Applications of Coral Bio-Optics to Coral Reef Management

By

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Dedications

To my late father, whose love has served as my greatest motivation and encouragement every day of this past year.

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List of Acronyms Used

AGRRA	Atlantic and Gulf Rapid Reef Assessment
AIMS LTMP	Australian Institute of Marine Science
BIOS	Bermuda Institute of Ocean Sciences
CARICOMP	Caribbean Coastal Marine Productivity Program
CBD	Convention on Biological Diversity
CBO	Coral bio-optical
CEEP	Collection and Experimental Ethics Protocol
COI	Commission de l’Océan Indien (Indian Ocean Commission)
CRAMP	Hawaii’s Coral Reef and Monitoring Program
CREOL	Coral Reef Ecology and Optics Lab
FKNMS CRMP	Florida Keys National Marine Sanctuary Coral Reef Monitoring Program
GCRMN	Global Coral Reef Monitoring Network
ICON	International Coral Observation Network
ICRI	International Coral Reef Initiative
MBRS SMP	Mesoamerican Barrier Reef System Synoptic Monitoring Program
MPA	Marine protected area
NDVI	Normalized Difference Vegetation Index
NIR	Near infrared wavelength
NOAA	National Ocean and Atmospheric Association
RED	Red wavelength
RFMO	Regional fisheries management organization
SCUBA	Self-contained underwater breathing apparatus
SEA	Strategic environmental assessment
TEV	Total Economic Valuation
USD	United States Dollar

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Abstract

The unabated decline of coral reefs has led to criticisms of both coral reef monitoring and management: monitoring data provides management with a limited capacity to detect current sources of stress acting on the reef, address sources of stress before they significantly affect the reef, and predict future trends in order to prevent further harm. This project evaluates the management merits of developing coral bio-optics, the study of coral pigmentation using underwater spectrometry, into a uniquely precise and proactive reef monitoring methodology and part of a monitoring program. This includes an evaluation of the technology's ability to pre-emptively detect nutrification and bleaching stress in aquaria. The evaluation informs a discussion of how coral bio-optical monitoring might provide management decision support for the control of human activities in Bermuda's reef ecosystems, given the country's recent marine policy initiatives. Recommendations include the implementation of coral bio-optical monitoring to expand our understanding of stresses and pigmentation health, further develop the technology, and apply the technology to monitoring the optical properties of multiple coral species.

Keywords: coral reef, bio-optics, spectrometry, management, monitoring, nutrification, bleaching, Bermuda.

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Chapter 1. Introduction

1.1 The Management Issue

Coral reefs are the primary source of livelihood, quality of life, revenue and physical protection for the majority of tropical island communities. In 2008, the lives of roughly 30 million people were entirely reliant on coral reef ecosystems, while hundreds of millions of people worldwide were partially dependent on reef resources such as for recreation and biotechnology (Wilkinson, 2008). However, published primary literature has increasingly recognized the worldwide ongoing degradation of coral reefs over the course of the past three decades. Research studies now unanimously cite that rarely more than 10% of coral reefs are in pristine condition, and more than 19% have been irreversibly degraded (Hughes, Graham, Jackson, Mumby & Steneck, 2010). This decline is largely due to anthropogenic stresses, and if unabated, could result in the loss of the world's reef resources.

While the perceived hazards to reefs have varied over the past 40 years, the awareness and concern of scientists, managers, students, and non-governmental representatives regarding threats to coral reefs have remained high (Kleypas & Eakin, 2007). The anticipation that the state of reefs will continue to worsen has led to a growing number of conventions and calls to action, [*e.g.* the 1971 Convention on Wetlands of International Importance (The Ramsar Convention), the 1992 Convention on Biological Diversity (CBD), and the International Coral Reef Initiative (ICRI)]. These international agreements have highlighted the importance of improving management practices in order to confront the problem of reef decline. In 1995, the ICRI released *Framework for Action* to motivate governments and stakeholders to act on maintaining coral reef health, and thereby highlighted a major management gap in urgent need of addressing: “Research and monitoring are needed to assess the status of coral reefs, evaluate the success of management and conservation actions and develop more effective practices” (p. 6). The 17 years since have seen the rise and implementation of dozens of substantial monitoring initiatives worldwide [*e.g.* Reef Check, Coral Watch, the National Ocean and Atmospheric Association’s (NOAA) International Coral Observation Network (ICON), Hawaii’s Coral Reef Assessment and Monitoring Program (CRAMP), and Global Coral Reef Monitoring Network (GCRMN)]. Together, this broad array of different monitoring programs has proven ultimately useful and insightful in assessing the state of coral reefs and noting the changes that reefs have undergone all over the world. It is the resulting data that collectively chorus the continued decline in coral cover and which renders monitoring successful in achieving its purpose: without it, these trends would be unconfirmed or unknown.

Coral reef monitoring provides a means of resource assessment, resource status, and mapping, which can allow for the evaluation of impacts, disturbances, human activities and uses, while also raising awareness and providing education (Hill & Wilkinson, 2004). Thus, monitoring is designed to have an overarching goal of supporting effective management (Hill & Wilkinson, 2004). However, the unabated decline of coral reefs has led to criticisms of both coral reef monitoring and management (Bellwood, Hughes, Folke, Nyström, 2004), in large part because reef management as it is currently informed by monitoring is inherently reactive. In other words, monitoring data provides management with a limited capacity to detect current sources of stress acting on the reef, address sources of stress before they significantly affect the reef, and predict future trends in order to prevent further harm. This is for two reasons. Firstly, monitoring data are not typically collected and processed on time scales suitable to detect stresses at their outset. Because reef monitoring most often focuses on long-term community-level trends, the data are compared inter-annually and relate information about processes that have occurred months if not years in the past. As reefs are dynamic complex systems, there are undoubtedly biological responses to stressors that occur on time scales smaller than those of community-level changes and whose expressions are presently unmonitored. The comparatively early detection of trends through frequent monitoring of short-scale changes would mobilize management in addressing stresses as they arise. Secondly, biological monitoring data cannot demonstrate causal relationships, nor can interpretations forecast what changes the reefs might experience in the future. Despite being capable of quantifying a negative trend in reef community structure ('What?'), management practises cannot determine the proximate cause ('How?'), nor can they indentify the ultimate cause of stress or decline unless the biological parameters are supported by environmental data ('Why?'). Monitoring trends occurring on both intra-annual and inter-annual scales would further enhance the input of monitoring data to management. Compiled together, monitoring data could provide additional insight into the processes of change and resilience as trends run their course, and allow causal relationships to be characterised. In order to be ultimately arrest reef decline, it is imperative that the purpose of reef monitoring programs be expanded to empower management in these ways.

1.2 Research Questions and Methodology

The purpose of this research is to pursue the opportunity to build on the capabilities of modern day reef monitoring through the incorporation of a new technology. The coral reef monitoring community has already witnessed and welcomed the benefits of adding novel, consumer-grade technologies to traditional survey methods, such as the use of high definition photo and video for benthic community transect and quadrat surveys (Hill & Wilkinson, 2004). Similarly, this project will evaluate the management merits of incorporating into a reef monitoring protocol the study of coral pigmentation using underwater spectrometry, termed coral bio-optics. This research aims to provide recommendations for creating an interface between the scientific and management applications of coral bio-optics such that reef management bodies can achieve more short-term predictive reef data and a greater understanding of the processes of reef health. The project's objectives are guided by three research questions: (1) can the measurement of coral bio-optics be developed into a monitoring tool? (2) can coral bio-optics be used as part of a qualitative coral reef monitoring methodology? and (3) can information from coral bio-optical monitoring inform and benefit coral reef management?

To address these questions, the research strategy is intentionally interdisciplinary between coral reef science and management. First, existing and common coral reef biological monitoring techniques are reviewed, and popular monitoring programs that use them are listed. They are described and compared using six evaluative criteria: (1) indicators obtained, (2) spatial scale, (3) effort, (4) level of training required, (5) precision, and (6) replication. Secondly, the scientific rigor and technological considerations of monitoring coral pigmentation are evaluated based on aquarium and field trials using a hand-held diver-operated spectrometer. Lastly, a desktop study of published peer-reviewed and government literature is used to determine how information from coral bio-optics might provide management decision support for the control of human activities in reef ecosystems. This includes consideration of the past success of reef monitoring in informing international marine management and policy decisions, as well as the capacity of reef monitoring to support the environmental and coastal management decisions and policies of Bermuda. Drawing on the merits and limitations of the technology in these assessments, recommendations are then made with for the adoption of coral bio-optical monitoring by monitoring programs and managers.

1.3 Project Scope and Limitations

The evaluations and final recommendations of this project are intended to suggest possible ways in which the use of underwater spectrometry can be developed into a coral monitoring technique, integrated into a monitoring program, and how appropriate local and national policies may be structured to respond to the outcomes of coral bio-optical monitoring. However, developing a comprehensive plan of action for implementation of coral bio-optical monitoring and a structured bio-optical monitoring program are not within the scope of this research. A large, concerted effort in both the scientific and management fields of coral bio-optics will be required before implementation and widespread adoption will be possible.

Secondly, with reference to coral bio-optics as a monitoring technique, this project is not intended to present coral bio-optics as an independent and complete monitoring protocol, nor a protocol to replace those already in practise. It is important to note that due to the time restraints of this project, not all current monitoring protocols are included in the review, nor were they evaluated in depth. By reviewing the similarities of the most common protocols and the most extensive monitoring programs, generalized recommendations can be made about the incorporation of coral bio-optics to an extended management audience. As a result of the current capabilities of the existing supporting scientific relationships and technology, more specific and targeted recommendations to integrate coral bio-optics with management programs are not yet possible.

Finally, Bermuda is selected as the location of this evaluation due to the accessibility of the technology and the opportunity to conduct trials. It should be recognized that this constitutes a case study and that additional evaluations of national management considerations would be required elsewhere.

1.4 Report Structure

This report has been structured into six chapters, organized as to answer each research question most effectively:

Chapter 1, this chapter, introduces the management issue at hand as being the need for informed coral reef management through enhanced monitoring protocols. It also serves to outline the research questions, evaluation methodology, report structure and scope.

Chapter 2 introduces the practices and programs coral reef monitoring, grouped by their scope, either benthic community structure and diversity (2.1.1) or organism status (2.1.2). A review of the major regional and global reef monitoring programs that use these methodologies is provided. The second half of the chapter then focuses on reef complexity as a confounding factor in reef monitoring: the complexity that arises in trying to effectively study and monitor reef ecosystems, and the importance of properly understanding and monitoring reef processes to evaluate reef health. This highlights the compromises that persist in today's reef monitoring programs, and introduces the alternative of predictive and process-oriented monitoring protocols.

Following an introduction to the key concepts of coral pigmentation, Chapter 3 considers the measurement of coral bio-optics for its scientific rigor and technological merits within the context of a spectrometer being used as a tool for monitoring the progression of changes in coral pigmentation. This evaluation was conducted based on the results and experiences of first-hand coral nutrification and bleaching experiments done in aquaria.

Chapter 4 builds on the previous chapter by evaluating the implementation of the tool in the field (*i.e.* being used by a diver on natural reefs as a component of a reef survey). Based on the successes and difficulties of these field trials, and in light of the survey methodologies evaluated in Chapter 2.1, Chapter 4.1 considers the potential for integration of coral bio-optical monitoring as an additional methodology within monitoring programs.

Chapter 5 consists of an discussion of how a coral bio-optical monitoring protocol or program might provide management decision support for the control of human activities in Bermuda's reef ecosystems, given the relevant policy initiatives to monitor reef health and key legislative considerations. The potential for this protocol to be incorporated into monitoring programs internationally is also discussed.

Finally, Chapter 6 summarizes the evaluations and concludes on the potential for coral bio-optics to inform management as a monitoring tool and as pat of a protocol. Recommendations are made for how each of these components can be actualized and discusses what future steps must follow in order to achieve implementation of each.

Chapter 2. Review of Coral Reef Monitoring

Coral reef monitoring can consist of monitoring the biological, physical, chemical, or usage characteristics of coral reefs. Biological monitoring is informed by parameters of the reef's living resources, whereas physical and chemical monitoring form the basis of environmental data, and usage monitoring monitors human impacts and by inference, their impacts on the reef. As does this review, the majority of monitoring programs centre, if not focus exclusively, on biological monitoring.

In order to evaluate a reef as "healthy" versus "stressed", directly observable indicators are used to quantify biological reef processes. Table 1 lists which indicators measure which processes and the scales on which they occur. Whether for research or management purposes, monitoring of these indicators ideally involves a regimen of observation and assessment of reef health tailored to these scales (Rogers, Garrison, Grober, Hillis & Franke, 1994). These indicators are most often informed by key species abundance, population size-frequency, species diversity, and abundance of mortality (Hughes & Connell, 1999; Hill & Wilkinson, 2004; Rogers *et al.,* 1994). Methodologies can be used to obtain these indicators either by collecting information at the benthic community level or on the status of individual organisms, such as coral colonies. The most common methodologies are discussed in the following section.

Table 1. Commonly Used Indicators of Biological Reef Processes, Compared By Scale

Indicator	**Biological processes**	**Spatial Scale**	**Temporal Scale**
Benthic cover	Coral growth Macroalgal growth	1m – 10m 10m - 100m	Years Seasons
Disease and bleaching	Coral morbidity and mortality	1cm – 1m	Days-Months
Diversity (species, alpha, beta, gamma)	Population structure Ecosystem health	10m – 100m	Years Decades
Topographical relief	Calcification	100m – 1km	Decades
Coral recruitment	Larval dispersal	100m – 1km	Years
Coral recruitment	Larval dispersal Juvenile recruitment	100m – 1km 10m – 100m	Years Years

2.1 Comparison of Common Biological Survey Methodologies

There are dozens of different coral reef monitoring methodologies that are in practice and that typically form part of monitoring programs around the world (Hughes *et al.*, 2010). To best understand the variety of methodologies that exists and how they are used, the following sections consist of a comparison of the most current and accepted biological monitoring methodologies**.** Table 2 lists the five criteria with which the methodologies are compared. Table 3 compares the methodologies focused on the benthic community scale while Table 4 compares methodologies focused on the status of individual organisms. Also included in these two tables are the well-established and recognized programs that utilize these methodologies.

Table 2. Criteria Used to Describe and Compare Coral Reef Monitoring Methodologies

Criteria	**Covers**	**Variables**
Indicators	Which indicators can be measured with this methodology?	Benthic cover Morbidity & mortality (disease & bleaching) Diversity (species, alpha, beta, gamma) Topographical relief Recruitment
Spatial scale	On what scale is this methodology used?	Small (<5m^2) Medium (<100m^2) Broad (>100m^2)
Effort	How much time is required to effectively use this methodology relative to the area studied?	Brief = >10m/min Detail Dependent = +/- 10m/min Time Consuming = < 10m/min Permanent record = Data analyzed after collection.
Training required	How much training is required in order to effectively use this methodology?	Minimal = No/Little Experienced Required Average = Experienced Divers/Technicians Required High = Expert Oversight Required
Precision	How precise are the data?	Low = difficult to achieve, mostly estimation Medium = achievable with appropriate meticulousness High = easy to achieve or inherent in protocol
Replication	How easily can the data be replicated between samples?	Low = difficult to achieve consistency among observers, sites, or samples Medium = achievable with appropriate meticulousness High = consistency achievable easily

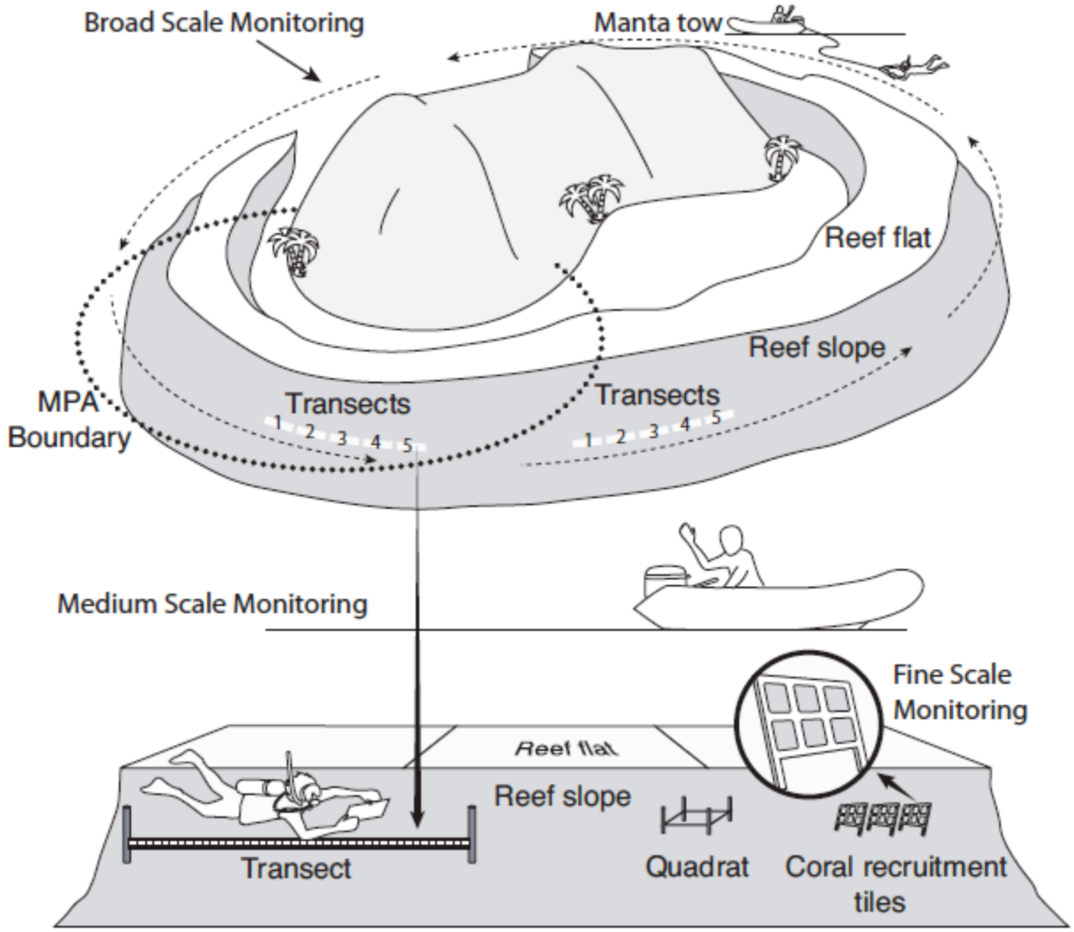

Figure 1. Illustration of Reef Biological Monitoring Methodologies of Differing Spatial Scales, from Hill & Wilkinson (2004).

It should be noted that all methodologies require considerable and flexible time budgets due to the reliance on boating and SCUBA diving. The risks of SCUBA diving are assumed, while the time and financial costs of boat-based diving surveys are considered baseline operating costs of any biological monitoring program. Although they are not to be overlooked, these are in addition to the effort and training criteria included in Tables 3 and 4. All other financial criteria are considered nominal unless stated otherwise.

2.1.1 Benthic Communities

Methodologies that are considered to quantify the biological parameters of benthic communities include transects (*e.g.* line, point, belt, chain, video), quadrats (*e.g.* hand count, photo, coral recruitment), recruitment tiles, and manta tows (Table 3). Many of the methodologies may provide multiple indicators, and many of the methodologies can provide the same indicator. However, not all methodologies are equally appropriate. Other than the criteria listed in Table 2, financial expenditures also vary between each program. Generally speaking, the financial cost of a methodology is compounded by the necessary effort, training, equipment, and the temporal scale of the process(es) being indirectly monitored. Because most community-level biological indicators are monitored on the scale of years and thus the methodologies are used with a similar sampling frequency (Hill & Wilkinson, 2004; Rogers *et al.,* 1994), these methodologies mostly differ in financial cost based on effort (*i.e.* cost per unit time) and training (*i.e.* costs of training and compensation). Cost of equipment, as previously stated, is typically uniform among methodologies with the exception of those that use video and photo technology. The use of these methodologies has traditionally been cautioned due to the high costs of technology acquisition and upkeep, as well as analysis software (Hill & Wilkinson, 2004).

Due to differences in procedure, some indicators are more reliably obtained than others by a given methodology. For example, all transect-based methodologies require transect tapes to be either permanently or temporarily laid on the reef and observations of the benthic community to be made in the transect's vicinity. However, point intercept transect surveys involve observations directly beneath the transect at distance intervals,

Table 3. Common Coral Reef Benthic Community Monitoring Methodologies and Associated Programs

	Indicators obtained	**Spatial scale**	**Effort**	**Training**	**Precision**	**Replication**	**Programs**
Line intercept transects	Benthic cover Morbidity & mortality Topographic relief	Medium	Time consuming	Average	Medium	Medium	AGRRA, MBRS SMP
Point intercept transects	Benthic cover* Morbidity & mortality Topographic relief	Medium	Brief	Minimal	Medium	Medium	Reef Check, MBRS SMP, ReefKeeper
Belt transects	Morbidity & mortality	Medium	Detail dependent	High	Medium	High if fixed	Reef Check, CARICOMP
Chain transects	Benthic cover Morbidity Topographic relief*	Medium	Time consuming	High	Medium	Low	CARICOMP
Video transect	Benthic cover Mortality	Medium	Detail dependent, permanent record	Average	High	Medium	GCRMN, AIMS LTMP, FKNMS CRMP
Quadrats (random)	Benthic cover* Morbidity & mortality Recruitment	Small	Time consuming	Average	High if standardized training	Medium	COI, AGRRA
Photo quadrat (permanent)	Benthic cover* Diversity Morbidity & mortality	Small	Detail dependent, permanent record	Average	Medium, only superficial estimates	Variable by apparatus and frame	GRCMN, FKNMS
Recruitment tiles	Coral recruitment	Small	Time consuming	High	High if successful identification	High	GCRMN, MBRS SMP
Recruitment quadrats	Coral recruitment	Small	Time consuming	Average	Medium	Medium	AGRRA, FKNMS CRMP
Manta tow	Benthic cover* Mortality Topographic relief	Broad, shallow only	Brief	Minimal	Low, estimates only	Medium	AIMS LTMP GCRMN

* denotes indicator best obtained by the methodology

(Hill & Wilkinson, 2004; Rogers et al.,1994) whereas line intercept transects involve observations of the benthic organisms that intercept the transect line throughout its entire length, and belt transects involve the same observations within a two meter buffer on each side of the line. Chain transects, however, use weighted chain that conforms to the topography of the reef and therefore can give a much easier estimate of structural complexity (topographic relief). Methodologies that are broad and brief such as manta tows, where an observer is pulled by boat across a reef, are generally best used to assess generalized community structure, since the observations are superficial or made rapidly. For a full description of methodology procedures and operational specifications, see Hill and Wilkinson (2004) and Rogers *et al.,* (1994).

2.1.2 Organism Status

The majority of biological monitoring at the organism scale focuses on hard corals (Hill & Wilkinson, 2004). Observations are made of individual coral colonies to determine, for example, species, size, bleaching status, and disease status. However, unlike community-scale methods that extrapolate and average these parameters of coral abundance, diversity, and health in relation to other functional benthic groups, organism-scale methods for monitoring individual coral status only provide indications of the coral population. It is logistically necessary for a methodology to involve tagging of individual coral colonies in order to monitor the same individual's status over time. However, colouration cards and non-tagging methodologies are also considered a method of monitoring organism status if information about an individual coral, such as the pigmentation of individual corals against a coral pigmentation spectrum, is collected but not used to evaluate percent coral cover or other community parameters. Some measures can be considered both (*e.g.* permanent photo quadrats can measure the benthic community as well as monitor the status of individual coral colonies). Because the quadrat is permanent, it is equivalent to tagging.

Table 4. Common Coral Reef Organism Status Monitoring Methodologies and Associated Programs

	Indicators obtained	**Spatial scale**	**Effort**	**Training**	**Precision**	**Replication**	**Programs**
Colony tagging	Diversity Morbidity & mortality	Small	Time consuming	Average	High	High	GCRMN
Colouration cards	Morbidity & mortality	Medium	Detail dependent	Minimal	Medium	Low	Coral Watch

2.1.3 Principal Monitoring Programs

Monitoring programs vary logistically as much as the set of methodologies that they employ. The major monitoring programs listed in Table 3 and 4 are presented according to their differences in geographical extent and their objectives in Table 5. Ideally, a monitoring program will sample the reef as often as is required to adequately match the temporal scale of the reef processes being measured (Table 1), and thus collect the data with appropriate resolution. However, this may not always be the case as both the aims and the geographic area over which a monitoring program must extend their resources vary. Any method can be applied as often as logistically possible as temporal resolution relies solely on funding and manpower. The MBRS SMP demonstrates this trade-off: the program prioritizes its two-dozen monitoring locations into four categories with differing data resolutions. The sites with the highest priority are measured as often as six times annually with the least number of parameters to ensure efficiency (Hill & Wilkinson, 2004). Similarly, differences in the aims of the protocols used by these programs can reduce the resolution of the data. Some programs such as AGRRA were intended to only be conducted once and not to resolve causality, while others are rapid assessments only (*e.g.* COI). Thus, the resolution of the data can be variable between monitoring programs using the same methodologies. Data resolution can be further compromised when programs aim to rigorously monitor reef processes using unsuitable methodologies. These compromises will form the discussion of the next section.

Table 5. Fundamental Logistical Differences Exhibited By Principal Coral Reef Monitoring Programs

Program	**Location**	**Years**	**Aims**
Global Coral Reef Monitoring Network (GCRMN)	Global	1995 - present	Involve developing countries & engage communities and volunteers
Reef Check	International	1997 - present	
Coral Watch	International	2002 - present	Engage diving community
Atlantic and Gulf Rapid Reef Assessment (AGRRA)	720 reef sites in 34 sites across Western Atlantic and Gulf of Mexico	1998 - present	Baseline study to establish a practical scale of comparative reef condition continued thereafter
Caribbean Coastal Marine Productivity Program (CARICOMP)	29 sites in 22 Caribbean countries	1992 - 2004	Determine productivity of mangroves, seagrasses, and reefs
Coral Reef Degradation in the Indian Ocean (CORDIO)	Indian ocean	1999 - present	Investigate the ecological and socio-economic consequences of the mass coral bleaching in 1998
Commission de l'Ocean Indien (COI)	Comoros, Reunion, Madagascar, Mauritius & Seychelles	1998 - present	Regional node of GCRMN
Mesoamerican Barrier Reef System – Synoptic Monitoring Program (MBRS SMP)	25 sites in Belize, Guatemala, Honduras & Mexico	2001 - present	Long-term, four-tier regional monitoring program
Florida Keys National Marine Sanctuary Program Coral Reef Monitoring Program (FKNMSP CRMP)	Florida Keys	1997 - present	Administered as part of the National Oceanic and Atmospheric Association

2.2 Complexity of Monitoring Reef Processes & Resilience

2.2.1 Complexity and Reef Monitoring

As noted in Chapter 1, the ability of biological monitoring data to inform management action is limited by the information that can be gleaned from community-level metrics about causal factors and reef dynamics. Further, the broad time scales of community-level trends mostly provide hindsight. These difficulties cannot be considered the fault of the monitoring program's objectives or efforts: systematic biological monitoring was developed long after the start of coral reef decline but while the instability of a reef community, and thus reef dynamics, was still a revolutionary concept (Hughes *et al.,* 2010, Sale 2008). To expect the metrics of biological monitoring to provide insight into the processes causing such instability, and thus to provide decision support for management intervention, is to put the cart before the horse. However, over the course of the 30 years that monitoring programs have been in effect worldwide, reefs have become increasingly recognized as complex and vulnerable natural ecosystems, and the management demands placed on monitoring programs have increased.

In an effort to meet these demands while still maintaining long-term data sets, biological monitoring programs have made compromises in order to achieve the greatest possible data resolution (outcomes) while using the same metrics. First, the selection of monitoring protocols when establishing and executing a monitoring program is guided by several trade-offs (Hill & Wilkinson, 2004; Rogers *et al.*, 1994). Some reef health metrics are more difficult to monitor than others, and there exists an overarching caveat that no monitoring program can reasonably aim to monitor all metrics currently correlated to reef health (Hill & Wilkinson, 2004; Rogers *et al.,* 1994). There is no doubt that all monitoring programs require significant staff, training, time, and money. Depending on the question that the program seeks to answer, broad, time-efficient, and training-minimal monitoring protocols are generally applied across the whole reefscape. More precise and informative protocols have greater constraints on time, financial resources, and highly trained staff, and thus are only typically used to on scales that are of value to localized management (Hill & Wilkinson, 2004; Rogers *et al.*, 1994). We see this to be true in Table 1, where the methodologies used on smaller scales, such as quadrats and tiles, provide higher precision but are more time consuming and require experienced technicians. To sufficiently sample the complexity of the reef, the most robust monitoring programs maximize the number of monitoring methodologies used within the program, but this can introduce a trade-off in data quality. For example, many monitoring programs employ volunteers for in-water surveys, thus increasing data volume per unit cost, but a high turnover of staff and variability in quality of surveyor training can make data precision highly variable across years and sites (Hill & Wilkinson, 2004). Ultimately, while this means that not all monitoring programs use the same methodologies with the same training standards, and integration of data from different monitoring programs and meta-analyses are rarely consistent (Hughes *et al.*, 2010).

The second compromise revolves around the fact that community-level biological parameters of reef health are often not directly quantifiable. Many individuals of many species must be monitored over many years in order to monitor the health of a 'community', but rarely do the time-scale and resources of monitoring studies allow such inferences to be made (Hughes & Connell, 1999). As a result, multiple survey methods arrive at more easily measured surrogate indicators of the community's health that provide insight at the moment of sampling (Hill & Wilkinson, 2004; Hughes & Connell, 1999; Rogers *et al.*, 1994). These indicators are more often informed by local abundances of key organisms and then extrapolated to form indicators reef health processes, such as benthic cover and diversity (Table 1). Percent hard coral cover (relative abundance of hard coral) is in fact the most used indicator of reef health with the simple reasoning that coral cover is an easily observable metric, and coral is functionally central to the maintenance of the reef ecosystem (Hill & Wilkinson, 2004; Hughes & Connell, 1999). Changes in coral cover between years are then used as indicators of changes in reef community structure. However, simplification in the process of forming these indicators reduces their ability to reliably reflect the variability and complexity of healthy reef conditions. Hughes *et al.* (2010) note, "a healthy reef that is recovering towards a coral-dominated equilibrium can have substantially less coral than one that is locked into a downward trajectory to dominance by macroalgae" (p. 635). Although it is possible to correlate declines in percent coral cover to a disturbance (the ultimate cause), surrogate indicators often can not inform on the proximate causes of changes in community structure unless the reef's underlying ecological mechanisms are known (Hughes *et al.*, 2010). In this instance, a decline in percent total coral cover can't reveal whether changes in recruitment, changes in adult colony mortality, or both, contribute to the trend[1]. It also does not consider functional group redundancy: if it is known that there are multiple

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[1] *E.g.* A reef is found to be healthy and mature due to high coral cover, but unbeknownst to managers, high levels of sedimentation from coastal run-off are present. Following a short-term shock such as a cyclone, there is high adult mortality and monitoring data finds a lower percent coral cover, which are attributed to the cyclone as the ultimate cause. However, indicators based on individual coral status and size-frequency would correctly reveal the sedimentation load has been too high for coral juvenile recruitment, and the reef would no longer degrade if sedimentation load was reduced. (Hughes *et al.*, 2010).

species that perform the same functional roles, one can determine the likelihood of the reef to overcome the ecological consequences and recover from a given species extinction (Bellwood *et al.*, 2004). Thus, even when data quality is not compromised and a methodology is standardized among reef monitoring programs, surrogate indicators may not be aptly correlated to reef health and may lead to incorrect interpretations (Sale, 2008).

2.2.2 Complexity & Reef Resilience

It is now well known that the complexity of coral reefs as natural systems, coupled with variable stress exposure and resilience, create spatial and temporal diversity in the susceptibility of reefs to decline (McClanahan *et al.*, 2009; Nunn 2009). Hence, despite general degradation, reef health and their ability to recover varies around the world. Current reef research is investigating the underlying biological and ecological mechanisms that have caused some reefs to be more resilient to shocks and stressors (Nyström *et al.*, 2008). Ecological mechanisms of reef resilience include dynamic ecosystem thresholds, feedback mechanisms, and hysteresis[2] (Hughes *et al.*, 2010). As was exemplified in the previous sections, it is therefore important that false assumptions

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[2] Footnote #1 describes an example whereby two thresholds exist that would independently create tipping points allowing them to be surpassed. Together they create a loop, causing the reef ecosystem to persist between them, a trend termed hysteresis. Hysteresis is described by Kopfová (2006) as "processes whose state variables change due to a change of parameters in such a way that when the parameters go back to the old values the system does not follow its steps in reverse and thus a hysteresis loop is formed" (p.130). In this example, without knowing the history of high sedimentation affecting juvenile colonies, the expected progression following the cyclone would be that a mature reef without further disturbance (parameters returning to normal) could eventually recover. The upper (positive) threshold is the abundance of adults that beyond which would tip to encourage a coral-dominated state, and the lower (negative) threshold leading to decline is low recruitment. Because the sedimentation rate is not high enough to affect the mature colonies, the reef persists between these two thresholds until the cyclone disturbs the adults.

about causal relationships are not inferred from monitoring data so as to lead to unsuitable management action. Conversely, if the ecological mechanisms acting on a reef are understood, it is possible to differentiate the biological responses to these mechanisms being specifically exhibited by each functional group (*e.g.* corals, algae, herbivores). In other words, if it is known what feedback mechanisms and tipping points are present on a reef, responses in each functional group can be monitored using appropriate indicators. Then, targeted actions (*e.g.* alleviating the appropriate causal factor in reef ecosystem change) can be taken to alleviate the shock prior to the full decline in environmental state. It is imperative that monitoring indicators draw on the concepts of reef resilience so that they may provide insight into the reef's functioning and processes, and so that past causational information can be used to anticipate and improve the reef's future.

Chapter 3. Coral Bio-Optics as a Tool for Measurement and Monitoring of Coral Health

3.1 Key Concepts

The colour of a coral is the result of the pigments it contains: skeletally-fixed pigments, tissue-based pigments, and pigments within zooxanthellae (Hedley & Mumby, 2002). Zooxanthellae are endosymbiont dinoflagellate algae present in all tropical reef-building corals. Their symbiotic relationship with corals is such that the process of algal photosynthesis provides the coral colony host with energy and compounds for growth calcification (Hochberg, Apprill, Atkinson, & Bidigare, 2006). Spanning the genus *Symbiodinium*, all zooxanthellae provide their host coral with the same five photosynthetic pigments in relative concentrations (chlorophyll *a*, peridinin, chlorophyll *c*, diadinoxanthin, diatoxanthin, and β-carotene) (Hedley & Mumby, 2002). The interaction of the light spectrum with these pigments creates a coral's optical signature (Hochberg *et al.,* 2006). The measurement and consideration of both the empirical spectral measurements of wavelength within a coral's optical signature and the structure and significance of pigmentation in the functioning of coral as an organism is herein termed the study of coral bio-optics (Hedley & Mumby, 2002).

While the skeletal pigments are rare, tissue-based pigments are highly variable among and within species (Hedley & Mumby, 2002). However, zooxanthellae are peridinin-containing dinoflagellates, and, while pigment concentrations may vary the same suite of pigments is present in all zooxanthellae (Hedley & Mumby 2002; Hochberg *et al.,* 2006). Studies that document this consistency across coral taxa were also careful to note that total concentrations of photosynthetic pigments and thus density of zooxanthellae were highly unpredictable (Hedley & Mumby, 2002). Studies have since linked variations in zooxanthellae density within-cell and per unit coral colony surface area to indirect indicators of stress conditions (*i.e.* irradiance, sea level, rainfall, nutrients, sea surface temperature) (for a review see Hedley & Mumby 2002), trends in spectral reflectance between stressed and unstressed coral populations (Holden & LeDrew, 1998), and some have begun to describe the natural ranges and densities of pigments by inference from optical spectra (Hochberg *et al.,* 2006; Hardy, Hoge, Yungel & Dodge, 2002; Joyce & Phinn, 2003; Myers, Hardy, Mazel & Dustan, 1999).

3.2 Scientific Rigor of Coral Bio-Optics

Because the health of a coral is directly related to the photosynthetic activity of its endosymbiont population, deviation from normal photosynthetic pigment densities (*i.e.* changes in photosynthetic state) correlate to various environmental stress factors (*e.g.* low salinity, increased temperature, nutrient loading[1]). In turn, because they determine the spectral reflectance characteristics of coral, changes in pigment densities are expressed as changes in the optical signature. Previous studies of coral bio-optics have successfully demonstrated the use of a spectroradiometer in differentiating the reflectance of visibly bleached versus unbleached corals in the field (Holden & LeDrew, 1998), as well as differences in fluorescence spectra due to temperature stress using a spectrofluorometer in the lab (Hardy *et al.,* 2002), and *in situ* (Myers *et al.,* 1999). A spectrometer has also been used in the field to evaluate the spectral radiance differences

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[1] When nutrients are added to the water (*i.e.* sewage outfall), more zooxanthellae that will inhabit the coral (biomass), and thus more photosynthesis will be carried out, creating more pigments, and the optical signature will change. This is relevant to coral health because it has been shown that too many zooxanthellae will starve the coral of CO2, which leaves it with no means of skeletogenesis and makes it less resilient to future shocks or stresses.

between bleached and unbleached corals (Hochberg et al., 2006), and various between reef features including corals (Joyce & Phinn, 2003). However, no known study has attempted to use changes in optical signature to predict changes in coral photosynthetic pigment concentrations *during* stresses of any kind, while the relationship between nutrification stress and any of the optical properties of a coral have never been empirically demonstrated in scientific literature. Thus, this chapter investigates the application of coral bio-optics as a tool to measure and monitor changes in coral pigmentation within coral colonies and relate them to the coral's health.

The quantification of photosynthetic pigment concentrations in relation to changes in coral optical signature is not within the purview of this project due to time and facilities constraints. Albeit unquantified, increases or decreases in the concentration of the sum of photosynthetic pigments can still be inferred by changes in reflectance, measured by changes in the amplitude of the optical signature curve (Hardy *et al.,* 1992). Furthermore, increases or decreases in the concentration of chlorophyll *a* over time can be inferred by measuring changes in the normalized difference vegetation index (NDVI), calculated using reflectance values at the red wavelength (RED, 0.67–0.68 µm) and near infrared wavelength (NIR, 0.7–1.1 µm). In terrestrial systems, NDVI evaluates the presence of live green vegetation. Because NDVI is sensitive to chlorophyll content, it should be useful for evaluating the pigment levels of any plant, including corals.

To affirm and expand the theoretical basis of measuring changes in coral pigmentation via optics, and thus assess the scientific rigor of coral bio-optics as a tool for monitoring coral health, two aquarium trails were conducted. 15 colonies of the massive/encrusting coral *Porites asteroides* were collected from the reefs on Bermuda's south shore in accordance with the Bermuda Institute of Ocean Sciences (BIOS) Collection and Experimental Ethics Protocol (CEEP) guidelines. Colonies were placed in large aquaria to acclimatize for a minimum of 24 hours. Eight colonies were then used in a nutrification experiment, and seven were used in a bleaching experiment. The corals were kept in dosing chambers each with a recirculating seawater reservoir. The seawater in each reservoir was replaced every morning, and corals were shaded to prevent excessive light conditions.

Using a portable fibre-optic spectrometer, a minimum of five optical measurements was measured for a diffuse reflectance target. This was immediately followed by the collection of a minimum of 15 spectra for a given coral colony. Measurements were made daily between 11am and 1pm for the duration of each experiment. At the time of spectral measurement, the corals and the reflectance target were kept shaded from the sun while being illuminated by xenon light to prevent irregularities in the light field between measurements. Reflectance was calculated as the ratio of the coral spectra to the reflectance target spectra. Upon analysis, the mean reflectance per coral per day was used to determine any changes in reflectance (%) as well as NDVI (NIR–RED / NIR+RED) over the course of the experiment.

3.2.1. Bleaching

Two corals were kept in each of four dosing chambers, each with a total recirculating volume of 10 L seawater. To induce bleaching, the corals were stressed by constant exposure to a temperature of 29°C for 11 days, 3 degrees above ambient.

However, upon noting that the *Porites* colonies are notably resistant to bleaching stress, temperatures were increased to 31°C for 10 days, 2 degrees above the summer mean maximum for Bermuda (Hardy *et al.,* 1992). Fresh seawater was heated prior to being exchanged and maintained at these temperatures through the use of a Polyscience recirculating chiller/heater unit with coils in each dosing chamber. To determine if changes in optical signature could be seen by the naked eye prior to the colony showing visible differences in coral pigmentation, macro photographs were taken of each colony beneath the water's surface at the time of measurement. Spectral reflectance was measured daily at the same spot on each coral.

The reflectance of all corals increased by at least 15% during the exposure to 31°C (July 11 – July 19, day 11 - 21), while some increased by as much as 20%. All but one coral had the highest reflectance on the last day of the experiment. Only one coral (Tank 3 Coral 1) showed a monotonic increase in reflectance throughout July 11 to July 19 (Figure 2). It is unclear if the day-to-day variability in reflectance is in fact due to fluctuations in pigmentation concentration on the scale of hours, or if there were other sources of error in the acquisition of the spectra.

However, the results of calculations of NDVI do suggest that the corals were experiencing bleaching stress. Although absolute reflectance fluctuated, the sample mean normalized difference of red and near infrared wavelengths shows a clear negative trend (Figure 3). Based on the error bars set at a confidence interval of 95%, no daily measurement is significantly different than the day before. However, NDVI values recorded on June 29th to July 4th do not overlap with those from July 11th to 16th, and the

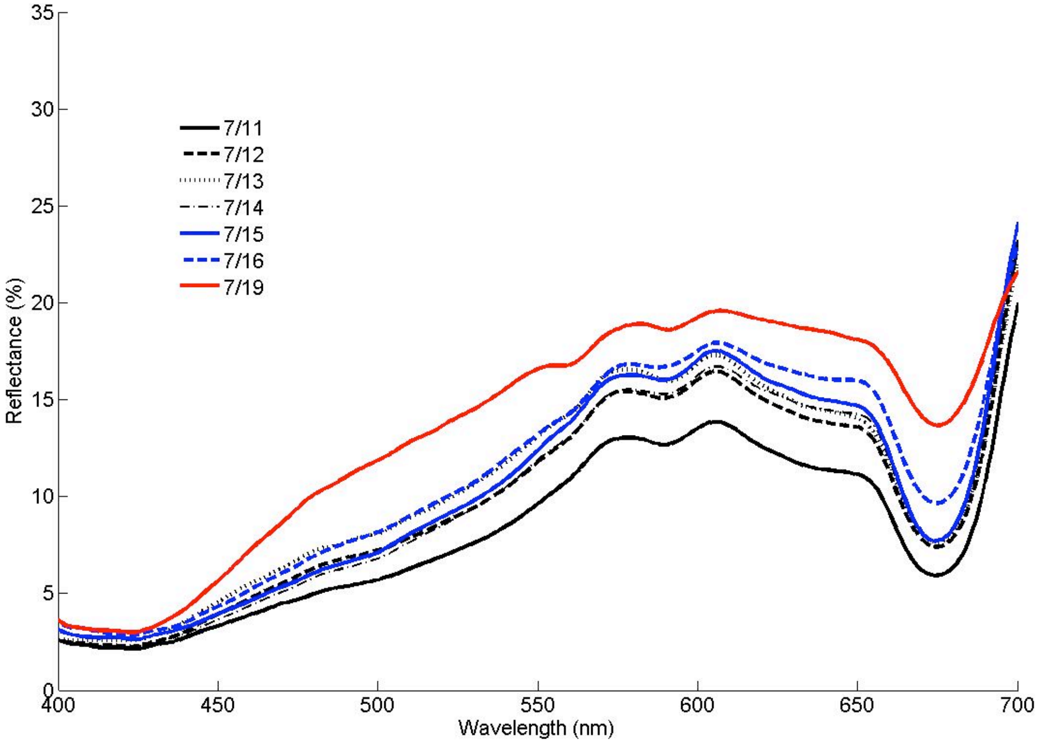

Figure 2. Observed monotonic increase in optical signature reflectance (%) in a *Porites asteroides* colony (T3C1) following bleaching stress induced by elevated temperature

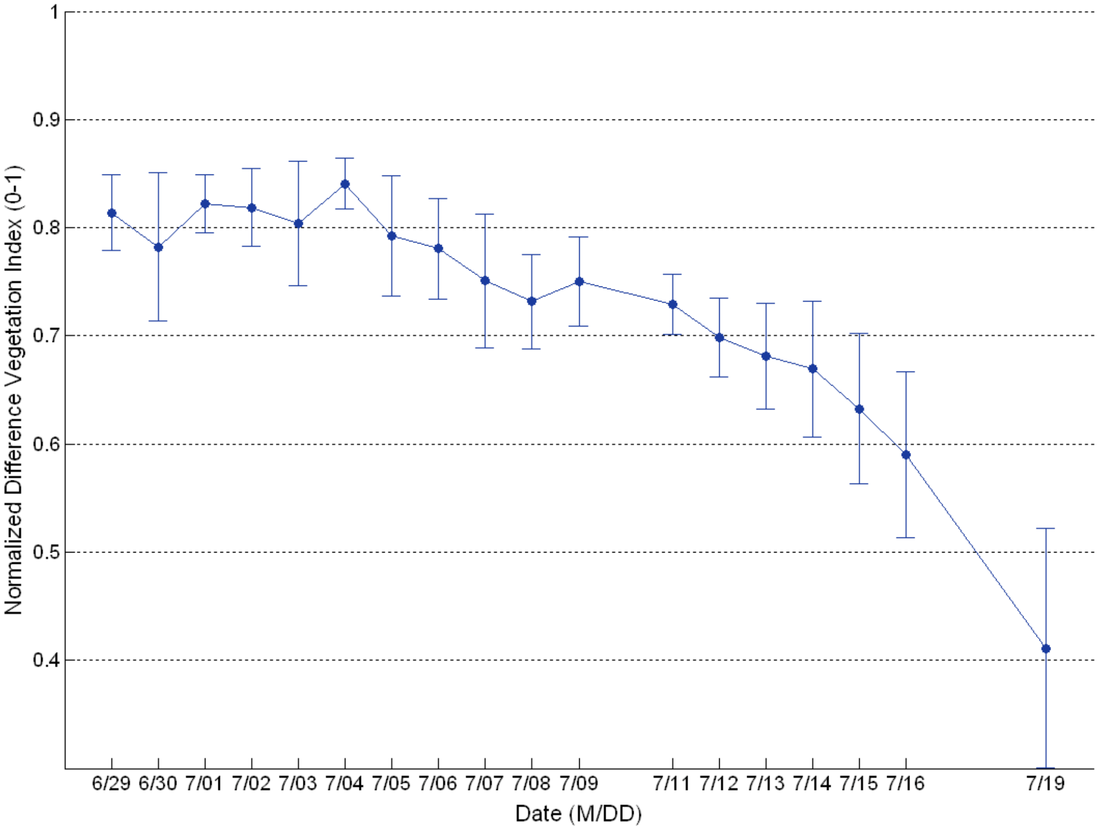

Figure 3. Changes in sample mean NDVI for *Porites asteroides* coral colonies (n=8) following bleaching stress induced by elevated temperature

measurement on July 19 does not overlap with all days other than July 16. The error bars in mean sample NDVI are large due to a small sample size and variance, this change coincides with the day that the temperature was increased (July 11th) and the day that paling was first observable (July 16th), and bears further investigation. When NDVI was calculated for each coral, the lack of overlap in the error bars suggests all values significantly decreased daily, but no trend analysis was done (Figure 4). The greatest total difference was 0.7 in the colony labelled Tank 4 Coral 2. On July 13, Tank 4 Coral 2 was the only colony to be visually pale in comparison to its original pigmentation, but would not have been considered pale to a first time observer. Although NDVI for both corals in Tank 4 decreased ~0.15 during July 11-13, Tank 4 Coral 1 did not appear pale until July 19. It is possible that July 12 and 13 were not accurate measurements for Tank 4 Coral 1 because of the fluctuation that can be seen in the graph. Alternatively, Tank 4 Coral 1 was a brown variation of *Porites asteroides* whereas Coral 2 was a green variation. This suggests that the human eye may be particularly insensitive to initial phases of bleaching of brown coral variations, *i.e.* the brown zooxanthellae pigment masks changes in green coloration (coral-host pigment fluorescence). Regardless, these results suggest that NDVI in *Porites asteroides* is typically in the range of 0.7 - 0.85 in healthy corals, and that changes in pigmentation are not distinguishable to a first-time observer unless NDVI changes by 0.4, or to a trained observer unless NDVI changes by 0.2. Because the corals did all eventually bleach under these conditions, decreases in NDVI beyond a value of 0.6 serves as a reliable, early predictor of a significant change in the health of a coral colony.

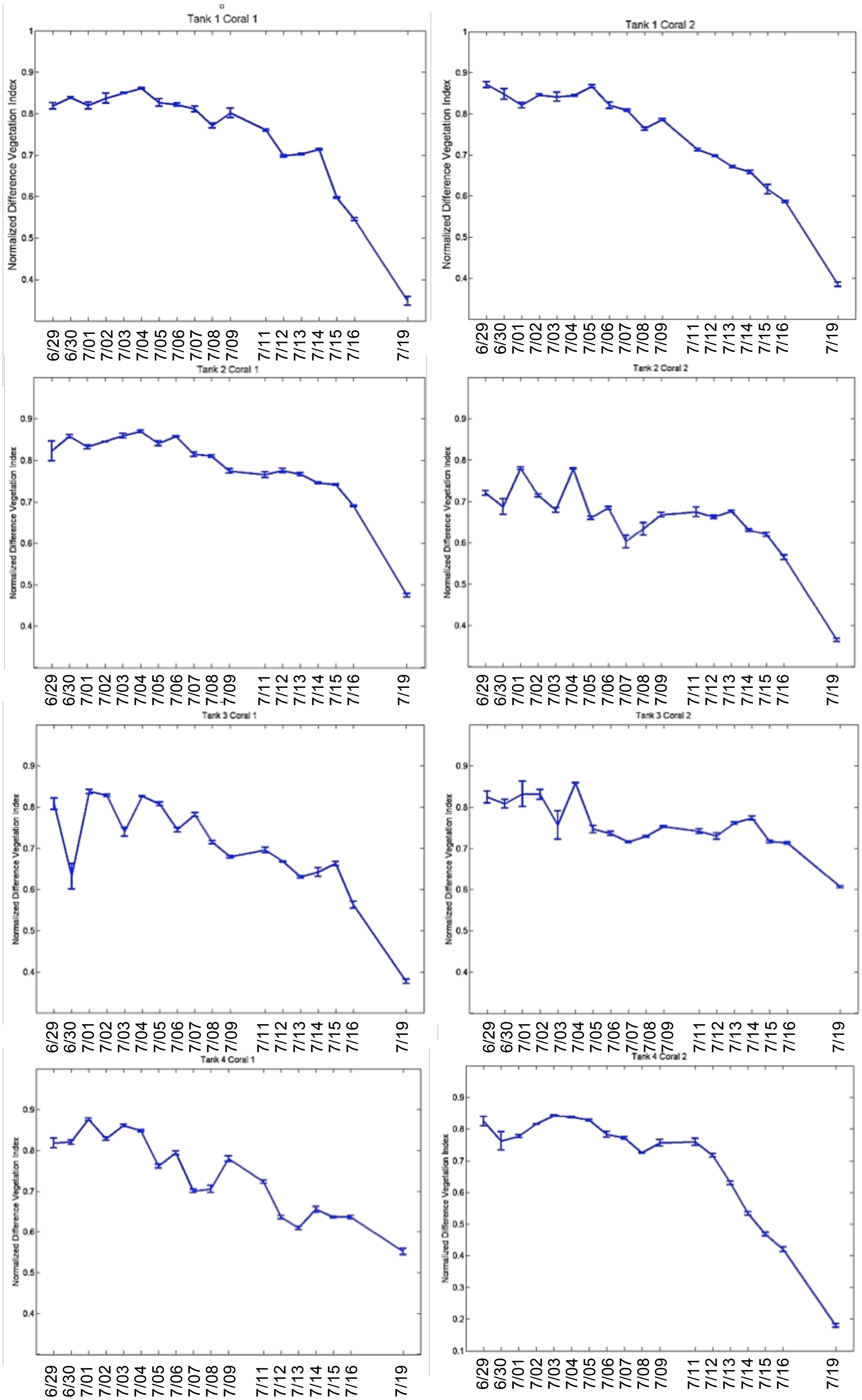

Figure 4. Observed changes in NDVI in each of eight *Porites asteroides* coral colonies following bleaching stress induced by elevated temperature

3.2.2. Nutrification

Each coral was placed in a separate dosing chamber, each with a total recirculating volume of 10 L seawater and maintained at 24°C for 12 hours per day through the use of a Polyscience recirculating chiller/heater unit with coils in each dosing chamber. After sunset, the corals were returned to a communal **#L** open-circuit flow-through aquarium and left overnight. Nutrification stress was induced by adding concentrations of ammonium sulphate ($(NH_4)_2SO_4$) dissolved in 500 mL seawater to the dosing chambers once daily. Two corals were exposed daily to a concentration of 10 μmol l^{-1} ("Low"), two were exposed to 20 μmol l^{-1} ("Medium"), and two were exposed to 30 μmol l^{-1} ("High"), leaving one control which was not exposed to ammonium sulphate.

For the same potential reasons described in 3.2.1, no decreasing trend in reflectance was found in the individual corals, with the exception of one colony (High Dose #1) (Figure 5). Similarly, no decreasing trend was documented in corals when NDVI was averaged per treatment using 95% confidence limits. All corals were considered as a single sample (n=6) to determine any significant effect on NDVI from the addition of nutrients regardless of level, but again no clear trend was found at 95% confidence limits. When NDVI was calculated for individual corals, no monotonic changes were found with the exception of the same colony (High Dose #1) (Figure 6). Both the change in reflectance (~15%) and NDVI (~0.15) in the coral labelled High Dose #1 are considerable, but because these results were not mirrored in any of the other corals it is likely that there were several sources of error. Error in measurement could have been caused by measuring variable spectral reflectance by pointing the fibre-optic cable at multiple locations across the colony's surface, or by creating uneven light gradients between the corals and the reflectance target. Otherwise, error in the uptake of nutrients in the coral could have been caused by inadvertent dilution of the ammonium sulphate by refilling reservoirs after some leaks, adhesion of the ammonium sulphate to surfaces within the dosing chamber, or not enough of a constant exposure by being returned to a larger tank overnight. Although these results suggest that nutrification can decrease the total reflectance of *Porites asteroides,* corresponding to an increase in chlorophyll-*a* concentration, this experiment would need to be repeated to validate the trend.

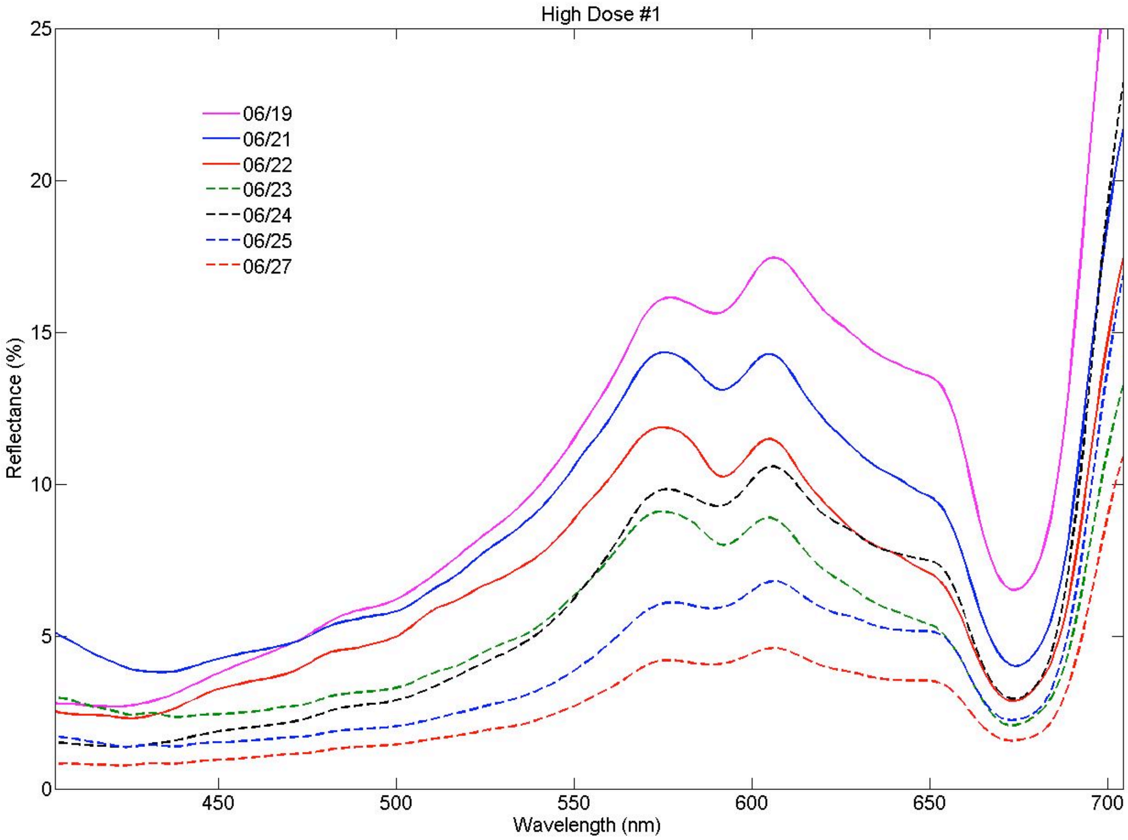

Figure 5. Observed consistent decrease in optical signature reflectance (%) in a *Porites asteroides* colony (High Dosage #1) following nutrification stress induced by regular exposure to a concentration of # 30 µmol of ammonium sulphate.

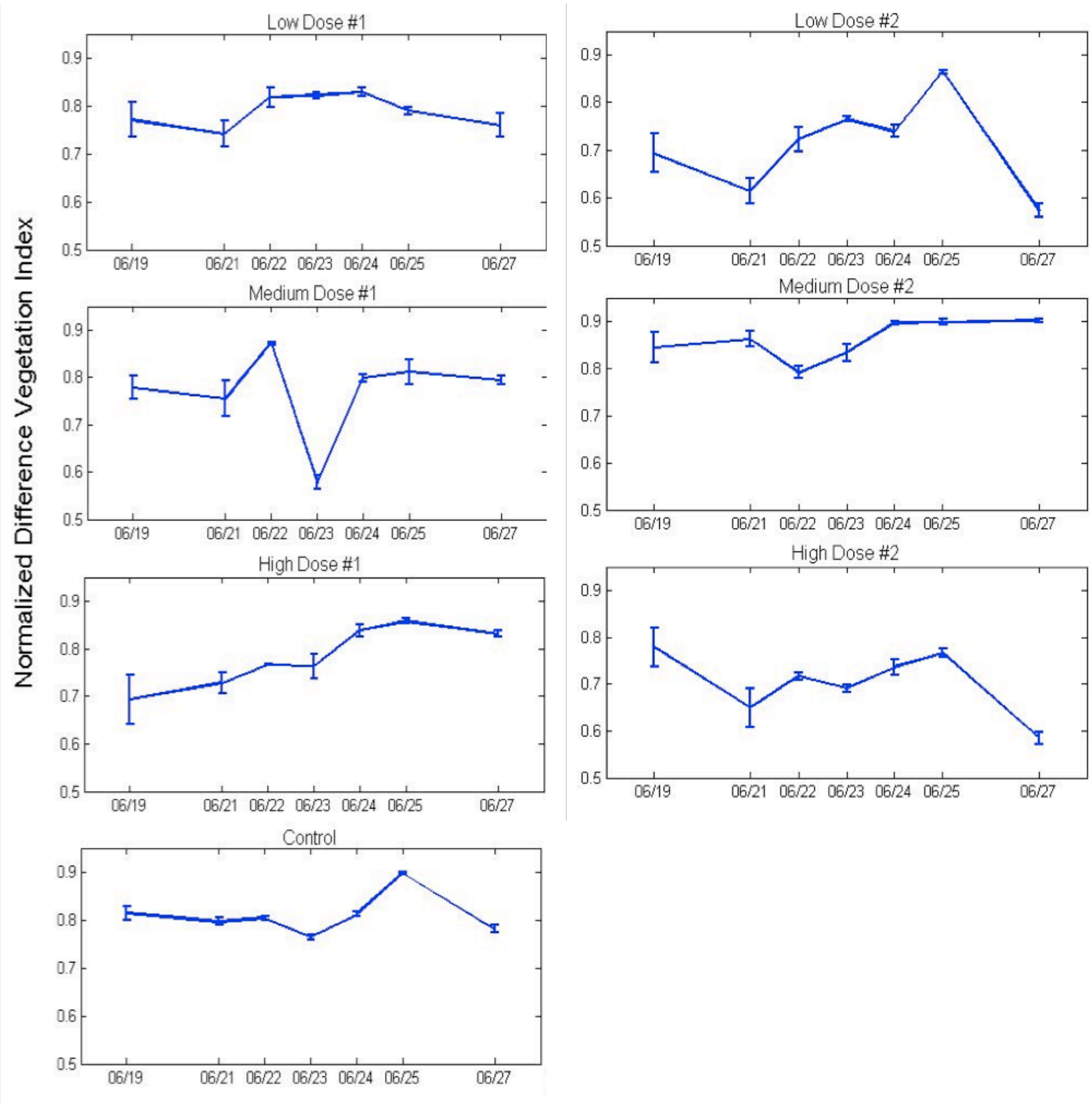

Figure 6. Observed changes in NDVI in each of seven *Porites asteroides* coral colonies following nutrification stress induced by exposure to three ammonium sulphate concentrations

3.3 Technological Considerations

Coral bio-optics were measured for these trials using a portable spectrometer (Ocean Optics USB2000**)** attached to battery pack and a hand-held computer (Compaq

Pocket PC H3900 series), loaded with software for displaying the spectral readings during their acquisition (OOIPS2000, Ocean Optics, Inc.). The spectrometer was connected to a two-metre steel-wrapped fibre optic cable affixed to a xenon flashlight to provide a consistent light source. Spectra were acquired for a diffuse reflectance standard using a Labsphere Spectralon tile with a uniform reflectance value of 10% so as to match the reflectance intensity of corals (Hochberg, Atkinson, Apprill, & Andréfouët, 2004). After the collection of data, the files were transferred from the Pocket PC to a desktop computer where they were processed and analyzed using MATLAB software.

This configuration was custom-made explicitly for the purpose of measuring corals. At the time of assembly in 2005, the sum of the equipment pieces cost roughly $7000 USD. Most impressively, this assembly included the custom design and construction of an underwater housing for a spectrometer (with handheld PC and battery) for in-water measurements (~$2000 USD). Both the housing and the spectrometer equipment pieces were uniquely assembled and are now obsolete, and the software was a one-time purchase. However, Ocean Optics has since developed a full range of consumer grade spectrometry equipment that can be customized (*e.g.* Jaz), making the technology available to a wider user group and at lower cost (Ocean Optics, 2012, para. 2). Complete with an underwater housing estimated at $2500, top of the line to budget spectrometers range from ~$19 000 USD to ~$8 500 USD (Hochberg, personal communications).

Because the assembly is unique and can be considered an underwater spectrometer prototype, there are multiple steps necessary to assemble, use, and maintain the equipment that make the learning curve steep while introducing sources of error. Most significantly, it is difficult to ensure that the placement of the fibre optic cable is aligned with the light source of the flashlight such that the spectrometer is reading reflectance under even light conditions across the fibre's field of view. Xenon flashlights provide a full range of visible and even near-infrared light, making them ideal light sources for amplifying coral spectral measurements, but they rarely have a uniform light field. Thus, angled wedges made of cardboard were attached to the flashlight such that the cable could be attached and aligned with the light source for each use.

The measurement distance from the coral affects the area measured (fixed field of view). Inconsistent measurement distances coupled with variable ambient sunlight have a strong effect on the amplitude of the optical signature. To overcome these, the fibre was always held at the same distance from the coral and the area of the coral being measured was shaded from direct sunlight at the time of measurement. Finally, a spectrum reading can fluctuate significantly while holding the fibre relatively still due to particulate matter, air bubbles, or slight movement. Thus learning to recognize odd readings (*i.e.* abnormally high, low, or distorted readings) is an important skill acquired with practise.

Many of these technical complications that affect reliability, data precision and learning curve may be avoidable by using newer technology and software such as the new and simple spectrometer interface available in the Ocean Optics Jaz modules. Unlike the Pocket PC, the software could be programmed to simplify the measurement and analysis process by storing a reflectance constant in the memory at the start of measurements rather than measuring the constant repeatedly for each coral. This would reduce any source of error due to fluctuations in the light field between measurements of the coral and the spectralon. It could also allow the coral optical signatures to be automatically analyzed and compared against ideal reflectance and NDVI values at the time of measurement, offering the user an instantaneous evaluation of the coral's pigmentation health. There also exist fibre optic cables that emit a light source, which would eliminate any error from misalignment of the light source and the optical field of the cable. It would also allow for precisely replicating the location of the measurement, which is important as the coral's concentration of zooxanthellae varies significantly across the colony surface on the scale of millimetres.

This cost of a modern spectrometer and accessories is likely accessible to reef managers, especially as part of monitoring marine protected areas, given the millions that are being invested into their enforcement and compliance. However, the ultimate technological limitation is the availability of the desktop MATLAB software. This software necessary to process spectra and conduct statistics is an interface used in MATLAB that was designed entirely by Dr. Eric Hochberg, and thus is not available to the public. It would be possible to create a user-friendly software for widespread distribution should this spectrometry technology become adopted elsewhere for coral bio-optics investigations. Alternatively, MATLAB software could provide the basis for development of a spectrometer interface software such as for the Jaz modules from Ocean Optics to process the data directly, eventually negating the need for MATLAB.

Chapter 4. Development of Coral Bio-Optics as a Reef Monitoring Methodology

4.1 Field Applications of Underwater Spectrometry

As was described in the previous chapter, the development of underwater housings for spectrometry equipment has made it possible to collect spectra of corals *in situ*. Other studies have used underwater spectrometry to study the bio-optics of corals and for applications to remote sensing (Holden & LeDrew, 1998; University of Puerto Rico Bio-Optical Oceanography Laboratory, n.d., para. 2), but a fully underwater hand-held spectrometer has never been used to routinely document the optical properties of a coral to detect the presence and progression of stresses *in situ*. Both Holden & LeDrew (1998) and Myers *et al.* (1999) documented differences in reflectance between bleached and unbleached coral populations *in situ*, but only on one sampling event*,* and Hardy *et al.* (2002) documented the relationship between fluorescence and induced bleaching stress *in vivo*.

This project is the first to evaluate the application of underwater spectrometry to coral bio-optics for the purposes of monitoring *in situ*. This chapter differs from the previous chapter in that it doesn't consider the theoretical and technological aspects of using a spectrometer to resolve the relationship between stress and signature, but rather the logistical merits and limitations of such a tool's implementation. In such an application, the underwater spectrometer is used to collect spectra of corals at a selection of reef sites over time, and any expressed changes in their optical signature are evaluated as changes in health. To date, the most similar evaluation of underwater spectrometry was a study by Hochberg *et al.* (2006) whereby the optical properties of haphazardly selected bleached and unbleached coral colonies at multiple sites were measured three times within one year. However, the results of these measurements were used to determine the ability of the optical properties of already bleached versus fully pigmented corals to accurately predict pigmentation concentrations, not to monitor coral optical properties over time. Similarly to the evaluation of methodologies in Table 2 and Table 3, this chapter considers the effort, training, precision and replication of using an underwater spectrometer for this purpose.

This evaluation was possible due to the integration of optics with the Bermuda Institute of Ocean Science's (BIOS) Coral Reef Optics and Ecology Lab's (CREOL) reefscape assessments, which are conducted in fulfilment of an ongoing partnership with the Government of Bermuda's Department of Environmental Protection. Although BIOS previously conducted monitoring as a participant of the Caribbean Coastal Marine Productivity (CARICOMP) Program (BIOS, n.d., para. 8), the current reefscape monitoring methodology is not intended to be integrated with any specific monitoring program elsewhere. The CREOL SCUBA and snorkel team consisted of four divers and a minimum of three snorkelers that aim to collect data at a representative number of reefs within half of Bermuda's platform per year. In a given study area, the snorkel team guides two divers to survey the benthic and fish communities using photo quadrats (benthos) and counts (fish) at ~20 m intervals along the reef. A second pair of divers observes coral colony status and measures coral optical properties at a single site. At each site, colonies are arbitrarily selected. To build on and reference the relationships developed in Chapter 3, the same species of corals as was used in the aquaria trials, *Porites asteroides,* were selected for field study. At least ten Spectralon measurements were recorded within the same light level as the coral (*i.e.* at the same depth and as close as possible to minimize variation in light fields), followed by at least 15 measurements of the coral colony itself. As the corals are not tagged, the spectra are measured from various points across the surface of the coral and averaged as opposed to only measuring at a single location on a given colony.

4.1.1 Merits

Reef resources are so heavily relied upon that it can be argued that conservation efforts are too socioeconomically costly unless they are critically and carefully designed (McClanahan *et al.*, 2009; Nunn, 2009). Therefore, effective monitoring and assessment are of practical importance to reef stakeholders. This is in large part for the purposes of informing policy and potentially conserving the reef and resources, but also for the costs of continually monitoring their reefs to be of greatest benefit to the community or nation. The use of coral bio-optics within a monitoring protocol regardless of sampling regime has the potential to enhance the effectiveness of monitoring by precision while providing (1) rapid, (2) non-invasive, and (3) universally repeatable observations on coral-zooxanthellae status.

(1) Measurements are executed in a time-effective manner, where upwards of 30 coral colonies can be measured within a 45-minute SCUBA dive, depending on the relative abundance of the target species. As such, adding the use of the coral bio-optic technology to field surveys does not create additional time requirements as measurements can be conducted simultaneously to traditional surveys. This does not impose a manpower requirement. Although this may be fewer corals than can be observed directly and evaluated for coral bleaching by eye, the effort required to conduct coral bio-optic

measurements *in situ* are balanced by the high degree of precision in the measurements. In other words, the measurements recorded are not subjective impressions made by the observer. The majority of other methodologies applied at medium spatial scales such as coral bio-optics cannot provide high precision without being time consuming (Table 2, Table 3) (Hill & Wilkinson, 2004).

(2) The technique is non-invasive. With care given to selection of corals to ensure the Spectralon can be placed on bare reef surface, and as the fibre optic cable can be held several centimetres away from the colony surface, the reef can be sampled without any physical damage. This was not used as a criterion to evaluate the other biological monitoring methodologies because physical damage to the reef is often not attributable to the equipment and not significant if SCUBA diving is done properly. However, this is a point of interest for a coral bio-optical (CBO) monitoring methodology as prior work in determining changes in pigment concentration required the use of invasive and time-consuming techniques such as high performance liquid chromatography (HPLC), thin layer chromatography (TLC) or spectrophotometry. Based on the findings of the study by Hochberg *et al.* (2006), the evaluation of the stress-spectra relationships in Chapter 3 assumes that optical properties are a predictable measure of pigment concentration. Because those results present clear circumstantial evidence of a relationship in optical properties and stress, this project is the first time that monitoring of changes in coral pigmentation has been done reliably in a non-invasive manner.

(3) Importantly, this methodology has the potential to be applied globally. It has previously been determined that the same relative abundance of photosynthetic pigments

are present in all corals, regardless of species and geographical location (Hedley & Mumby, 2002). Thus, if corals elsewhere experience similar stress, they should exhibit a similar bio-optical response. Until and unless a global reference curve could be compiled, the stress-response relationship would likely require tuning for different localities and species. Nonetheless, this could serve as the basis for evaluations of coral pigmentation around the world. The bio-optical response to other stresses (*i.e.*, not temperature) could be investigated analogously. Ultimately, if the spectrometry software was programmed to automatically produce reflectance and NDVI values, the software could also automate species-specific calibrations based on selection of the species by the end user.

4.1.2 Limitations

The present limitations to the implementation of a CBO monitoring programme include the (1) complexity of the spectrometer interface and software, (2) unknown sampling regime necessary to account for variable environmental conditions, and (3) the considerable effort required for monitoring due to the temporal scale of coral bio-optics.

(1) The most obvious limitation to widespread adoption of this tool in forming a methodology is the need for simplification of the technology so that it may be used by a diverse audience of non-experts. Without simplification, there would be high information and human resource barriers in the processing and interpretation of data, and therefore consistent evaluation of coral pigmentation. However, in order to achieve such simplification to the technology and interface, the empirical relationships between spectra and pigmentation away from normal conditions for different stresses and coral species would need to be characterised. However, these limitations were not an impediment to

the use of coral bio-optics by BIOS' CREOL in collecting data of *Porites asteroides* because the experts who helped develop of the first underwater spectrometer were on hand for assistance.

(2) In this project, as many *Porites asteroides* corals as possible were randomly selected and measured without delaying the CREOL point intercept measurements to maximize statistical confidence in determining the mean optical properties of the site's coral community. The sample variance in NDVI and reflectance from the data presented in this project as well as the data from the field collections remain to be calculated before a range in number of sampled *Porties* corals per site can be suggested for a CBO monitoring program. This would also need to be done for other species and other optical properties in future experiments. Furthermore, it is unclear what variance in optical properties is introduced by different environmental conditions, *e.g.* light and temperature with increasing depth, proximity to trace metals from a wreck, etc. If there is variance, the monitoring observer must ensure that spectra from corals under different conditions are treated separately, and to take reef conditions into consideration when comparing values from different sites. There may also be intra-annual fluctuations in coral optical properties due to seasonal changes in reef conditions (phenology) that would necessitate adjustment of expected optical properties before evaluations of coral health can be made by a CBO monitoring program. Until the relationship between reef conditions and optical properties is characterized for corals in all seasons, the resolution of CBO monitoring to reliably determine the expression of stress in corals *in situ* is limited.

(3) The results of the aquaria trials of this project demonstrate that coral pigmentation can significantly change on brief (hours to weeks) time scales. Despite the efficiency of data collection itself, to capture these changes, the design and sampling intensity of a CBO monitoring protocol must suit a high frequency of monitoring. In other words, the number of reef sites and number of corals therein will need to be modest in order to monitor the reef sites as often as possible. Instead, if monitoring not done frequently or only once, the CBO data will only be useful to compare the sample mean optical properties to expected normal values (*e.g.* reflectance ~10%, NDVI 0.6-0.8). Without weekly monitoring, the ability of the data to reveal early progression in the degree of stress affecting the reef and thus for the data to provoke management intervention is weakened.

Finally, the temporal needs of CBO monitoring make it difficult to supplement the work of monitoring programs without exceeding available resources. The task of systematically measuring a maximum number of corals and coral species across as many sites as possible within a short period of time is too much of an ambitious and costly design for most reef management programs. Once the information gaps regarding the spatial/depth variance and climatology are resolved, the most efficient protocol and effective sample size for various depths and species present at a site can be standardized. In doing so, consideration must be given to coordinating allocation of time and resources between CBO monitoring and other methodologies, because CBO monitoring cannot constitute nor replace benthic community-level monitoring.

4.2 Integration with Existing Monitoring Protocols

It is first important to state that CBO monitoring is considered a methodology of evaluating organism status as it provides information on the coral population health and species-specific processes, rather than on the whole benthic community. Rather than a methodology of measuring individual coral status independently, the greatest potential for integrating CBO monitoring within a monitoring program is to use CBO monitoring data to supplement the data collected by other benthic community or individual status monitoring methodologies. For this purpose, CBO monitoring could be carried out in systematic reef-wide monitoring surveys or as a means of localized and applied monitoring of coral health.

As was explained through the functional limitations above, CBO monitoring when conducted at multiple sites across the entire reefscape would likely not allow for the same site to be repeated often (days to weeks) and thus would not provide an opportunity to monitor changes in pigmentation health on appropriate temporal scales for intervention. However, if coral bio-optics are sampled at each site across the reef at the time of each community-level monitoring sample, a baseline of pigmentation can be mapped. Integration of coral bio-optical and community-level monitoring data across the reefscape would allow for new insights into processes affecting reef health. Once community-level data are analyzed for such sites, the combined dataset could help to better resolve the linkages between small and large scale processes (*e.g.* what trends are observable on the community-level when corals are expressing stress) and create a means of detailing the most likely cause and effects relationships behind any community-scale patterns of change. Furthermore, pigmentation data gathered by CBO monitoring could be used to calibrate community-level observations of bleaching and disease and allow for more robust estimates of the bleaching and disease health of a reef. In other words, a comparison of the estimates of bleaching and disease from CBO monitoring versus other methodologies used (transects, photo quadrats) would reveal the proportion of the coral population that is experiencing stress through optics without showing obvious signs. This proportion could be used to refine the estimates of stress affecting the reef. Lastly, if analysed in keeping with the collection of data and compared between sites, the CBO monitoring data could provide an indication of sites where corals are presently experiencing significantly higher or lower stresses.

In the case that corals are found to express significantly different levels of pigmentation health between sites through the use of reef surveys, or if there is a particular site of interest, CBO monitoring can be applied on a localized scale to monitor changes in the coral optical signatures of a particular reef over time. A smaller focus such as this would relax spatial and temporal limitations to allow for continual CBO monitoring while still providing benefit to reef managers. If used to subsequently monitor a reef found to be comparatively healthy, coral bio-optical data can evaluate the resilience of corals over time and be used to support the protection of such areas of reef by management. Alternatively, if used to closely monitor a site where corals are expressing signs of stress, and if the relationships between optic properties and environmental conditions are known (Section 4.1.2), coral bio-optical data measured at set distance intervals can potentially determine the extent and source of the stress. Furthermore, the success of interventions could then be evaluated by monitoring previously tagged corals. Finally, the potential also exists for managers to use CBO monitoring on localized scales to evaluate the differences in pigmentation health between sites to support site selection for other extractive and non-extractive marine uses, such as diving, resource extraction, and shipping routes. The full potential of CBO monitoring to support management decisions is discussed in the following chapter.

Chapter 5. Evaluation of Coral Bio-Optic Monitoring as a Component of Reef Management

The previous chapter has highlighted the scientific rigor and merits of incorporating coral bio-optics within coral reef monitoring (*e.g.* a more effective and globally-systematic manner of collecting monitoring data, that can lead to a more informative dataset). However, the adoption of this tool and protocol may prove most worthwhile through the direct benefits of CBO monitoring to reef management. Two major qualities of CBO monitoring make it a desirable addition to existing monitoring programs that support reef management actions. First, because the spectrometer provides such precise information about coral pigmentation, the spectrometer allows smaller changes in pigmentation health to be detected than through observations made by the naked eye. The aquaria trials conducted and reported in Chapter 3, especially with regards to changes in NDVI, supported this advantage of the technology. Thus, the use of a spectrometer may be a superior method for detecting the onset of coral thermal stress than colouration charts or photography. Second, because routine CBO monitoring would reveal the onset of changes in reef health expressed by corals earlier than other monitoring methodologies, it is possible to use CBO monitoring to detect stresses to a reef likely while they are still present, as opposed to after-the-fact change detection. This is supported by the fact that the majority of indicators used to make assessments of reef health are correlated to processes acting on the scale of years or greater, whereas indicators linked to coral pigmentation would inform on changes occurring on the scale of days to months (Table 1). This begs the question of how management might benefit from a precise quantitative data set that reveals changes on short time scales. Based on the discussion in Chapter 2, the reasons that reef management has generally been limited in arresting reef decline can be said to result from the delayed time scale on which monitoring has been traditionally conducted and the use of simple indirect indicators. Therefore, these two qualities make CBO monitoring unique in presenting managers with the opportunity to be proactive: earlier detection and thus earlier or more targeted management actions could prevent or mitigate coral decline rather than try to reverse it.

Remaining for discussion is whether management can be mobilized to respond and intervene on short notice, and what possible actions could constitute proactive intervention. Of all ways that management may be capable of acting proactively, there are two fundamental limitations that arise. Inherently, effective actions will only be those that can be implemented on temporal scales that match those of reef degradation processes. In other words, actions intended to address a stress must come into play while the stress is still acting and before health thresholds are passed. For example, it may be relatively easy to declare an area off-limits to recreational and commercial users when CBO monitoring reveals high levels of stress. However, the process of physically and legally enforcing the protection may be too delayed in order for the proactive insight of CBO monitoring to remain relevant. Secondly, the need for rapid response ultimately constrains the potential management actions to addressing local sources of stress rather than buffering larger anthropogenic stresses such as ocean acidification and expansion, as these have proven to be far beyond the grasp of a single government within a short time frame. For example, the detection through CBO monitoring that corals are experiencing thermal stress at otherwise undetectable levels will not prove useful to managers in acting to reduce warming sea surface temperatures. Instead, CBO monitoring could create early awareness among managers (and government) to the weakened reef state and create more impetus to address other local sources of pollution than if the corals are found to be already significantly degraded. In the case of thermal stress, action to alleviate other stresses could reduce the severity of the later bleaching event by improving the resilience of the corals. Therefore, the ability for CBO monitoring to support only relatively easily and rapidly implemented actions for local stresses is not necessarily a limitation of this monitoring tool and protocol. In fact, it is a clear requirement for the future direction of coral management: addressing and reducing local impacts can 'buy time' for corals to address the inevitable large-scale changes that will come from a warming climate (Burke *et al.*, 2012). Beyond these considerations of spatial and temporal scale, if and how management can act on these time scales will be primarily governed by (1) the real-time information about reef stresses provided by coral bio-optic monitoring, (2) the existing regulatory, policy and legal frameworks and (3) the capacity of the policy implementation system to respond effectively to real-time information.

Information gained from bio-optical monitoring can allow management to form directed, proactive actions because trends can (1) be seen prior to severe coral health degradation, (2) likely differentiate the response to certain stressors, and (3) be present across fine spatial scales**.** The early detection of coral stress (1) is a benefit to management because it may reduce the intensity of intervention necessary to improve reef health. Otherwise, if acting after ecological health thresholds are passed, management solutions would require greater resources, likely require greater time for the effects to be seen, and need to be more stringent in restricting reef uses in order to return to the healthy reef state. Furthermore, sudden and stronger restrictions placed on the marine users would reduce compliance and thus also effectiveness of the management actions. If particular deviations in coral optical signatures can be attributed to particular stressors (2), *e.g.* changes in the reflectance peaks of chlorophyll-a are only characteristic of bleaching stress, it may be possible to determine what stresses are affecting the corals of a given reef based on their combined expression in the optical signature. Although this was not demonstrated in the data of this project, it is thought that the coral optical signature is such an intricate interaction of multiple pigment concentrations that it has the potential to show significantly different response in individual pigments and pigment degradation products to different stressors (Eric Hochberg, personal communication; Hochberg *et al.*, 2006**)**. Practically, this may increase the feasibility of improving local reef health by clarifying the stresses present within a local management area and simplifying management decisions to address only those. A more tailored management response will increase the action's time-efficiency so as to match the temporal scale resolution of the CBO monitoring. Thirdly, it is of further benefit to management to detect specific sources of stress on small scales (3) as they would otherwise go unnoticed by monitoring methodologies until they caused community-scale damage, making the task of management intervention significantly larger and requiring more resources. Small-scale resolution in stress to corals is possible to attain through CBO monitoring if the optical signatures of coral colonies vary consistently and significantly between two locations (*e.g.* corals at 500m, 300m, 100m, and 50m away from shore show a consistent change in optical signature). In this case, it may be possible to hone in on the more 'unhealthy' coral optical signature of the coastal colonies to a localized stressor, like a point source of coastal runoff. The ability to pin point sources of stress facilitates and quickens management response as it would be possible to prioritize each stressor source rather than address all suspected sources in a generalized plan of action (*i.e.* not all sources of runoff may be known or have equally strong an effect on the reef). Unfortunately, exploring spatial relationships was not within the scope of this project's field trials. However, if the relationship between a particular stress and coral optical signature (2) can be distinguished between stress and *also* be seen to vary spatially (3), CBO monitoring would be of great potential to marine spatial planning applications of marine management. If it is known through spatial trends in optical signature how far from a localized source of stress the reef is impacted (*e.g.* 1km radius), then decisions can be sufficiently informed on where the placement of that source of stress will have the least effect on a particular reef of interest (*e.g.* where to place a shipping lane), or which sources of stresses need to be addressed to ensure a nearby area of protected reef is not affected (*e.g.* whether shipping lanes should be moved outside the reef).

These practical and localized implications of CBO monitoring information suggest management actions can be tailored to make a rapid intervention possible and resource-effective. However, the potential political implications of executing such measures are dictated by the priority placed by the government on conservation of the reef environment and willingness to act on the findings of reef research and monitoring. The strength and commitment of government to coral reef conservation is exemplified by the thoroughness and adaptive capacity of the coastal and marine policies and regulatory frameworks, and the integration of stakeholder and environmental considerations within these (International Coral Reef Initiative, 1995). Because implications of CBO monitoring include added foresight and precision of action focus to reef managers, CBO monitoring could provide support and renew commitment for environmental policy decisions and initiatives while minimizing the degree to which other national marine priorities are compromised.

If CBO monitoring can refine the scale of the suspected stress's impact, differentiate the relationship between stress and optical signature for multiple stresses, or resolve the presence of stresses on small scales, policies informed by CBO monitoring could become more accommodating to reef stakeholders or be tailored to political boundaries. For example, if a decline in reef health (*e.g.* algal overgrowth, low coral cover, and sparse fish) is assumed through other monitoring methods to be correlated to fishing pressure (a particular stress), the use of coral bio-optics could potentially confirm that there are no other substantive stresses acting on the coral component of the community. If it is determined that in fact sedimentation (a different particular stress) is the cause of the decline, then proper management intervention would be more assured. In this example, policy implications of this new, stressor-specific information could allow fisheries to reopen once the sedimentation was addressed.

Insights into the spatial resolutions of certain stressors could allow for tailored marine spatial planning, coastal planning and development. The most likely policy implication is that, because the optical measurements are likely able to distinguish pigmentation changes specifically due to nutrification (Hedley & Mumby, 2002), coral bio-optics will have the ability to strengthen policy on coastal water quality. For example, 'unhealthy' coral optical signatures may be attributed to nutrient loading near populated coasts. This information could be used in the short term to intervene locally and rapidly, but also as a basis for supporting improvements in coastal pollution policies to better address non-point sources of pollution in the long-term.

5.1 Bermuda Context

It is of value to identify the frameworks and initiatives and their associated gaps that might be strengthened or informed by practical implications of CBO monitoring in the context of an individual country. This context is provided for the islands of Bermuda because the technology is already available and in use, and because Bermuda has unique environmental, socio-economic, and legislative characteristics.

The islands of Bermuda form a populated atoll-like landmass of roughly 55 km^2 in the North Atlantic. Due to close proximity to the Gulf Stream, the limestone islands are surrounded by nearly one thousand kilometres of reef platform which make Bermuda host to the northernmost coral reefs in the Atlantic. Biogeographically, Bermuda is considered part of the Caribbean despite being 1350 km northeast of the Bahamas. In contrast to the wider Caribbean, Bermuda's reefs appear to have coped well in the face of human population pressure, coral bleaching, and coral diseases. Similarly to the Turks and Caicos Islands and Cayman Islands, Bermuda has a strong economy routed in international business, finance and marine tourism, which promotes a high perceived value in reef-based goods and services (Bermuda Government Department of Conservation Services, 2010), and a high conservation ethic (Creary *et al.*, 2008; Government of Bermuda Ministry of Environment, 2005). However, economic and tourism growth over the past 25 years has made Bermuda an exceptionally densely populated country, where no point is further than 1.5 km from the shore, and has introduced high pressures to the reef environment and marine resources.

Despite Bermuda's adoption of policies to conserve its marine environment and resources over the years, threats to Bermuda's reefs have persisted primarily from coastal development, waste disposal, and fishing pressure (Government of Bermuda, 2005). The earliest piece of marine legislation to manage the human uses of Bermuda's reef is the Fisheries Act of 1972, followed subsequently by the Fisheries (Protected Species) Order 1978, Fisheries (Use of Fishing Nets) Order 1990, Fisheries (Protected Areas) Order 2000 and the Black Grouper Notice (2011). Although the Fisheries (Protected Species) Order 1987, Black Grouper Notice and their multiple amendments protect (no-take) 21 species of fish, coral and molluscs, most fisheries management has been on the regulation of input controls (permits and gear restrictions), not output nor outcome controls. Furthermore, Bermuda's Development and Planning Act 1974 does not include legislation for developments that originate in the water, such as the designation and alteration of the seabed for shipping routes including dredging (Development and Planning Act, 1974; Government of Bermuda Department of Conservation Services, 2010). Nor is there a process for assessing damages to the marine environment from coastal developments (Bermuda Government Department of Conservation Services, 2010). The continued presence of these threats are the result of the 'lack of formal procedure when "planning" or "developing" in the marine environment, and the absence of a mechanism for integrating environmental values into those decisions' (Bermuda Government Department of Conservation Services, 2010, p. xii).

In 2000, recognition of these shortcomings rapidly grew with the release of the Green Paper on Marine Resources and Fishing Industry in Bermuda by the Ministry of the Environment. The vociferous positive response of Bermudians to the Green Paper lead to a renewed commitment of the Ministry toward sustainable resource management using conservative and comprehensive approaches, released as the 2005 White Paper on The Marine Environment and Fishing Industry in Bermuda (Government of Bermuda Ministry of the Environment, 2005). This spurred two further major developments. First, under direction of a new minister, the Department of Environmental Protection built on the intentions of the government outlined in the White Paper by releasing a 15-year strategic plan for the management of Bermuda's marine resources in early 2010. With the majority of focus placed on fisheries, it also echoed the goals of promoting healthy reef ecosystems and ensuring stakeholder representation within the decision making process. Then, also in 2010, the Department of Conservation released a total economic valuation of Bermuda's reefs, which was estimated at $722 million annually (USD 2007). In combination with the various amendments to the Fisheries Act, this body of policy and legislative work demonstrates that Bermuda has gapped more holes in managing their marine activities in the past 12 years than ever before.

However, the *Total Economic Value of Bermuda's Coral Reefs, Valuation of Ecosystem Services* (TEV) (2010) found that threats to reefs remain: coastal development, and cruise industry-related vessel traffic tourism. On the basis of these findings, several policy recommendations were made. At the 2011 Throne Speech made on November 4th, 2010, the Government expressed their commitment and underscored the importance of fulfilling these recommendations:

> "Madam President and Members of the Senate, Mr. Speaker and Members of the House of Assembly, the environmental miracle of Bermuda's coral reefs must be preserved. During this Session the Legislature will be invited to take note of a report entitled "A Summary of the Economic Valuation of Bermuda's Coral Reefs" prepared by the Department of Conservation Services. The Government will lead the development of sustainable coral reef management, prioritising the passage of legislation specific to marine ecosystems" (Hugh Turton Gozney, 2010, para 22).

The four recommendations made in the TEV are to (1) 'prioritize potential policy interventions in an economically sound manner', (2) 'make use of the cultural importance residents place on marine ecosystems to improve coral reef management', (3) 'actively involve the tourism industry in the development of sustainable coral reef management', and (4) 'balance consumptive and non-consumptive uses of coral reefs by strategizing spatial management and protecting critical marine areas' (Government of Bermuda Department of Conservation Services, 2010,). These are discussed at length in conjunction with five explicit needs of coral reef management and research to support the TEV, the first being the need for "monitoring and early detection of natural/human-induced changes" (Government of Bermuda Department of Conservation Services, 2010, p. xvi). The document also supported the notion that there is a strong conservation ethic in Bermuda on the basis that Bermudian residents, as well as tourists, are willing to pay a combined total of $53 million for efforts that "maintain/improve coral reef quality, avoid swimming restrictions, increase fish catch, and maintain/improve water clarity" (Government of Bermuda Department of Conservation Services, 2010, p. xxiii). This document is the most recent development in Bermuda's efforts toward comprehensive marine and environmental management, and it is likely to prove an extremely powerful tool for decision-support in future marine and/or coastal developments in such a financially minded country. Because the government has stated it plans to adapt policy in these ways, and because CBO has genuine potential to meet this management need, the discussion of the ability of CBO monitoring to provide management decision support for the control of human activities in and around Bermudian waters will begin with consideration for how it may support the new policy applications of the TEV.

The first recommendation for how the TEV is applied to policy can be rephrased to suggest that the value of marine environment to the economy lost by future coastal developments must be considered and used as a primary basis for policy interventions. Strategic environmental assessments (SEA) are recommended such that developments in the marine environment that are currently under no planning guidelines can be evaluated for potential loss of valuable goods and services. If losses are high, it is suggested that cost-benefit analyses would be executed in order to determine whether the damages to the environment are economically sound. It is also suggested that a damage cost procedure be established to recuperate some of these costs.

There are avenues for CBO to assist in supporting both the assessment of damages for SEAs and the damage cost procedure. In conducting SEAs for a proposed coastal or marine development near reefs, CBO monitoring could be used to evaluate comparable sites with existing stresses from similar developments versus the current state of coral at the desired area of development. This would provide an indication of the potential degradation caused by the stress from the coastal development, which could then be included in the cost-benefit analysis as value lost by percentage of total reef area.

Alternatively, such as in the choice of routes for larger cruise ships, if the spatial relationship between stress source and the expression of stress in corals is known, CBO monitoring can be used to determine the relative health of corals at various reef locations and determine the location for development which would implicate the loss of the least reef-related economic value. In supporting the damage cost procedure, if CBO monitoring is used routinely throughout the Bermuda platform as part of the CREOL reefscape surveys, a baseline of coral pigmentation would exist, against which other corals could be compared to determine stress level, and thus help form an estimate of reef value lost.

The application of CBO monitoring to the other policy applications of the TEV is not as direct as the first. Both the second and third recommendations regarding the intrinsic value of coral reefs perceived by residents and the involvement of the tourism industry, respectively, relate to the acquisition of donations, grants, and funds to support coral reef management based on the willingness of tourists and residents to pay to preserve and improve the marine environment (Government of Bermuda Department of Conservation Services, 2010). CBO monitoring can at once be considered an aspect of reef management effort that is in need of funding as well as deserving of funding as it represents a means of preserving and improving the marine environment by its ability to resolve and address human-induced stresses. Alternatively, CBO monitoring could be used to make use of the estimated $53 million (USD 2007) to pinpoint previously unnoticed sources of human-induced stress, especially those affecting water quality and clarity such as sewage, and address and eliminate them systematically.

CBO monitoring could be used as indirect support for application of the fourth and final TEV recommendation to policy. As stated in Chapter 3, the management applications of CBO monitoring can be used to portray spatial differences in coral stress, and thereby inform marine spatial management and marine protected areas (MPAs). As such, CBO monitoring can help determine the areas where the greatest balance of consumptive versus non-consumptive revenues would be achieved. Presumably, the areas with consistently moderate to low stress would support greater consumptive uses, whereas areas with corals under moderate to high stress would be best to recover in areas designated for non-consumptive uses or be fully protected. As CBO monitoring resolves trends on short time scales, these designations could be adjusted seasonally.

5.2 International Context

If CBO monitoring is adopted as part of a regional monitoring program, the precision of the technology may allow for added confidence in changes to the regulation of marine activities areas within regional seas that would require international cooperation, such as the establishment of trans-boundary MPAs or amendments to a regional fisheries management organization (RFMO). Although it is managed solely by the United States, there is the potential of reef monitoring to inform the Western Pacific Regional Fishery Management Council, as two of that RFMO's guiding principles are to "promote an ecosystem approach in fisheries management, including reducing waste in fisheries and minimizing impacts on marine habitat and impacts on protected species" and to "encourage development of technologies and methods to achieve the most effective level of monitoring" (Western Pacific Regional Fishery Management Council, n.d).

Beyond the ability for CBO monitoring to act as a decision-support tool for local governments, international adoption of CBO monitoring could benefit global reef management most directly by supplementing the on-going worldwide reef assessments. For example, the Reefs at Risk project evaluates and publishes the relative risk to all reefs in the world from local anthropogenic stresses. This involves the contribution and support from dozens of international management organizations and monitoring programs. Should data from CBO monitoring be part of the data provided, these evaluations of total threat may become more precise and improve the basis on which the data can be integrated. Furthermore, in summary reef assessment documents such as *Reefs at Risk: Summary for Decision Makers* (Burke, Reytar, Spalding & Perry, 2012)*,* CBO monitoring could be advocated as a tool for local managers to identify and reduce the sources of threat from marine-based pollution and damage, coastal development and watershed-based pollution if they are expressed in coral pigmentation.

Chapter 6. Recommendations and Conclusions

Coral bio-optics has been evaluated in three components. (1) The potential use of coral bio-optics as a tool for the measurement and monitoring of coral pigmentation has been evaluated in terms of its scientific rigor and technological considerations. (2) The merits and limitations of measuring coral bio-optics in the field as part of a reef monitoring methodology have been presented. (3) Based on this information, the ways in which CBO monitoring could inform and benefit coral reef management in Bermuda and internationally has been discussed. The outcomes of these evaluations and discussions are summarized in the following section, followed by recommendations for how each of these components can be actualized.

6.1 Coral Bio-Optics as a Monitoring Tool and New Protocol

In the course of the aquaria experiments, it was found that the underwater spectrometer could uninvasively detect precise changes of as little as 3% reflectance due to bleaching, and that the normalized difference vegetation index (NDVI) provided a reliable means of documenting increasing bleaching stress before paling was visible to the eye. Thus the underwater spectrometer can be considered precise and predictive despite **not** clearly demonstrating the relationships between reflectance and stress. It is possible that some of the sources of error affecting the demonstration of these relationships could be eliminated through the use of newer technology, the cost of which can be considered affordable to managers. On the basis of these results, there is no reason to suggest that coral bio-optics is not an apt tool for measuring coral pigmentation and that it has good potential to indirectly but reliably measure the stresses to zooxanthellate corals that are expressed as a change in pigmentation. Before monitoring programs use CBO to evaluate coral stress, however, experiments must clearly demonstrate decreases in reflectance under nutrification conditions and an increase in reflectance under bleaching conditions in the future.

Over the course of field experiments, conducting coral bio-optical monitoring alongside other monitoring methodologies was possible and beneficial to the collective data set. Due to measurement time and spatial replication requirements, CBO monitoring does have logistical limitations. Nevertheless, CBO monitoring is suited to supplement transects or other medium-scale monitoring methodologies as a means to determine variability in coral pigmentation across different species, reef habitats and locations. However, closely monitoring small areas with CBO methods, such as investigating the presence or extent of known stressors at predetermined sites, is likely what will make CBO monitoring of most value: these are the applications that can directly affect management decisions.

6.2 Recommendations

CBO monitoring has a strong potential to improve reef research, enhance the compatibility of international monitoring practises, and to encourage proactive, solution-focused management decisions. In light of these positive outcomes, the following recommendations are made:

(1) Expand the underlying scientific knowledge of coral bio-optics;

(2) Simplify the technology so that it is accessible to non-experts;

(3) Implement CBO monitoring as a supplement to reefscape surveys; and

(4) Determine the spatial relationships between spectra and stress.

(1) Expand Underlying Scientific Knowledge of Coral Bio-Optics

Optical data (reflectance and indices such as NDVI) should be collected for corals undergoing the full progression of stress to provide a baseline against which to compare data from stressed corals. In addition to bleaching and nutrification, relationships between optics and other stresses should be investigated, such as disease and sedimentation. It is important that managers use CBO monitoring to develop a database of the coral optical properties exhibited in various coral species, environmental conditions, and across reef types (*e.g.* rim reef, patch reef). A natural progression of this study would be to determine the differences in optical signature demonstrated in *Porites lobata* compared to these optical signatures in *Porites asteroides*. Because *Porites spp.* are nearly universal, the characterisation of the optical properties of the *P.lobata* would allow Pacific monitoring programs to begin evaluating reef health, while also potentially revealing geographical variations in optical signature.

(2) Simplify Technology of Underwater Spectrometry

Reef managers and researchers should seek out partnerships with industry experts and businesses to develop a spectrometer user interface and analysis software for the newest mini spectrometers so that non-experts can effectively utilize bio-optical techniques. The software and interface should allow the manager to conduct analyses of an optical signature instantaneously, reducing the time and knowledge required to process the data, as well as eliminating the need for a central data processing centre.

(3) Implement CBO monitoring as a supplement to reefscape surveys

Laboratory trials should be conducted to build suitable stress-response data sets, but the collection of data in the field can begin in the meantime, especially in Bermuda where the underwater spectrometer prototype exists. In the short-term, coral bio-optic data can be collected at sites where other biological monitoring methodologies are simultaneously being used. In the medium-term, the CBO monitoring data can be analysed to reveal variability in optical properties between and within sites, which can then allow for sites of suspected higher stress or of interest to be flagged and monitoring more closely thereafter. In the long-term, changes in optical properties can be correlated with trends observed in the benthic community, and the data can help resolve the empirical relationships between variable species and stresses, as listed in (1).

(3) Determine the spatial relationships between spectra and stress

It is important to know the distance from a source of stress at which point the bio-optical stress response is no longer expressed. The collection of data for this purpose does not require a complete scientific knowledge of coral bio-optics. As was just explained, local areas of suspected stress can be determined through comparisons to other sites and then monitored using a sampling spatial pattern. Alternatively, corals at incremental distances away from a known source of pollution or disturbance (*e.g.*

sewage outfall) could be monitored. Trends may not be apparent until the coral optical expression of the stress in question is well understood, but the data can contribute to developing the database discussed in (1) (*i.e.* resolving these relationships by supplementing any data collected in aquaria).

In Bermuda there exists a need for CBO monitoring to be used to evaluate the level of nutrification stress as soon as possible: the Reefs at Risk determined Bermuda's reefs to be under high threat, but the spatial extent of the impact of sewage disposal in Bermuda remains unclear. This could be evaluated once the spatial relationships between coral optical spectra and nutrification are clear. To facilitate support from government and thus the time scale on which solutions are implemented, it is recommended that CBO monitoring be used to investigate the relationships that would inform policy such as coastal development and marine spatial planning. For example, a move to investigate sewage with CBO monitoring in Bermuda is supported by the government commitment to implement the TEV's recommendations, because the CBO monitoring findings can improve how SEAs are conducted. It is also important that sources of funding be prepared in order to alleviate delay in the implementation of solutions and thus to keep with the temporal scale of the stress's progression. In keeping with the prior example, should there be an impact of septic tanks on nutrification stress to corals, funding to update the septic system of private homeowners might be possible as the TEV found that residents have a willingness to pay for improvements to water clarity and quality.

6.3 Conclusions

It is clear that there can be immediate applications of the CBO monitoring and the associated technology that would greatly benefit and inform management. The sum of this project finds many limitations to such an immediate adoption but no indication that the necessary advances in coral bio-optical science and technology are not possible. Instead, although this tool cannot prevent large-scale threats such as ocean acidification, nor can it address the complex challenges of coral reef governance and coastal zone management economics, it appears as though the application of coral bio-optics to coral reef management in identifying local threats and monitoring the effectiveness of management interventions may constitute a considerable beacon of hope for the future.

> "Reducing local pressures on reefs—overfishing, coastal development, and pollution— is the best way to "buy time" for reefs. Doing so would help reefs survive warming seas and ocean acidification while the global community works to reduce greenhouse gas emissions, particularly carbon dioxide."
> - *Reefs at Risk Revisited* (Burke *et al.*, 2012, p.2)

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