all bleak. The adaptive bleaching hypothesis provides hope that corals may be able to adapt or acclimatize to a certain extent to climate change (Buddemeier and Fautin 1993). Also, the Montastraea faveolata lesion experiment (chapter 2) exhibited that M. faveolata can have faster calcification and tissue regeneration in CO₂ concentrations predicted by the year 2050. These flickers of hope do not mean that no action is required but that there is time and with action, coral reefs can be managed into the future despite climate change.

While CO₂ levels have been higher in the past, this also cannot lead one to believe there is nothing to worry about. The past is an imperfect example of the present; changes in atmospheric CO₂ occurred much more slowly allowing carbon to be buffered. Corals did, though, experience extinctions due to climate changes during the Permian-Triassic and Cretaceous-Tertiary extinctions (Doney et al. 2008). Fine and Tchernov (2007) demonstrate that corals can entirely lose their skeletons when seawater pH is lowered but
when the seawater pH is returned to the normal pH, the corals re-grew their skeletons. Corals re-emerged relatively quickly in geological timescales after the Permian extinction (Stanley and Fautin 2007). Corals may have, alternatively, survived mass extinctions without coral skeletons leaving no fossil records and began calcifying again and leaving fossil records when the seawater pH returned to normal (Stanley and Fautin 2007).

The resilience of coral reefs can be affected by many factors. To increase coral reef resilience, the positive factors should be increased while the negative threats should be decreased. Resilience indicators, such as coral skeletal growth and lesion healing rates, can be identified and compared between areas with protection and areas without protection to exemplify what management actions are increasing coral reef resilience, assuming that MPAs can increase reef resilience. Then managers could focus on those actions maximizing their time and money. Many organisms and people depend on coral reefs, and the recurring management actions suggested for coral reefs is the implementation of MPAs and to build and support coral reef resilience.

The building of resilience by MPAs is not a new idea, but an idea that needs to be further tested. There is conflicting evidence of the ability of MPAs to increase resilience of coral reefs to disturbances. Graham et al. (2008) suggest that after bleaching events, no-take areas do not support increased resilience. Mueller and Booker (2008) found a difference in coral lesion healing rates between a Caribbean no-take area and an unprotected area only in some of their lesion healing assessments in only the winter season. Selig and Bruno (2010) propose that because MPA coral cover returns to change rates not significantly different than zero after large scale disturbances (storms, coral diseases, and bleaching), MPAs do increase coral resilience. More field studies
performed on MPAs and adjacent unprotected areas may be able to elucidate whether MPAs can increase coral reef resilience and if and how MPAs can protect coral reefs from climate change.

The experiment, the effects of increasing carbon dioxide concentrations on *Montastraea faveolata* skeletal growth and lesion regeneration: using coral skeletal growth and lesion healing as indicators of coral resilience, demonstrated trends not previously shown. Both the summer and fall lesion experiments revealed that increasing CO$_2$ concentrations can promote faster skeletal growth and lesion healing. A threshold effect seems to arise where increasing CO$_2$ up to a certain concentration is beneficial to coral calcification and tissue regeneration. Once the CO$_2$ concentration becomes higher than the threshold, calcification and lesion healing are negatively affected. The relationship between corals and their symbionts could be studied further to help clarify how increasing CO$_2$ concentrations may be enhancing symbiodinium, which then leads to enhanced coral calcification and tissue regeneration. Calcification was significantly lower at a pCO$_2$ of 800 µatm, the atmospheric pCO$_2$ predicted at the end of the century. Slowed calcification of corals may reduce competitive edge and sexual maturity age and may also affect buoyancy and light behavior (Doney et al. 2008).

In addition, the *M. faveolata* lesion experiments showed that other factors besides CO$_2$ concentration control lesion healing rates. CO$_2$ concentration was shown to only have a small affect on lesion healing rates. The experiments, specifically the fall experiment, demonstrated that coral colonies will respond variably to ocean acidification. More experimentation could be performed to determine skeletal growth rates and lesion healing under different time frames, with the same and different coral species, larger
sample sizes, and with simultaneous temperature changes to try to understand the trends more clearly and help to illustrate what can be expected in the future if greenhouse gas emission policies do not change.

The survey of current management frameworks for reducing climate-induced changes on coral reefs by ensuring coral resiliency using the TNC Resilience Model as a framework demonstrated that most MPA management plans list climate change as a threat. Yet, there is no consensus on climate-based management strategies between the MPAs. All the MPA management plans have management strategies with the potential to increase coral reef resilience. The weaknesses of the Resilience Model demonstrated that there are several management barriers to managing coral reefs in MPAs: institutional incapacities, a lack of resources (money and people), enforcement, compliance, and local stressors.

Because of the weaknesses identified in the TNC Resilience Model in chapter 3, revised resilience guidelines were developed for the FKNMS in chapter 4 that addressed the gaps of the Resilience Model by discussing pertinent institutional capacities and incapacities and social concerns regarding the management of the FKNMS. The guidelines were partially developed from the management implications and management actions suggested from the M. faveolata lesion experiment by FKNMS staff and SAC’s ERWG. The revised climate-based coral reef resilience guidelines are to 1) incorporate more no-take zones and hedge the risks against ocean acidification, 2) identify resilient coral reefs and perform more climate change research, 3) reduce local stressors, 4) enhance coral reef recovery, and 5) increase public awareness and education on climate change impacts to coral reefs. While the revised climate-based coral reef resilience
guidelines, except for using coral calcification and lesion healing as indicators of resilience to ocean acidification, are activities commonly suggested by policymakers and scientists, the *M. faveolata* lesion experiment provides additional evidence of the priority of these management actions to FKNMS managers and other MPAs. Scientists in the Kleypas and Eakin (2004) survey, though, identify the top three management actions to increase worldwide coral health as increasing education and communication about coral reefs, reducing the rate of CO$_2$ increase in the atmosphere, and reducing the rate of population growth. The second and third management actions are not achievable by MPA managers, but the revised resilience guidelines could be incorporated by MPA managers with available resources.

Guideline 1, a suggested management action from the coral lesion experiment results, aims to increase the amount of no-take area in the FKNMS. Meaningful participation of FKNMS stakeholders may be the key to successfully incorporating more no-take zones, if more-no take zones are deemed necessary by FKNMS managers. The research priorities that guideline 2 suggests from the coral lesion experiment results, to identify resilient coral reefs, is dependent on partner agencies’ willingness and having the resources to implement a coral lesion field study. MPA managers have the ability to reduce local stressors, not climate change. Reducing local stressors is a priority action for MPAs. Guideline 3 highlights the incentives and obstacles of the FKNMS coordinating several agencies and organizations to reduce local stressors. Many articulate that for coral reefs to mitigate climate change all destructive human activities and local stressors need to be reduced including increasing water quality, decreasing pollution, and decreasing overexploitation of functional reef groups (Hoegh-Guldberg et al. 2007,
Hughes et al. 2007, and Baker et al. 2008). Guideline 4 suggests evaluating the cost effectiveness of coral reef recovery techniques, but that reducing local stressors may remove the need of these techniques. Hoegh-Guldberg et al. (2007) mentions the idea of coral restoration but highlights that there is a scale mismatch between the possible scale of restoration and the scale of damage. Guideline 5 emphasizes that public outreach is not sufficient; increased outreach and education could decrease the magnitude of local stressors. Although there are disabling conditions to overcome, managers can effectively work toward reducing local stressors in the hopes of increasing coral reef resilience, which in turn will help reefs survive future climate change impacts.

The revised climate-based coral reef resilience guidelines were developed using the FKNMS as a case study, but the guidelines could also apply to other wider Caribbean MPAs as long as they are incorporated considering institutional capacity and social concerns to identify enabling and disabling conditions of building reef resilience to climate change. Actions that the FKNMS can and cannot implement will not be the same for all wider Caribbean MPAs. Science is critical when making management decisions and can help drive management hypotheses and assess management success and/or failure (telephone interview, March 24, 2010 and March 25, 2010). Coral reef climate change impact studies, in particular, are necessary for designing the FKNMS’s climate change action plan (telephone interview, April 2, 2010). Climate science and evidence can be used to apply pressure to decision makers (telephone interview, April 2, 2010). FKNMS and wider Caribbean MPA managers may be able to use the same process outlined in chapter 4 to incorporate climate change experiments into coral reef management. FKNMS managers, staff, and the SAC, or wider Caribbean MPA
management bodies, can discuss the management implications and actions of pertinent scientific studies followed by MPA institutional capacity to determine the feasibility of proposed actions.
APPENDIX 1

Different methods to determine coral and coral reef resilience that can be implemented into coral reef monitoring programs

Alizarin coral staining, x-radiography (Dodge and Brass 1984), vertical growth measurements, and coral lesion studies can all be performed in situ. In the laboratory, growth/density bands, stable isotopes, and buoyant weighting (Jokiel et al. 1978) can be used to determine coral calcification. Performing an in situ coral lesion experiment and measuring vertical growth rates will be discussed in more detail. Several different species on several coral reefs can be given small lesions, by several methods, (around 1 cm$^2$) and photographed as early as 5 days later. Within 5 days healing will be between 25-75% according to Muller’s (2008) experimental results. The photographs can then be used to calculate lesion healing rates for coral species and reefs and compared to determine which corals and coral reefs heal faster. Coral reefs being compared must be experiencing similar physical conditions and stressors.

Faster coral growth of the same species at equivalent reefs will identify corals and coral reefs that have more resilience. Because the average vertical growth rate of the lesioned *M. faveolata* corals, extrapolated to a yearly growth rate, is only 0.17cm/year directly measuring vertical growth rates is not suggested to include into a MPA monitoring program. Using techniques like alizarin staining, analyzing growth bands, and buoyant weighting might be logistically easier and faster ways to see growth.
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