Data Collection for the Southeast Florida Action Network (SEAFAN) to Assess Reef Conditions Before and During the 2015 Coral Disease Outbreak

Florida Department of Environmental Protection
Coral Reef Conservation Program
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Florida Department of Environmental Protection

Data Collection for the Southeast Florida Action Network (SEAFAN) to Assess Reef Conditions Before and During the 2014–2015 Coral Disease Outbreak

Final Report

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Cover Photo: Esther C. Peters, Pathobiology Consulting Services

Executive Summary

The Southeast Florida Action Network (SEAFAN) received numerous reports from citizens, scientists, and agency staff concerning the loss of tissue from multiple stony coral species, beginning in the fall of 2015 as the corals were recovering from a severe bleaching event the previous summer, and continuing into 2016. A study to comprehensively understand the extent, severity, and contributions of diverse environmental factors that may have led to this event was initiated by the Florida Department of Environmental Protection Coral Reef Conservation Program. Many sources of data about the marine environment and biota in the northern Florida Reef Tract (north of Biscayne National Park to St. Lucie Inlet) were identified by staff and members of the Southeast Florida Coral Reef Initiative's Technical Advisory Committee in April 2016. The period to be examined included the years 2012–2013 (when coral disease reports were minimal) and 2014–2015 (peak reporting years). Research assistants contacted data owners (agencies, scientists, nongovernmental organizations) and obtained datasets. Information about the data (metadata) was entered into a spreadsheet and data files were catalogued and archived for future access. In the future, multiple analyses may be performed by statisticians and epidemiologists to examine the conditions that might have led to the disease outbreak and to identify data gaps and monitoring needs that can improve the conservation of these valuable coral reefs.

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List of Acronyms

AOML	Atlantic Oceanographic and Meterological Laboratory
BNP	Biscayne National Park
CADDIS	Causal Analysis/Diagnosis and Decision Information System
CRCP	Coral Reef Conservation Program
DOI	Digital object identifier
FAU	Florida Atlantic University
FDEP	Florida Department of Environmental Protection
FRRP	Florida Reef Resilience Program
FRT	Florida Reef Tract
FWC	Florida Fish and Wildlife Conservation Commission
FWRI	Florida Wildlife Research Institute
GIS	Geographic information systems
LAS	Local action strategies
MARES	Marine and Estuarine Goal Setting for South Florida
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NSU	NOVA Southeastern University
QA	Quality assurance
QC	Quality control
RSMAS	Rosenstiel School of Marine and Atmospheric Science
SEAFAN	Southeast Florida Action Network
SECREMP	Southeast Florida Coral Reef Evaluation and Monitoring Program
SEFCRI	Southeast Florida Coral Reef Initiative
TAC	Technical Advisory Committee
TNC	The Nature Conservancy
UM	University of Miami
URL	Universal resource locator
USACE	United States Army Corps of Engineers
USCRTF	United States Coral Reef Task Force
USF	University of South Florida
USGS	United States Geological Survey
WP	White plague

1. INTRODUCTION

The Florida Reef Tract (FRT) is the third largest barrier reef system in the world and extends from the Dry Tortugas to St. Lucie Inlet in Martin County. The northern portion of the FRT [Biscayne National Park (BNP) to St. Lucie Inlet] runs parallel to the southeast Florida coast, a heavily urbanized shoreline with the population of residents estimated to be at least 6 million (Office of Economic and Demographic Research, 2015) and visited by tens of millions of tourists each year (Satchell, 2016). These reefs support diverse species of tropical western Atlantic ocean-dwelling algae, invertebrates, fishes, sea turtles, and marine mammals in seasonally cooler waters than those of the Florida Keys reef. The scleractinian coral colonies appear to be more sparsely distributed than in the Florida Keys, except for extensive thickets of the staghorn coral, *Acropora cervicornis* (Banks et al., 2008), one of six corals, listed as threatened under the U.S. Endangered Species Act [National Oceanic and Atmospheric Administration (NOAA), 2016].

Reefs in the northern FRT and elsewhere face serious threats. In addition to local impacts (e.g., sewage and chemical discharges, vessel groundings, marine debris, beach nourishment, dredging, and overfishing), regional and global changes in seawater temperatures and pH have been more of concern in recent years. These stressors can damage reef structure and cause morbidities or mortalities of the organisms, altering habitats and ecosystem functions that will adversely affect the humans who depend on them for their livelihoods (Carpenter et al., 2008; Nuttle & Fletcher, 2013). The U.S. Coral Reef Task Force (USCRTF) adopted a National Action Plan in 2000 to conserve coral reefs by implementing efforts to understand coral reef ecosystems and reduce the adverse impacts of human activities (http://www.fws.gov/coralreef/CRTFAxnPlan9. PDF).

In 2003, with guidance from the USCRTF, the Florida Department of Environmental Protection (FDEP) and the Florida Fish and Wildlife Conservation Commission (FWC) coordinated the formation of a team of interagency marine resource professionals (state, regional, local, and federal), scientists and other stakeholders, known as the Southeast Florida Coral Reef Initiative (SEFCRI). This team came together to develop local action strategies (LAS) for the conservation and management of coral reefs and associated reef resources from Miami-Dade, Broward, Palm Beach, and Martin counties.

1.1. Background

One of the first LAS for SEFCRI was to develop the Southeast Florida Action Network (SEAFAN) to improve protection and management of these reefs using a reporting and response system to collect observations made by citizens (divers, snorkelers, boaters, fishers) and agency personnel (researchers, law enforcement, managers). Programs may be planned and implemented to address the reported problems and coordinate responses, for example, removing marine debris, stabilizing ship grounding damage for reef restoration, or investigating other “marine events” affecting the reefs. In August, September, and October 2014, numerous sightings of bleaching corals were reported to SEAFAN. Bleaching, the loss of the coral’s symbiotic algae (known as zooxanthellae) or their pigments, results in the coral colonies turning white as the white skeleton shows through the translucent coral tissue when the brown color of the zooxanthellae disappears (Glynn, 1996; Jones, 1997). Zooxanthellae play a key role in coral metabolism and calcification. The algae use carbon dioxide and nitrogen wastes produced by the coral when exposed to sunlight to photosynthesize and provide the coral with oxygen and nutrients. This symbiotic relationship can be impaired when the coral is exposed to adverse environmental conditions, such as low or high salinity, light levels, or seawater temperatures. Either or both the zooxanthellae and coral polyps might be stressed and can no longer contribute to the intricate and beneficial cycling of gases and nutrients. The zooxanthellae can be expelled from the coral's cells, die within the coral's cells, or the gastrodermal cells containing the zooxanthellae might slough off (Basti, Bricknell, Beane, & Bouchard, 2009). Coral bleaching events have recently been linked to exposure to higher than normal seawater temperatures for prolonged periods in late summer (Kuffner, Lidz, Hudson, & Anderson, 2014). Prior to this bleaching event, dredging to widen and deepen the Port of Miami shipping channel began in November 2013. The dredging resulted in widespread turbidity plumes that reduced water clarity and light quality reaching benthic organisms, as well as increasing sediment particle loading on surfaces through the winter of 2014 (Barnes et al., 2016).

Cases of tissue loss, in which the normally brown-pigmented tissue disappeared from the skeleton leaving it stark white, were also reported to affect several species of scleractinian corals in fall of 2014 near Key Biscayne and elsewhere in the region. This pattern of tissue loss resembled the coral disease known as white plague (WP) (Richardson et al., 1998a; Bythell, Pantos, & Richardson, 2004; Weil & Rogers, 2011). The disease outbreak continued into 2015 and increased in frequency and severity during the summer months. Additional surveys conducted by scientists and agencies—such as the Florida Fish and Wildlife Conservation Commission (FWC), Florida Wildlife Research Institute's (FWRI) Southeast Florida Coral Reef Evaluation and Monitoring Program (SECREMP), and The Nature Conservancy's (TNC) Florida Reef Resilience Program (FRRP)—revealed that a high proportion of coral species were losing tissue, sometimes associated with bleaching (cover photo), with partial to complete mortalities. Octocorals and sponges were also noted to be diseased. This disease outbreak was initially observed in Miami-Dade County, and reports later came in from Broward and Palm Beach counties.

Coral bleaching and tissue loss are both types of diseases impairing the affected organism's structure and function (Oxford Dictionaries, 2016). These diseases may be influenced by both biotic (viruses, microorganisms) and abiotic (physical and chemical) factors that are pathogens (causing disease) (Peters, 2016). It is important to understand what factor(s) may have caused the unprecedented outbreak on the northern FRT and whether all necessary data were collected on the environmental factors that may have contributed to it. Although early disease investigations usually followed Koch's postulates (Koch, 1882) to establish one culturable pathogenic microorganism causing a disease, recent research has shown that these are inadequate and that many diseases may be multifactorial in nature, involving interactions among infectious and noninfectious pathogens (Thrusfield, 2016a). Epidemiology, the study of disease, can aid in determining the cause (etiology) of a disease and its ecology to manage or control it and assess the economic impacts of the disease (Thrusfield, 2016b). In this case, the data will be used to test the hypothesis that certain environmental conditions recently changed on the northern FRT, thus causing the outbreak of coral diseases.

1.2. Study Goal

The goal was to obtain datasets and information from diverse sources that were collected on environmental conditions and organisms of the northern FRT before (2012–2013) and during (2014–2015) the coral bleaching and tissue loss outbreak events for later epidemiological analyses. The comparisons of available data from these time periods will help the FDEP Coral Reef Conservation Program (CRCP) and the public understand the events, whether any acute or chronic exposures to adverse environmental conditions or activities occurred that may have led to the loss of coral colonies in this area, and whether any additional data or information should have been collected that might help FDEP and FWC provide improved evaluations and recommend management actions in the future. This study meets the following high priority FRT management needs:

- Characterize physical and chemical changes in coral reef environments by enhancing and refining monitoring to fill gaps in our current observations. This both establishes a baseline to assess climate change impacts on coral reef ecosystems and reveals changes through time which are essential to understanding observed and forecasted impacts.

- Identify areas of perceived resilience and areas of high vulnerability (which may or may not contain high coral cover/abundance) within the FRT and provide additional protection to those areas via appropriate marine zoning and reduction of existing stressors.

- Identify, characterize and rank priority areas for protection within each jurisdiction, including (but not limited to): spawning site, nursery habitats, or other areas critical to particular life-history stages; biodiversity hotspots; areas with greatest resilience or potential for restoring resilience; areas facing the greatest threats.

- Identify and prioritize those coral reef ecosystems that will benefit the most from implementing management conservation strategies to reduce land-based sources of pollution.

- Create a full inventory of status, trends and threats to coral reef resources across the entire FRT within five years.

- Promote conservation of coral reef ecosystems through identification of areas that are potentially resilient to climate change and vulnerable areas where actions are likely to increase resistance. Encourage and promote management actions necessary to avoid or minimize impacts and spread the risk due to climate change and ocean acidification.

This data collection effort will provide resource managers the materials needed to evaluate any changes in environmental conditions, the exposure of corals and other reef organisms to stressors affecting their health, and ultimately, the health of the human population of southeast Florida.

2. METHODS

Several efforts were undertaken to locate as much data as possible on environmental factors, coral populations, biodiversity, habitat, and major marine events from the northern FRT during the period of January 1, 2012–December 31, 2015, and to assess their usability for the study.

2.1. Data Sources

The first task was to compile a list of agencies, university researchers, nongovernmental organizations (NGOs), and others who might have collected such data from sites on the FRT. FDEP provided a list of known ongoing monitoring and research programs and local agencies.

In an effort to identify other data sources, SEFCRI's Technical Advisory Committee (TAC) was engaged during the April 2016 meeting. The TAC is a body of selected professional scientists, reef managers, and technical experts with expertise in the reef environment, specifically in southeast Florida. The TAC was informed about the disease outbreak in the region and a brief overview of this study. Kristi Kerrigan (FDEP) provided a summary of key dates when observations of corals affected by tissue loss disease increased during the fall of 2014, researchers became involved, and monitoring programs were initiated. She was followed by Dave Gilliam (Nova Southeastern University, NSU) presenting an update on SECREMP, James Byrne (TNC) explaining the results of FRRP's Disturbance Response Monitoring after the 2014 bleaching event, and Brian Walker (NSU) discussing the large coral assessment underway. In the afternoon, Esther Peters (George Mason University) provided an overview of this comprehensive conditions study, then the TAC broke up into small groups to add additional sources of data that might be available. The additions were compiled and provided again to TAC members so they might make any additions necessary or provide resource contact information to Dr. Peters or FDEP.

Resource leads were entered into an Excel spreadsheet to facilitate tracking of activities and grouping of information for later analyses. Columns and sub-columns were established to track detailed information about each resource. The owners or authors of web sites, datasets, associated reports, and publications were sent letters to request their data (Table 1). The universal resource locator (URL) or digital object identifier (DOI) was entered into the spreadsheet for datasets or other materials that were publicly available from web sites. Descriptions of the data including dates, availability, and other information were also entered into the spreadsheet. A notation was made if a contact indicated they did not have appropriate data for the study. In these cases, phrases were entered into the "Data Information/Comments" column before inserting text to facilitate sorting: "No data pertinent to this project for 2012-2015:", "Pertinent data but not available at this time:",

Table 1: Spreadsheet design for compiling metadata

Data Activity	Information Collected
Work Tracking	RA Assignment, Date Assigned, Status
Conditions Data	Category, Title of Dataset
Contact Information	Name, Address, E-mail, Phone
Data Information	Years Covered, Description of Data, Cross-Listed Study?, Comments
Data Format	Online, Spreadsheet, Database, Images
Data Products	Raw Data, Analyses Performed, Unpublished Report(s), Published Papers
Availability	Date
Data Quality	QAPP-Guided Study, Data Validated, Peer-Reviewed, Other

"Data available:", "Data available: http://.... [for online resources]", or "Currently waiting for response and/or data."

Permissions to use other datasets and publications were received and they were placed in individual folders according to type of data: biological, chemical, hydrological, physical, or interdisciplinary. As datasets were received, they were assigned a "File Folder Identifier," an alphanumeric code consisting of a category (biological, chemical, hydrological, physical, or interdisciplinary) and a consecutive number, which was added to the beginning of the file name so that it could be easily identified in the folders. A dash number (-0, -1, -2, etc.) was also assigned to each dataset; "-0" to indicate that the dataset was unique and "-1" or higher to indicate that the dataset consisted of multiple files. The spreadsheet and folders were shared with the study team.

2.1. Data Quality

For this project, no analyses of the data were performed; however, further information was collected on whether the studies were conducted with quality control (QC) checks and quality assurance (QA) oversight, so that estimates of data quality and credibility can be made. In addition, the association of the data as contributing to establishing a causal connection to the bleaching and tissue loss diseases outbreaks was assessed, to ensure that the data were collected during the specified time period, study area, and in the vicinity of coral populations. This information was also recorded in the tracking spreadsheet to assist in the future analyses of the data. The entries in the spreadsheet were also checked for correctness and consistency and the hyperlinks to web resources were determined to be correct.

3. RESULTS

3.1. Data Sources

Contacts with potential owners of monitoring or other data were made during May and early June 2016. Sixty-two contacts were made by e-mail and phone, and online searches revealed another 16 datasets without direct contacts, identifying more than 49 databases or reports that might be useful for analyses of biotic or abiotic stressors that might have led to the outbreak of tissue loss diseases on the northern FRT. Twenty-nine datasets were found posted online, and of those, 15 were downloaded for the years 2012–2015 for Miami-Dade, Broward, Palm Beach, and Martin counties. Datasets were contributed by 13 respondents and will be contributed by seven more respondents. Another 14 datasets contained hundreds of stations and further information is needed to determine which station data should be used. Of the 62 people contacted, 18 have not yet responded, and 14 responded but have no pertinent data. Other respondents reported having collected data from the northern FRT during this time period, but are still processing samples or analyzing the data, and the results will not be available until sometime after June 30, 2016. Pertinent datasets identified during this study are presented in Table 2.

Biological datasets that have been obtained include the SEAFAN reports from 2012–2015), monitoring data for corals and other benthic organisms (e.g., SECREMP and CREMP), catch data for commercial species of marine vertebrates and invertebrates, large corals being mapped, and reef visual census data on benthic features and fish populations. In addition, FWRI provided a list of diseased coral tissue samples that were collected in 2015 for processing for histological examination to help determine the cause(s) of the tissue loss. These samples are still being processed.

Water quality (chemistry) datasets obtained include soils runoff data, monitoring data for nutrients from Miami-Dade, Palm Beach, and Martin counties; and silica, nitrogen, and phosphorus data from the Boca and Hillsboro inlets (but only for 2012-2013). Other datasets that might be useful in this study include the U.S. Geological Survey's National Water Information data collection for precipitation, temperature, salinities, and discharge levels, and the U.S. Environmental Protection Agency's STORET database of water, air, and sediment parameters that were measured for Florida sites. Other water quality data were identified, such as point source discharge data and Lake Okeechobee water releases, and water, benthic, and inlet data collected by the Florida Area Coastal Environment (FACE) program at NOAA. However, responses to requests for these data have not yet been received.

Some hydrological data was provided, which might assist in the interpretation of water quality data, including ocean outfalls and injection well reports, GIS vector data from the inlet contributing areas assessment, a hydrodynamic model of St. Lucie Inlet, groundwater monitoring data from Martin and Palm Beach counties, flow rates through inlets and outfalls and rainfall data, and data from the Impaired Waters Rule database. Other monitoring data have been requested.

Table 2: List of data sources identified during this study

Dataset Identifier[1]	Contact Name	Affiliation[2]	Years: Dataset Description
B01-0	Kate Lunz, Jan Landsberg	FWC/FWRI	2015: Diseased coral tissue sample collection locations for histology
B02-0	Liz Larson	NSU	2011–2015: *Acropora palmata* monitoring data from SECREMP
B03-0	Brian Walker, Dave Gilliam	NSU	2012: Reef habitat, benthic survey of organisms in Martin County
B04-0	Katelyn Klug	NSU	2015: Large corals on Broward reefs
B05-0	Felix Martin-Blanco	FWC	2012–2015: Catch data, vertebrates and invertebrates
B06-0	Kirk Kilfoyle	NSU	2012-2015: Reef Visual Census benthic cover and fish counts on sites from BNP to Martin County
B07-1, -2	Dave Gilliam	NSU	2012 and 2014: SECREMP data on benthic habitat, coral cover, disease prevalence, temperature
B08-0	Rob Ruzicka	FWRI	2012-2015: CREMP raw data, percent cover by species on reefs
B09-0	Kristi Kerrigan	FDEP	2012-2015: SEAFAN reports of diseased or bleaching corals and other events
C01-0	Unknown, online	USGS	2012–2015: Geochemical landscape project testing soils for different elements
C02-1, -2, -3, -4	Unknown, online	Miami-Dade County	2012–2015: Miami-Dade County water quality parameters and measurements (e.g., coliform bacteria, chlorine, lead, uranium, radon)
C03-0	Jack Stamates	NOAA	2012–2013: Silica, nitrate, nitrite, and phosphate from Boca and Hillsboro inlets
C04-1, -2, -3, -4	Unknown, online	Palm Beach County	2012–2015: Palm Beach County water quality measurements (e.g., coliform bacteria, chlorine, lead, uranium, radon)

Dataset Identifier[1]	Contact Name	Affiliation[2]	Years: Dataset Description
C05-1, -2, -3, -4	John Polley	Martin County	2012–2015: Martin County water quality measurements (e.g., coliform bacteria, chlorine, lead, uranium, radon)
C06-0	Unknown	USGS	2012-2015: Broward County groundwater quality measurements (K, Na, P, Ca, Cl, Mg, DO, pH, Pb, total alkalinity, ammonia)
C07-0	David Giles	NASA Goddard Space Flight Center	2012-2015: Online aerosol optical depth (AOD) database
C08-0	David Sumner	USGS	2012-2015: Precipitation, temperature, and salinity map. Discharge levels are also available
C09-0	Unknown	USEPA	2012-2015: Water, sediment, and air parameters.
H01-0	Unknown	FDEP	2015: Reducing ocean outfalls impacts
H02-0	Unknown	FDEP	1978–2015: Impaired Waters Rule Stations
H03-0	Mingshuan Jiang	FAU	2015: St. Lucie hydromodel
H04-0	Kurtis Gregg	NOAA	2013–2014: GIS Vector data from Horsley-Witten Inlet Contributing Areas assessment
H05-0	Unknown	USGS	2012–2015: Daily data for groundwater in each county of Florida. Parameters include but are not limited to CDOM, DO, pH, salinity, turbidity, and temperature
H06-0	Sharon Peterkin	Southeast Florida WMD	2012–2015: Flow rates through inlets and outfalls, rainfall
H07-0	Unknown	National Climate Data Center	2012–2015: Selection by counties to get hourly, daily, monthly, or annual rainfall estimates
H08-0	Unknown	USGS	2012–2015: Daily data for groundwater
P01-0	Lindsey Visser	NOAA/AOML	2012–2014: Percent water transparency, chlorophyll a,

Dataset Identifier[1]	Contact Name	Affiliation[2]	Years: Dataset Description
			nutrients, some dissolved inorganic carbon since December 2014
P02-1, -2	Brian Barnes	USF	2013–2015: Study of causes of sediment plumes off the Port of Miami
P03-0	Luis Gonzalez	Port of Miami	2012–2015: Ship traffic data (cargo and passenger)
P04-1, -2, -3	Unknown	USGS	2012–2015: WaterWatch
P05-0	Teri Jordan-Sellers	USACE	2001–2015: Port Everglades turbidity and sedimentation
P06-1, -2, -3, -4	Unknown, online	NOAA/AOML	2012–2015: Florida Current transport
P07-1, -2	Unknown, online	Port Everglades	2012–2015: Port Everglades waterborne commerce and annual commerce report
P08-0	Nick Shay	UM/RSMAS	2012–2014: High frequency radar ocean currents
P09-0	Unknown	USGS	2012–2015: LANDSAT 8
P10-0	Unknown	NASA	2012–2015: MODIS (Chlorophyll or sea surface temperatures for each day for a specific region)
P11-0	Edward Ryan	UM/RSMAS	2012–2015: Sea surface temperatures for each day for a specific region
P12-0	Michael Jankulak	NOAA/AOML	2012–2015: Climatological and oceanographic databases (air and sea temp., wind speed/direction, salinity, precipitation)
P13-0	Todd Spindler	NOAA/AOML	2012–2015: Real-Time Ocean Forecast System. Parameters include temperature, surface height, mixed layer depth, heat flux, salinity, and current data
P14-0	Unknown	NOAA/AOML	2012–2015: Multiple datasets for temperature, salinity, chlorophyll, and more
I01-0	Lisa Krimsky	Miami Sea Grant	2015–2016: Volunteer data collection of temperature, pH, dissolved oxygen, chlorophyll a,

Dataset Identifier[1]	Contact Name	Affiliation[2]	Years: Dataset Description
			phaeophytin, nitrogen, phosphorus, silica

[1]Added to filenames to facilitate sorting in the spreadsheet and locating in the online archive. B = Biological, C = Chemical, H = Hydrological, P = Physical, I = Interdisciplinary; number is unique number for the study, - (dash) number indicates multiple datasets are included in the study. Datasets that were not available as of June 10 do not have a Dataset Identifier.
[2]See List of Acronyms

Physical datasets obtained covered ocean currents, precipitation, water commerce and ship traffic, water transparency, sedimentation and turbidity related to the Port of Miami dredging and Port Everglades. Ship traffic data into and out of the Port of Miami and high frequency radar measured ocean currents data may also aid in understanding the spread of the tissue loss outbreak through time. Satellite data being collected by the Ocean Biology Processing Group in NASA and LANDSAT are available. Several of these datasets are extensive and the sites to be examined need to be determined first; then specific data can be downloaded for analysis.

Some databases were already available online; their URLs were noted in the spreadsheet. Portions of some of these databases (years 2012-2015) were downloaded into the OneDrive folders. Review of these databases is necessary to be sure that appropriate parameters and sites are analyzed, and analysis decisions will be made in the future (e.g., oceanographic and fisheries catch data). Other data were available in diverse formats and may require special software for proper viewing and interpretation (e.g., GeoTIFF files for the Port of Miami turbidity study). Some contacts had done research in the Florida Keys but not north of BNP (e.g., Dr. Erin Lipp and Eugene Shinn); they provided peer-reviewed publications in case those can help.

In many cases, results of studies were not yet available. Attempting to reach the contacts during this busy field season was challenging, with multiple e-mail or phone requests made for information, but responses from some contacts have not been received, as noted. Materials obtained from these contacts will be archived through the summer (until August 31, 2016).

3.1. Data Quality

Little information pertaining to data quality was readily located during this study. Some datasets and associated reports or published papers had been through a peer-review process, such as the sediment plumes study from the Port of Miami dredging project. The *Acropora palmata* monitoring data from SECREMP sites was validated. Obtaining this information will probably require additional phone contacts to determine the protocols followed by different studies or programs to plan and implement data collection efforts and check the results before releasing them.

4. DISCUSSION AND RECOMMENDATIONS

Diseases in wild populations of organisms have been recognized amid concerns about changing environmental conditions and species extinctions (Harvell et al., 2002). The new field of conservation medicine was established with the intent to build connections among ecology, health, and sustainability, and furthering the links between ecosystem and human health and welfare by integrating knowledge across different disciplines, a transdisciplinary approach (Wilcox, Aguirre, & Horwitz, 2012). The health of all organisms, including humans who are also present in ecosystems, depends on controlling factors that might contribute to disease outbreaks, such as physical and chemical parameters, nutrition, and transmission of biological pathogens among species or to humans (zoonoses). Conserving biodiversity is thus also critical to maintain food webs, oxygen and carbon dioxide levels, and reduce contaminants and infectious agents for all organisms; however, parasites are also necessary because they limit their hosts' population growth to maintain the ecosystem and its services for the benefit of all species (Bernstein, 2012; Gómez, Nichols, & Perkins, 2012). Understanding why disease outbreaks occur requires an in-depth assessment of data from multiple disciplines and a broad range of parameters. In this study, datasets were obtained spanning the period before and during the coral tissue loss outbreak to help answer this. As of 26 June 2016, however, reports of diseased corals in the northern FRT were still being sent to SEAFAN.

Coral disease outbreaks have only recently been associated with changes in environmental conditions (Weil, Smith, & Gil-Agudelo, 2006) and additional studies of the biotic and abiotic pathogens that might be causing them are needed. In any disease situation, the susceptibility of the host (the species affected by the pathogen) can be affected by acute, chronic, or prior exposure to other pathogens. Pathogens are considered to be a subset of, and influenced by, the environment. The virulence of the pathogen (ease with which it causes disease) can be mediated by intrinsic (e.g., genetic, immune system, hormonal) or extrinsic (e.g., light, oxygen, temperature) factors as well. Pathogens affect different levels of biological organization (i.e., subcellular, cellular, individual, population, community, ecosystem) and can lead to changes in composition, structure, processes, and functions, potentially killing the affected organism and indirectly damaging the ecosystem.

Prior to death, organisms will attempt to restore, through homeostasis, their normal metabolic and immune systems functions whenever they are exposed to physical, chemical, or biological factors at levels outside the normal ranges—either too much or too little—to which they are adapted (Sokolova, Frederich, Bagwe, Lannig, & Sukhotin, 2012). Those factors are termed stressors in some literature, or drivers (most often by ecologists), but in this case, they are pathogens. The distinction between reversible and irreversible changes in an organism can be difficult to determine, and usually requires advanced biomedical clinical or anatomic pathology diagnostic procedures.

In the case of the corals and other reef organisms, most monitoring programs involve counting the number of individuals found for different species, and only visually assessing their external condition and behavior. A "healthy" coral colony is considered to have a uniform covering of normally sized and shaped polyps and coenenchyme (tissue between the polyps) appropriate to the species over its entire surface, without scraped or denuded areas of skeleton or tissue discolorations or microbial mats. SECREMP and other coral health monitoring data and SEAFAN reports indicate that visible lesions were detected between 2012–2015. However, just as humans may not show any external signs of internal functional damage when affected by cancer or a bacterial infection, a coral that appears to be grossly healthy may not actually be so. The earliest changes in disease occur at the molecular, subcellular level, which requires microscopic examination and biochemical analyses to detect. Paling of coral tissue, indicating loss of the zooxanthellae, cannot be detected by human vision until about 50 percent of the zooxanthellae have been lost (Jones, 1997). Thus, the earliest detection of a coral disease outbreak may be missed until significant tissue mortality has occurred (Figure 1).

Thus, a complicated "web of causation" (Wobeser, 1994) can begin to stress organisms and contribute to the development of diseases. Disease diagnosis programs not only study the victims (organisms showing particular signs, and in the case of humans only, symptoms), but also ecological factors associated with the event, to assist in the development of a preliminary diagnosis to guide additional collection of data from the environment and the affected organisms. After evaluating the field data and laboratory tests, a final diagnosis can be made. In the case of coral tissue loss-related diseases, we still have much to learn about the causes. Although a bacterium, *Aurantimonas coralicida*, was isolated from massive corals with the field identification of WP and shown to cause the same tissue loss when apparently healthy massive corals were exposed to it (Richardson et al., 1998b; Denner et al., 2003), other microbiology studies have not found this bacterium in white plague-affected corals (Sunagawa et al., 2009; Cárdenas, Rodriguez-R, Pizarro, Cadavid, & Arévalo-Ferro, 2012; Cook et al., 2013), and the pathogenicity of the original isolate has been lost (L. L. Richardson, personal communication to ECP). Dr. Mauricio Rodriguez-Lanetty, with Drs. Laurie Richardson and Diego Lirman, received a National Science Foundation Grant for Rapid Response Research when this coral disease outbreak began to examine coral microbial community and immune system changes in diseased corals. They were contacted for this study, but have not responded as of June 26, 2016. Scientists at the FWRI coordinated the collection of diseased and apparently healthy coral samples by other scientists diving on the northern FRT during the fall of 2015, and some were obtained for histological and microbial analyses, which are underway now, but when the results will be available is not yet known. These laboratory procedures, commonly performed for all disease diagnoses, will be critical to determine if particular microbial pathogens were causing the tissue loss and have been previously found to cause WP in corals, or if a different pathogen or pathogens was involved in this WP outbreak.

Several studies have found that tissue loss on massive corals is positively correlated with bleaching events, occurring even before the corals bleach (Selig et al., 2006) or after bleaching. The additional stressors of temperature and loss of the zooxanthellae have been shown to suppress reproduction and energy reserves, and decrease tissue regeneration and skeletal accretion even after corals recovered their zooxanthellae (Szmant & Gassman, 1990; Glynn, 1996; Mydlarz, McGinty, & Harvell, 2010). Jones, Bowyer, Hoegh-Guldberg, and Blackall (2004) were the first to report a coral epizootic (epidemic) on fringing reefs at the same time corals were bleaching. Borger (2005) documented disease

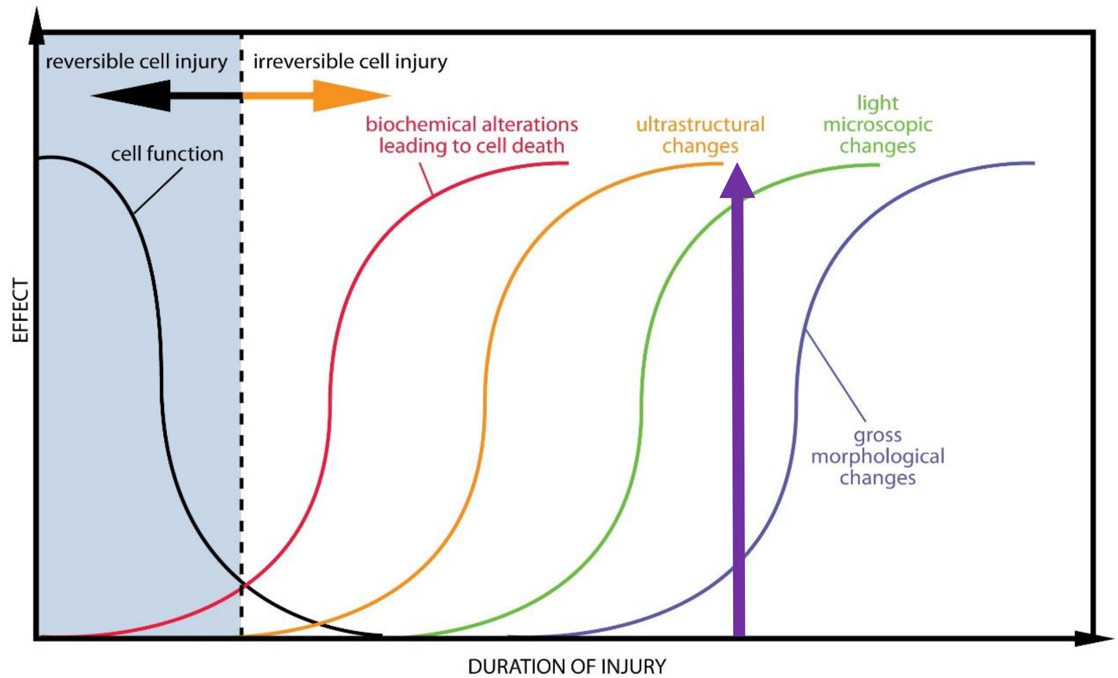

Figure 1*: Cell function changes can begin early, but require biochemical, physiological, or anatomic (electron or light microscopy) procedures to detect them before the organism shows visible signs of disease (to right of purple arrow). Adapted from Kumar, Abbas, Aster, and Fausto (2010) by Angela Richards Donà, University of Hawaii.*

prevalence, incidence, and disease progression rates at five sites in Biscayne National Park and upper Florida Keys National Marine Sanctuary, from July 2001 to September 2002 when corals did not bleach, estimating that 10% of the total diseased corals had WP in 2001 and 55% were affected in 2002. The most cases were seen in September both years, but in all cases only caused partial mortalities and stopped during winter months. Two colonies, however, began losing tissue again the second year of the survey as seawater temperatures warmed again. Her results suggested that temperature stress increased coral susceptibility to WP. Miller et al. (2009) found that coral diseases, particularly WP, became rampant on reefs following the summer 2005 northeastern Caribbean bleaching event in the U.S. Virgin Islands just after they started to recover the symbiotic algae, resulting in a mean loss of coral cover of about 60%. Increased incidences of WP, black band disease, and dark spot disease were also evident on upper Florida Keys reefs during the severe bleaching event of 2005, with some differences in which species were affected by which diseases (Brandt and McManus, 2009a). The incidence of white plague in *Montastraea* (now *Orbicella) faveolata* was highest when colonies were recovering their zooxanthellae after the bleaching.

Bleached corals might lose antimicrobial activity and become susceptible to opportunistic pathogens (Lesser et al., 2007; Mydlarz, McGinty, & Harvell, 2010). However, some specific bacterial pathogens cause bleaching. Ben-Haim, Zicherman-Keren, and Rosenberg

(2003) reported the discovery of a novel bacterium, *Vibrio coralliilyticus*, that caused bleaching and lysing of tissue in the Indo-Pacific coral *Pocillopora damicornis*. This bacterium multiplied more rapidly with increasing seawater temperature. *Vibrio harveyi* and other bacterial species have also been associated with bleaching coral tissue when temperature is increased (Higuchi et al., 2013). The problem is that microbiological analyses are not done during every bleaching event, even on one species of coral, so the nature of potential microbial pathogens as causes of bleaching, or disease, are limited. Doctors also do not test every human every winter in every location to determine which of the 100+ viruses that cause cold symptoms and signs are causing the outbreak of this disease. Thus, our understanding of the linkages between environmental factors, biotic pathogens, and diseases, is still developing.

Other pathogens have been implicated in the development of coral bleaching and tissue loss diseases, including chronic nutrient enrichment (Bruno, Petes, Harvell, & Hettinger, 2003; Vega Thurber et al., 2013), reduced coral cover and biodiversity (Selig et al., 2006; Aeby, Bourne, Wilson, & Work, 2011), macroalgal blooms (Brandt et al., 2012), and turbidity and sedimentation (Vega Thurber et al., 2013). Ban, Graham, and Connolly (2014) examined more than 150 research studies to investigate whether multiple stressors interacted to influence responses or produce synergistic effects (combined exposure to stressors produces effects that are greater than either individual stressor's effects). Sedimentation, storms, and water temperature directly affected many other stressors and have been most studied. They found that coral diseases were linked with many other stressors, indicating that disease outbreaks could serve as early indicators of nonspecific ecosystem stress. Datasets obtained during this study should provide good records of multiple stressors measured during the 2012–2015 period on the northern FRT, including temperature, turbidity, sedimentation, nutrient loading, ocean currents, groundwater, African dust events, shipping, coral cover, and biodiversity. However, such measurements were often made at limited locations, for "snapshots" and not continuous recordings, and thus might not provide the best evidence to support association with the disease outbreak. Hughes and Connell (1999) noted that complex suites of stressors affect coral reefs and that their impact is also determined by previous exposure to the same or other stressors, which might have occurred during short or long time periods. Thus, relying on data collected during a limited time period to explain causes of events is not recommended. The northern FRT has been exposed to land-based sources of pollution, as well as other environmental stressors, far longer than during 2012–2015 (e.g., Gregg, 2013; Pickering & Baker, 2015), and it might be difficult to identify the proximate cause(s) of the disease outbreak.

A framework for investigating the etiology(ies) of diseases has been developed and modified. Epidemiology is the study of factors related to the occurrence of disease, usually seeking to understand disease outbreaks with the goal of reducing their occurrence and impacts, especially social-economic cost effects (Thrusfield, 2016b). Analytical epidemiology identifies relationships between diseases and putative causal factors. Prevalence, incidence, species affected, transmission and spread of diseases (for infections: vectors, host densities, contact, and the like), are determined and statistical associations explored. Based on epidemiological principles and procedures, (ecological) risk assessment—first developed for toxicology, but broadened to include "…any chemical, physical, or biological entity that can induce adverse effects on ecological components…(Norton et al., 1992)—also examines exposures and effects to evaluate the condition of ecosystems and guide management actions.

The ecological risk assessment framework led to the development of the Causal Analysis/Diagnosis and Decision Information System (CADDIS), an online tool (https://www3.epa.gov/caddis/) presenting and explaining the steps to be undertaken and statistical analyses to be performed to identify causal factors of biological impairment (or disease) (Norton et al., 2009). The scientific method is used to test hypotheses about the causes of diseases. Several concepts for establishing cause have been proposed, following the now inadequate Koch's Postulates in the case of multifactorial and non-infectious diseases, including Hill's Criteria and Evan's Rules for establishing causality of infectious and non-infectious diseases), which may be useful here (Thrusfield, 2016a). An integrated conceptual coastal ecosystem model, one of the first steps undertaken to define the problem in ecological risk assessment, was developed during the Marine and Estuarine Goal Setting for South Florida (MARES) project (Nuttle and Fletcher, 2013), and could be used to further direct the identification of stressors affecting the northern FRT. During presentations at the SEFCRI TAC meeting, members learned about other approaches in applying epidemiological models, such as using focused geospatial analyses of FRRP bleaching data, presented by Danny Gooding and John Fauth.

In the future, datasets obtained during this study will be analyzed and used by local (county), state, and federal resource management agencies to improve our understanding of the events and environmental conditions encountered by the organisms on the northern FRT that may have contributed to the coral bleaching and disease outbreaks of 2014–2015. Additional outcomes include, but are not limited to:

- Site-specific documentation of environmental stressors present along the northern FRT during this period

- Identification of data gaps limiting the investigation of such events

- Reporting general trends in biodiversity and habitat condition

Brandt and McManus (2009b) developed an individual-based modeling tool (Simulation of Infected Corals) to examine factors involved in the pattern of diseased corals observed during six years of monitoring at four sites on reefs of Little Cayman Island, British West Indies. They noted that identification of a transmissible pathogen would greatly increase predictions of disease ecology and behavior, observe how it might be introduced and dispersed in a population, and identify factors affecting different species' susceptibilities to disease development. The analysis showed that increasing host resistance helped to prevent the disease when modeled populations consisted of susceptible species, but reducing transmission was more important when modeled populations consisted of non-susceptible species. About the same time, Sokolow, Foley, Foley, Hastings, and Richardson (2009), applied a metapopulation model with a susceptible-infected disease system to WP-affected coral spatial data that had been collected from the U.S. Virgin Islands and Florida Keys, which they could then use to test infectious pathogen dynamics after its introduction in the model. Model predictions for disease levels matched levels recorded from the reefs for all years except 1997, possibly due to anomalous environmental conditions produced by the El Niño (the model ended with 2005 data). The results supported the observation that the prevalence of chronic disease can be sustained in host populations and present great risk to corals. They noted that the effects of management actions need to be explored. These types of analyses could be applied to the northern FRT WP outbreak to assist reef managers in developing policies to conserve the corals. Parameterizing the model with baseline data on coral distribution, transmission (if an infectious agent is the primary pathogen and the tissue loss is not just caused by abiotic factors and opportunistic microbial pathogens already present in or on the coral mucus), and susceptibility remains a challenge, however.

In conclusion, statisticians with knowledge of epidemiology and risk assessment will be needed to analyze the different datasets to test the causal hypotheses that have been mentioned. Regressions, multivariate statistics, linear modeling, and geospatial disease models could be applied to detect causal associations, although the "patchiness" of measurements and observations made on the northern FRT, both in space and time, may limit the identification of one or more pathogens involved in this disease outbreak. Statistical significance is required to demonstrate a strong positive association between a hypothesized causal factor and the WP outbreak (Evan's Rules). Even if the analysis of environmental and tissue loss disease outbreak data can be conducted, identifying the pathogen(s) will be challenging. Valuable outcomes might be learning about how to strengthen disease surveillance, to link marine organism disease outbreaks to human population impacts, and to identify data gaps so that more appropriate monitoring data can be collected. Subject matter experts (e.g., pathologists, physical oceanographers, microbiologists, hydrologists, coral reef ecologists) will also be needed to properly interpret the results of the analyses.

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