Phase-I Final Report for a Meta-Analysis of Water Quality, Fish, and Benthic Data within the Kristin Jacobs Coral Reef Ecosystem Conservation Area

Florida Department of Environmental Protection
Coral Reef Conservation Program

Southeast Florida Coral Reef Initiative

Fishing, Diving, and Other Uses Focus Area
Local Action Strategy Project #51

Phase-I Final Report for a Meta-Analysis of Water Quality, Fish, and Benthic Data within the Kristin Jacobs Coral Reef Ecosystem Conservation Area

Prepared By:

Joshua P. Kilborn

University of South Florida, College of Marine Science
140 7th Ave South; Saint Petersburg, FL 33701

November 21, 2022

Completed in Partial Fulfillment of Contract BA21A6 for
Florida Department of Environmental Protection
Coral Reef Conservation Program
1277 N.E. 79th Street Causeway
Miami, FL 33138

FDOU-51: A Meta-analysis of Water Quality, Fish, and Benthic Data within the Kristin Jacobs Coral Reef Ecosystem Conservation Area

This report should be cited as follows:
Kilborn, Joshua P. 2022. Phase-I Final Report for a Meta-Analysis of Water Quality, Fish, and Benthic Data within the Kristin Jacobs Coral Reef Ecosystem Conservation Area. Report prepared for the Florida Department of Environmental Protection's Coral Reef Conservation Program. University of South Florida, College of Marine Science. Saint Petersburg, Florida. *ix* and 49 pp.

This report was prepared for the Florida Department of Environmental Protection, Office of Coastal Resilience and Protection by the University of South Florida. Though funded in part by a grant agreement from the Florida Department of Environmental Protection (DEP) through National Oceanic and Atmospheric Administration (NOAA) Award No. NA19NOS4820020, and by the Department, through its Office of Coastal Resilience and Protection, the views, statements, findings, conclusions and recommendations expressed herein are those of the author(s) and do not necessarily reflect the views of the State of Florida, NOAA, or any of its sub-agencies.

EXECUTIVE SUMMARY

The Southeast Florida Coral Reef Initiative has developed a series of local action strategies (LAS) for the Kristin Jacobs Coral Reef Ecosystem Conservation Area (Coral ECA) that are divided into five focus areas: (*i*) fishing, diving, and other uses (FDOU); (*ii*) land-based sources of pollution; (*iii*) marine industry and coastal construction impacts; (*iv*) reef resilience; and (*v*) awareness and appreciation. The FDOU focus area's LAS project #51 (FDOU-51), *A Meta-Analysis of Water Quality, Fish, and Benthic Data*, has the goal of conducting a holistic analysis of those three Coal ECA subsystems in order to identify patterns and trends within and among them. Phase-I of FDOU-51 is directed toward data discovery, the scoping of priorities and research themes for the Coral ECA, and the identification of knowledge and data gaps within the system. The results of Phase-I include recommendations for new research priorities and augmented monitoring efforts that would help to better inform the system-wide management of the conservation area, and a framework for the ultimate meta-analyses for Phase-II of FDOU-51.

The details of the Coral ECA as a complex adaptive system, and the interactions among its primary components – the water quality, fish, and benthic subsystems – were discussed, as well as those primary components that comprise those subsystems. In all cases, the dynamics and interactions among system members are described below, but the general theme is that the Coral ECA is a highly interconnected and spatiotemporally dynamic system. When considered individually, each subsystem is easily as complex as they are when considered holistically, and therefore the research and monitoring efforts are limited by the scope and resources available to them. Phase-I identified primary sources of data for FDOU-51 and outlined their strengths and weaknesses, as well as the comparability across them for the purposes of a holistic analysis. In general, the data sources to be most heavily relied upon are the Coral ECA Water Quality Assessment, the National Coral Reef Monitoring Program (and all three of its subsystem monitoring efforts), the Florida Reef Resilience Programs Disturbance Response Monitoring, and the Southeast Florida Coral Reef Evaluation and Monitoring Project.

After several collaborative meetings with numerous stakeholders, managers, and technical advisors a series of research ideas and were developed, ranked, and placed along feasibility vs. importance axes. These ideas were further aggregated into research focus areas that were ultimately formed into the final-four research themes recommended for FDOU-51 Phase-II. Their vision statements are as follows:

> RT_1: "*To investigate the diversity, abundance, and size composition trends in fish resources on natural habitats within the Coral ECA. Examine any relationships between changes to water quality and/or benthic habitat. Identify fish species/functional groups indicative of different environmental conditions.*"

RT2: "*To define the key environmental conditions that associate with benthic assemblages. Determine which benthic species are most indicative of water quality regimes in the Coral ECA.*"

RT3: "*Examine the varying rugosity and geomorphology of reefs in the Coral ECA, and determine how this impacts the capacity of the system to provide risk-mitigation services to adjacent coastal communities. Estimate any relationships between reef rugosity and fish assemblages and benthic composition.*"

RT4: "*Investigate the response of the Coral ECA's benthic communities (i.e., resilience and resistance) to coastal construction and sedimentation.*"

Of these, RT1 was selected for Phase-II of FDOU-51 and an analytical framework for this undertaking is detailed. However, prior to that, additional recommendations are given for those stakeholder-derived research ideas that were not ultimately reformed into the final themes listed above. In these cases, there were some data or monitoring gaps that precluded their feasibility, and thus those ideas deemed important were not able to be fully vetted. Therefore, the recommendations include new strategies and focus areas that, if followed up on would lead to new knowledge about the Coral ECA's systems that would be impactful to important ecological aspects that may lead to better ecosystem-based management of these resources. These new research areas include:

- ~ Sources and Transmission Vectors of Waterborne Pathogens
- ~ Acute vs. Chronic Impacts, Eutrophication, and Condition
- ~ Coral Larval Supply and Recruitment Success
- ~ Utilization of Additional Fish Monitoring Methods and Data

Further recommendations derived from the stakeholder engagement process and the processes outlined below relate to the augmentation of monitoring and data collection in the region. These recommendations are divided among the three subsystems, and range from relatively simple additions of new sampling gear to those with large budget requests and far-reaching implications (e.g., the addition of entirely new sampling programs). To summarize each subsystem's recommendations at a very high level:

<u>Water Quality Monitoring and Hydrodynamic Modeling:</u>

- ~ Improve analyte method detection limits.
- ~ Increase the spatial coverage and resolution of the survey design, and include more random sampling stations.
- ~ Increase sampling frequency and/or deploy autonomous monitoring platforms in order to work toward real-time water quality surveillance and prediction.

- ~ Add more analytes to the program, including nutrients, pollutants, and pathogens.
- ~ Upgrade field gear to safely obtain water samples at greater depths.
- ~ Add flow-through observation systems for water sampling while in-transit between regular monitoring stations.
- ~ Develop a hydrodynamic model that can be used to predict near real-time fluid dynamics for the Coral ECA.
- ~ Perform concurrent water quality sampling with the fish and benthic subsystems to the extent possible. However, lags in the biological response to physiochemical changes is always a consideration, and should the ultra-high-resolution spatiotemporal sampling design recommendations above be enacted to their full extent, concurrent water sampling may become less necessary.

Fish Monitoring:

- ~ Perform annual sampling within the NCRMP-RVC program.
- ~ Monitor artificial reefs across the entire Coral ECA for fishes.
- ~ Employ more diverse fish monitoring methods, particularly camera-based surveys that can be deployed in almost any environment or depth that might be encountered in the Coral ECA. Additional sampling such as plankton trawls or eDNA should also be explored.
- ~ Work with state and federal fisheries data analysts to develop a protocol for downscaling FDM data if possible.

Benthic Monitoring:

- ~ Collect high-resolution censuses of non-scleractinian biogenic habitats, including macroalgae, seagrasses, sponges, octocorals, anthozoans, gorgonians, tunicates, and macro-invertebrates.
- ~ Develop and implement a larval supply and recruitment success monitoring program in the Coral ECA, or augment an existing program to include this aspect.
- ~ Implement large-scale substrate monitoring for erosional and depositional-rate changes across the Coral ECA using stakes and sediment traps at fixed sampling stations.

Lastly, the project workflow for Phase-II of FDOU-51 includes a detailed discussion of the various mismatches with respect to timing and sampling design for the selected monitoring programs' data. The data preprocessing aspect of Phase-II will ultimately be critical, and the development of suites of variables that are representative of the different aspects of each subsystem, and the Coral ECA as a whole, will be the foundation of the various hypotheses tests and constrained analyses to follow. Holistic analyses for this phase will involve pattern recognition to capture the various water quality and benthic regimes throughout the conservation area and indicator analyses to assign representative fish species to the unique habitat patterns uncovered. Other constrained analyses that directly investigate directional effects on fish from water quality and benthic characteristics will also be employed, and in total all of these analyses will present a comprehensive view of the complex adaptive system that is the Coral ECA. Finally, projected timing (3-5 yrs.) and personnel requirements (1-2 full-time researchers) are outlined, as well as the need for post-project public access to data and derived products and sustained stakeholder engagement.

ACKNOWLEDGEMENTS

The Author would like to sincerely and wholeheartedly thank Katie Lizza, the FDOU Coordinator from the Florida Department of Environmental Protection's Coral Reef Conservation Program, for the opportunity to undertake Phase-I of this project and the support she provided throughout. Additionally, I am continually humbled by the impressive group of stakeholders, managers, and researchers that I have interacted with over the last year. None of this would have been possible without their involvement, expertise, and enthusiasm! Finally, a special thank you to all of the advisory and technical committee members to who helped guide the development of this phase of FDOU-51, your input has been invaluable.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

ANOVA	Analysis of Variance
CAP	Canonical Analysis of Principal Coordinates
CM_i	Collaborative Meeting #i
CO_2	Carbon Dioxide
Coral ECA	Kristin Jacobs Coral Reef Ecosystem Conservation Area
DBHYDRO	SFWMD Hydrographic Database
dbRDA	Distance-based Redundancy Analysis
DEP	Florida Department of Environmental Protection
DNA	Deoxyribonucleic Acid
DPSER	Drivers, Pressures, States, Ecosystem Services, and Responses
DRM	Disturbance Response Monitoring
EBM	Ecosystem-Based Management
eDNA	Environmental Deoxyribonucleic Acid
EPA	U.S. Environmental Protection Agency
ESA	Endangered Species Act
FDM	Fisheries Dependent Monitoring
FDOU	Fishing, Diving and Other Uses
FDOU-51	FDOU LAS Project #51
FIM	Fisheries Independent Monitoring
FCR	Florida’s Coral Reef
FWC	Florida Fish and Wildlife Conservation Commission
GIS	Geographic Information System
GPS	Geographic Positioning System
HB	House Bill
ICA	Inlet Contributing Area
IndVal	Species Indicator Value
LAS	Local Action Strategy
LBSP	Land-Based Sources of Pollution
LOO-CV	Leave-One-Out Cross-Validation
MANOVA	Multivariate Analysis of Variance
MDL	Method Detection Limit
NCRMP	National Coral Reef Monitoring Program
NCRMP-CCC	NCRMP Climate and Carbonate Chemistry Survey
NCRMP-RVC	NCRMP Reef-fish Visual Census Survey
NELAC	National Environmental Laboratory Accreditation Conference

NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
PAHs	Polycyclic Aromatic Hydrocarbons
PCBs	Polychlorinated Biphenyls
PERMANOVA	Permutation-based Multivariate Analysis of Variance
PERMDISP	Permutation-based Dispersion
RDA	Redundancy Analysis
RT_i	Research Theme #*i*
RVC	Reef Visual Census
SCTLD	Stony Coral Tissue Loss Disease
SCUBA	Self-Contained Underwater Breathing Apparatus
SECREMP	Southeast Florida Coral Reef Evaluation and Monitoring Project
SEFCRI	Southeast Florida Coral Reef Initiative
SFWMD	South Florida Water Management District
WIN	Water Information Network
WQA	Coral Ecosystem Conservation Area Water Quality Assessment
WQP	Water Quality Portal
WQX	Water Quality Exchange

1. INTRODUCTION

1.1. Project Background and Objectives

The Southeast Florida Coral Reef Ecosystem Conservation Area was officially established on July 1, 2018 after HB 53 passed the Florida House or Representatives on Jan. 25, 2018 and then subsequently passed the Florida Senate on Feb. 7, 2018 (Florida-Senate 2018). This area was renamed the Kristin Jacobs Coral Reef Ecosystem Conservation Area (Coral ECA) on July 1, 2021, and includes the sovereign submerged lands and state waters offshore of Martin, Palm Beach, Broward and Miami-Dade Counties. The Coral ECA extends from its northern boundary at St. Lucie Inlet southward to the northern extent of Biscayne National Park at its southern boundary (Figure 1). Although these boundaries were only recently established, collaborative action and research among marine resource professionals, scientists, and stakeholders from government agencies and other organizations has been ongoing within the area since at least 2003 when the Southeast Florida Coral Reef Initiative (SEFCRI) was formalized (DEP 2004).

The SEFCRI Team comprises 64 stakeholders and was formed to develop local action strategies (LAS) to protect the coral reef resources in the northern portion of Florida's Coral Reef (FCR) that spans approximately 160 km of coastline (Banks, Riegl et al. 2007, Finkl and Andrews 2008). These LAS are short-term, locally driven projects, or roadmaps for cooperative action among federal, state, and non-governmental partners, that identify and implement priority actions needed to assess or reduce key threats to coral reef resources in the Coral ECA (DEP 2004). The Florida Department of Environmental Protection (DEP) Coral Reef Conservation Program was established in 2004 to support and manage the SEFCRI Team and overall progress towards completion of LAS projects (DEP 2004). The SEFCRI Team identified five focus areas for immediate local action to address threats to the Coral ECA, including (*i*) land-based sources of pollution (LBSP), (*ii*) maritime industry and coastal construction impacts, (*iii*) fishing, diving, and other uses (FDOU), (*iv*) lack of awareness and appreciation, and (*v*) reef resilience. Each of these focus areas have specific LAS projects that are implemented and managed by DEP coordinators within the Coral Reef Conservation Program.

This LAS project, ***FDOU-51*: *A Meta-Analysis of Water Quality, Fish, and Benthic Data***, has the ultimate goal of conducting a holistic analysis of the three primary subsystems underlying the Coal ECA – water quality, fishes, and benthic coral and hardbottom habitats – and to identify patterns and trends within and among them. Additionally, FDOU-51 seeks to frame these analyses within the scope of selected management and research priorities, and will also identify knowledge gaps within the Coral ECA to help better inform future data collection or research and management efforts. Thus, Phase-I of FDOU-51 was focused on data discovery, scoping and development of research themes and analytical frameworks for the final analyses, and the identification of monitoring and research gaps to inform Phase-II of the LAS project. Phase-II consists of the analytical phase for FDOU-

51, and encompasses all of the data collection, pretreatment, modeling, visualization, and synthesis of results for the Coral ECA and its critical subsystems.

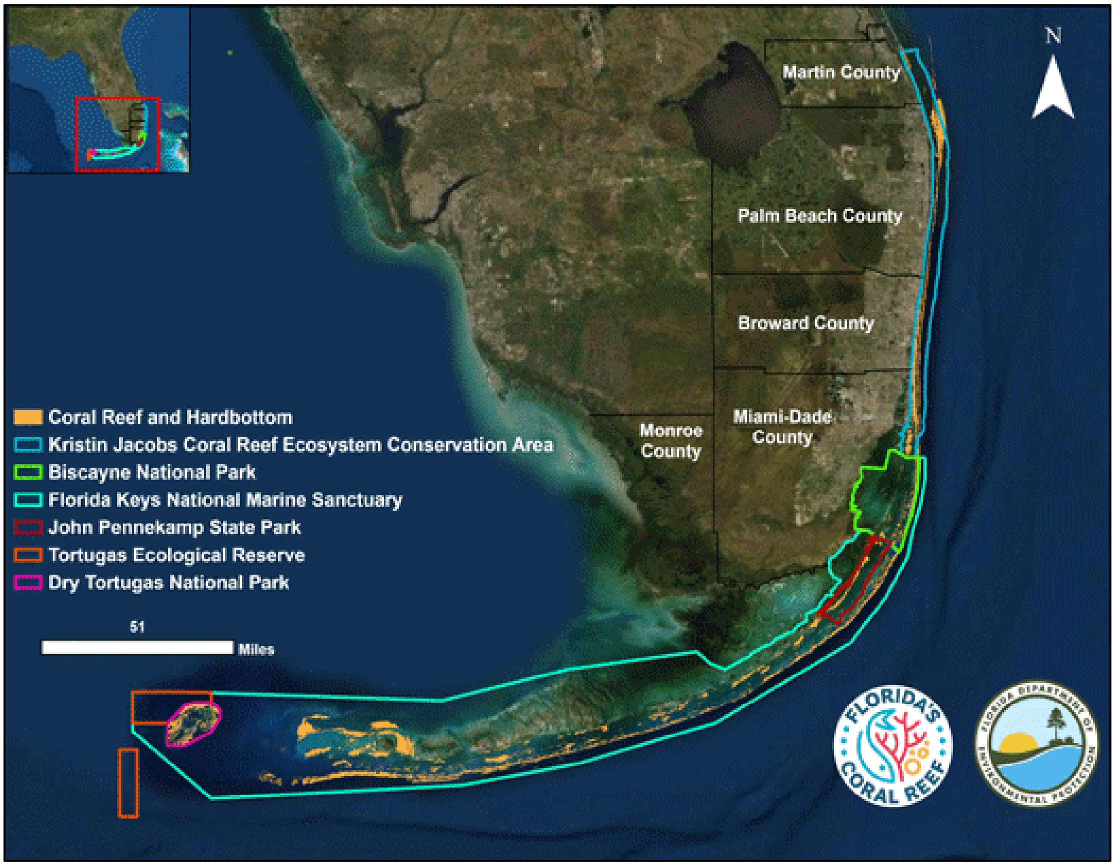


Figure 1. Map of the Florida Reef Tract's Subdivisions. The Kristin Jacobs Coral Reef Ecosystem Conservation Area (northern-most, dark blue outline) is the focus of this study and encompasses the entire norther portion of the Florida Reef Tract.

1.2. Synthesis of Phase-I Efforts for FDOU-51

1.2.1. Data Discovery

The FDOU-51 project team operated within a framework of conceptual models previously developed to describe the south Florida coastal ecosystem and its related subsystems (Fletcher, Nuttle et al. 2013), and attempts were made to incorporate aspects of ecosystem-based management (EBM; Christensen et al. 1996; Lubchenco & Sutley 2010) and the DPSER (*drivers*, *pressures*, *states*, *ecosystem services*, and *responses*) model for data organization (Bowen and Riley 2003, Tscherning, Helming et al. 2012, Kelble, Loomis et al. 2013). After partitioning the Coral ECA into the three critical subsystems of interest to FDOU-51, a data discovery process was undertaken to catalog relevant data sources that could inform any holistic analyses of the conservation area (Kilborn 2022).

While many scientific studies related to the Coral ECA's subsystems have been undertaken within its boundaries, it was decided by the project team that priority would be given to data from contemporary monitoring programs producing relatively long-term (i.e., ≥ 5 yrs.) data series with funding in place to continue their efforts into the foreseeable future. The latter point is particularly useful for implementing recursive EBM protocols (Levin, Fogarty et al. 2009) that require regular updating of information describing the status of the system and the resources within it. Another important aspect of the data discovery effort was attempting to incorporate as much work as possible that was previously developed under DEP and/or SEFCRI leadership. Together, these over-arching constraints were effective at filtering data collections that were neither focused on the entire spatial extent of the Coral ECA, nor persistent for long enough to be useful for trend detection, future goal setting, and the scoping of management priorities.

1.2.2. Collaborative Meetings

As FDOU-51 ultimately aims to frame its analyses within the scope of predefined management and research priorities, a systematic review of the Coral ECA's subsystems and their available data was performed by stakeholders and used to fully develop those research questions of interest in Collaborative Meeting #1 (CM_1, Kilborn & Lizza 2002). In addition to consolidating data sources and system-level stakeholder priorities, CM_1 also elucidated several knowledge and monitoring gaps within the established surveillance system for the Coral ECA that, if remedied, would help to improve future research, data collection, and management efforts of this unique coral reef ecosystem. The stakeholder pool for CM_1 included county, state, federal, and academic data providers, statistical experts, resource managers, and members of the SEFCRI project team (Kilborn and Lizza 2022).

Given that the activities of Phase-I seek to narrow the scope of work for the analytical portion of the project in Phase-II, Collaborative Meeting #2 (CM_2, Kilborn 2022) was convened to determine the analytical needs and likelihood of success for the highest priority research areas developed by stakeholders participating in CM_1 (Kilborn and Lizza 2022). The attendees for CM_2 were mostly limited to those with expertise in complex data analyses within the Coral ECA, but the general pool of stakeholders was similar to that of CM_1. This meeting was primarily used to formally define a series of research themes that comprised the stakeholder-defined research priorities and also fulfilled the overarching objectives of FDOU-51's holistic analysis of the Coral ECA.

1.2.3. Project Team and Advisory Meetings

In addition to the collaborative meetings facilitated for FDOU-51, a number of interim meetings transpired among the project team's administrative and technical advisory committees. These meetings were generally used to update these groups as to the progress of the project, but also to solicit advice and guidance on furtherance of particular project goals. For example, the interim meetings between CM_1 and CM_2 were used to focus the selected subsets of research priorities from CM_1 that ultimately became the focus areas that were subjected to the feasibility discussions in CM_2. In addition to refocusing the list of priorities, straw-man vision statements for each theme were developed and the results of these meetings became the starting point for future collaborative efforts among stakeholders (Kilborn 2022). By employing continual stakeholder engagement, the course of Phase-I was steered by the goals and objectives of FDOU-51, its project team and their advisory bodies, and the Coral ECA's users, managers, and advocates.

1.2.4. Project Reporting

Throughout the Phase-I project period, a number of reports have been produced that detailed the available data and ongoing monitoring programs across the three subsystems of the Coral ECA (Kilborn 2022) as well as the proceedings and outcomes from the two previously described collaborative meetings (Kilborn 2022, Kilborn and Lizza 2022). This report will describe the project team's conceptualization of the dynamic relationships and teleconnections within and among the Coral ECA's subsystems, and highlight the research priorities and cross-cutting themes developed by stakeholders. It will summarize the gaps in both knowledge and data gathering that were identified over Phase-I at both the scale of the individual subsystem and also that of the entire Coral ECA. Lastly, an outline of the recommended holistic analysis of the Coral ECA will be presented, including the questions of interest, relevant data sources and considerations to address them, analyses frameworks, and inferential scales.

2. PHASE-I RESULTS AND DISCUSSION

2.1. The Coral ECA as a Complex Adaptive System

During subsystem-specific discussions, the teams used conceptual models developed for the south Florida coastal marine system (Fletcher, Nuttle et al. 2013) to identify and interpret the primary DPSER indicators that best account for the dynamics of this complex ecosystem. However, in all cases it was noted that the original authors' models were meant to capture resources, habitats, and processes that spanned a much larger spatial scale than that of the Coral ECA. Therefore, in practice the original conceptual models served best as catalysts for discussions that revealed the important features and connections within and among each of the subsystems of interest. They were also particularly useful in highlighting areas where the benefit of ten additional years of research resulted in new knowledge of system dynamics or internal processes to be investigated or monitored moving forward.

The Coral ECA resides in the northern portion of FCR and its iconic coral reef habitats are composed of a series of three, shoreline-parallel terraces that become progressively deeper as distance from shore increases. These geoformations are termed the "inner", "middle", and "outer" reefs that, along with a nearshore "ridge complex" habitats, are interspersed with sand flats, and the occasional non-contiguous "intermediate ridge" (Moyer, Riegl et al. 2003, Banks, Riegl et al. 2007, Finkl and Andrews 2008, Fletcher, Nuttle et al. 2013, Riegl, Gilliam et al. 2013). North of the Broward/Palm Beach county line, however, the inner reef terrace is notably absent. The Coral ECA's reefs contain numerous geomorphological features such as “patch”, “spur and groove”, and “worm” reefs, and they support a diverse range of octocoral, stony coral, macroalgal, sponge, and fish communities (Moyer, Riegl et al. 2003, Finkl and Andrews 2008, Kilfoyle, Walker et al. 2018, Gilliam, Hayes et al. 2021).

The network of drivers and pressures that affect the statuses of the Coral ECA’s resources include those related to the large population centers nearby (Rayer, Doty et al. 2021), and high-traffic tourism destinations (Fletcher, Nuttle et al. 2013, Gilliam, Hayes et al. 2021) directly adjacent to the conservation area. The iconic reefs support vibrant recreational and commercial diving and fishing communities (Johns, Leeworthy et al. 2001, Collier, Ruzicka et al. 2008, NMFS 2018), and recreational vessel users, in particular, have displayed drastic rates of increased utilization of the Coral ECA when compared to commercial users (Johnson, Harper et al. 2007). With respect to fishes, the consistency and predictability of catches, along with their availability and sustainability, have high impacts on angler perceptions and valuations of the system. Thus, while the Coral ECA’s fish subsystem has historically supported high harvest rates (Johnson, Harper et al. 2007, NMFS 2014, NMFS 2018, NMFS, Cody et al. 2022), it is directly connected to the water quality and benthic subsystems, and therefore has outcomes that are dependent on their variability and state changes over time, which ultimately affect stakeholder perceptions. Additionally, while FCR is considered a highly prized natural resource to the many coastal inhabitants that rely upon it (Johns, Leeworthy et al. 2001, Johns, Milon et al. 2004, Storlazzi, Reguero et al. 2019), the effects of land-use, groundwater discharge, wastewater disposal, stormwater runoff, and regional water management are apparent throughout the Coral ECA (Caraco and Drescher 2011, Fletcher, Nuttle et al. 2013, Gregg and Karazsia 2013).

The South Florida Water Management District (SFWMD) was founded in 1949 to manage the regional water resources within the state and aims to protect aquatic habitats by “...balancing and improving flood control, water supply, water quality and natural systems” (SFWMD 1949). Within the Coral ECA, federal, state, county, and other regional partners survey and monitor their respective water resources. Together, a framework similar to watershed-based approaches is taken whereby the unique spatial footprints of the land areas that contribute distinct suites of drivers and pressures to the local water resources are defined. These unique areas of influence, each called an inlet contributing area (ICA), are directly connected to the Coral ECA through the barrier island inlets that act as point sources for the input of terrestrial water (and its dissolved constituents) into the marine system (Pickering and Baker 2015). Each ICA corresponds with one of the nine inlets located within the Coral ECA (from N to S: St. Lucie Inlet, Jupiter Inlet, Lake Worth Inlet, Hillsboro Inlet, Boynton Beach Inlet, Boca Raton Inlet, Port Everglades Inlet, Baker’s Haulover Inlet, and Government Cut; Figure 2). These ICAs can be used to model the ecological connection between human land uses and the nearby coral reef ecosystem (Pickering and Baker 2015).

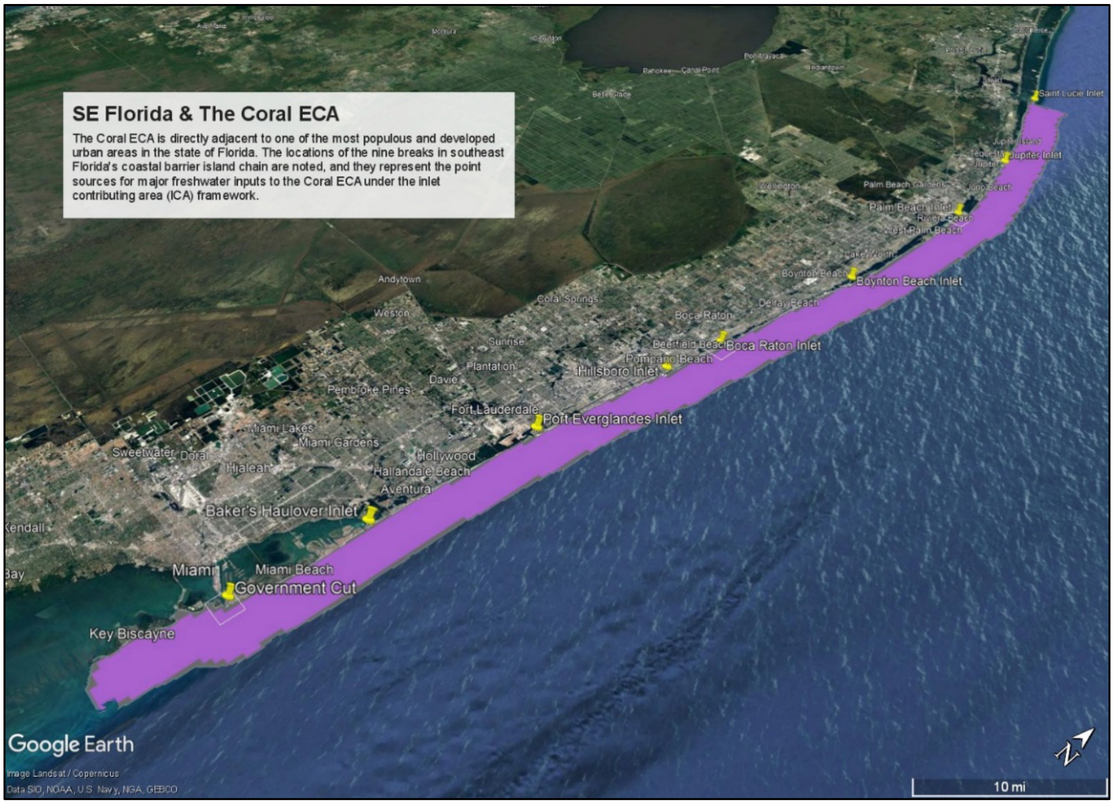


Figure 2. Coral ECA and SE Florida's Urban Coastline. See inset text for details.

Thus, when considered holistically, the Coral ECA is a highly dynamic, complex adaptive system (Holling 1987, Levin 1998, Walker, Carpenter et al. 2002) with new and emergent systemic properties, both described by and resulting from, the interactions between its drivers, pressures, statuses, ecosystem services, and management responses (Fletcher, Nuttle et al. 2013, Kilborn 2022, Kilborn and Lizza 2022). In more qualitative terms, the aquatic medium supports a highly variable physical and chemical environment within which the relatively sessile benthic and highly mobile fish resources reside. Therefore, the status responses among the components of the latter two subsystems, while themselves being interdependent, are disproportionately impacted by the variability of the former over both space and time. Of course, all are directly affected by the footprint of human activities within the region as well. Furthermore, these subtleties are complicated by the unique hydrology of the area (Lee, Yoder et al. 1991, Sponaugle, Lee et al. 2005, Fletcher, Nuttle et al. 2013) related to the Coral ECA's proximity to the Gulf Stream (Figure 3), the geomorphological features within the coral habitats that constrain or modify its flow, and the alteration of the reef's physical profile due to erosion or deposition of accretionary materials and sediments.

2.2. Monitoring the Water Quality Subsystem

The water quality subsystem is an integral part of the Coral ECA, and the drivers and pressures that affect its status and ecosystem services are not limited to only those activities

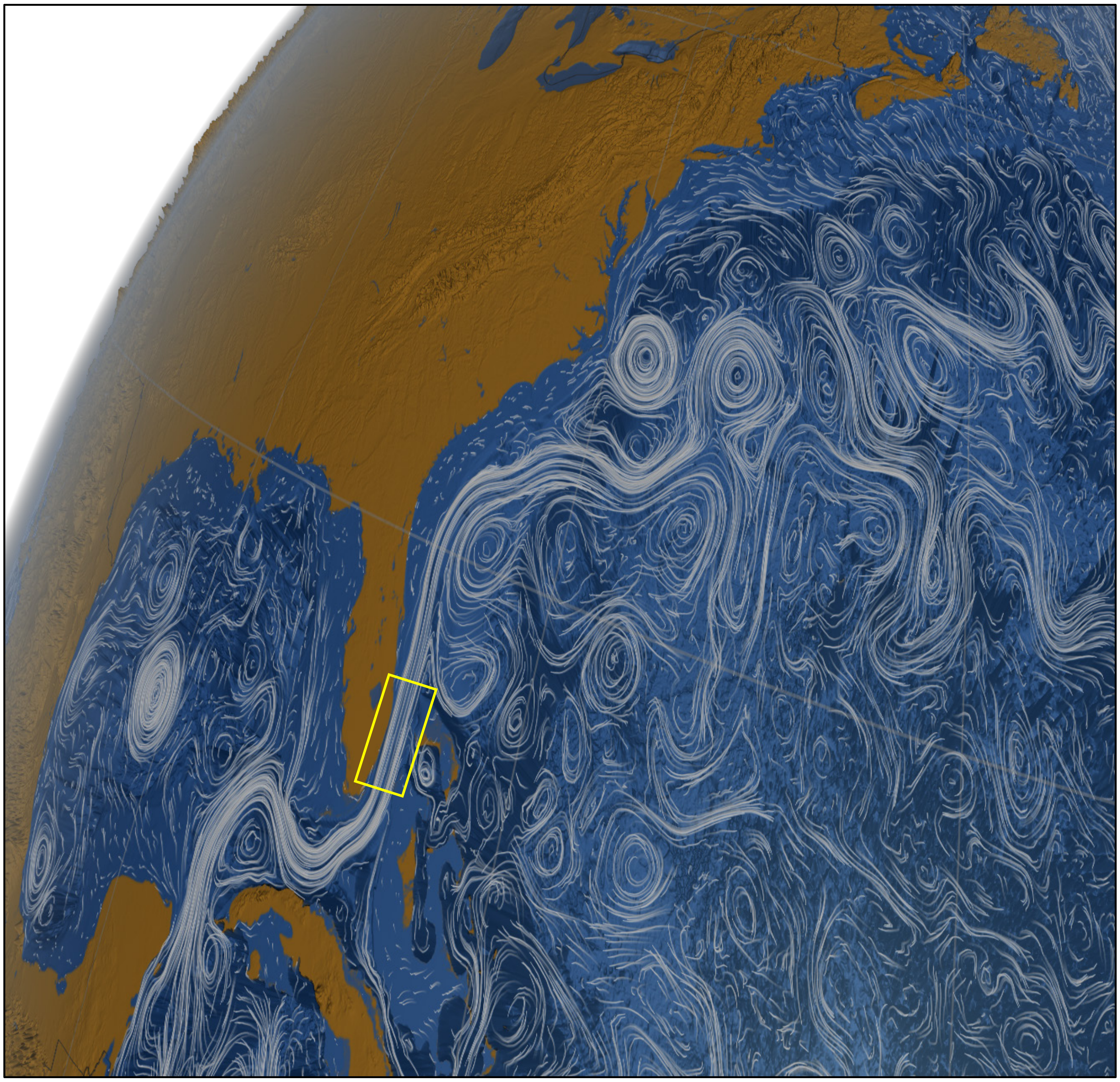


Figure 3. Visualization of the Gulf Stream Current. Modeled prevailing water flow regimes for the Gulf of Mexico and Atlantic basin from NASA/Goddard Space Flight Center Scientific Visualization Studio. The yellow box represents the approximate location of the Coral ECA.

occurring within the marine context (Carsey 2013, Fletcher, Nuttle et al. 2013, Gregg and Karazsia 2013, Whitall, Bricker et al. 2019). It is important to understand both the aquatic and terrestrial elements that may impact coastal water quality, particularly in a high population-density area, and include: sedimentation and coastal construction; fluvial, sub-aqueous, and run-off related freshwater inputs; nutrient and toxicological fluxes; pathogenic and other microbial constituents; and other chemical pollutants (e.g., dissolved metals, hydrocarbons, pharmaceuticals). Furthermore, the status, structure, and function of this subsystem can be measured by examining changes to: water clarity and the light environment; food-web dynamics; phytoplankton and zooplankton community compositions and turnover rates; and the concentrations (or levels) of many of the same characteristics that might otherwise be considered drivers and/or pressures (e.g., salinity, dissolved oxygen, nutrients) to the status of water quality.

In addition to traditional water quality characteristics, it is also important to account for the physical locations of input sources (e.g., sewage outfalls, ICAs) along with the local hydrological conditions into which they are introduced. The Gulf Stream's continuous northward flow (Figure 3) combines with the morphology of the coral reefs and ridges along the continental shelf to produce local hydrodynamics within the Coral ECA that amounts to a constantly evolving system of fronts, meanders, and eddies (Lee, Yoder et al. 1991, Sponaugle, Lee et al. 2005). Given these considerations, the various constituents entrained in the water from points upstream (including the Gulf of Mexico and Mississippi River via the Loop Current), and the strong coastal influences from high urban development, the water quality subsystem within the Coral ECA is considered highly complex and dynamic.

Covering the full extent of the Coral ECA, there are two programs that directly monitor and survey water quality attributes *in situ*, and they are the Coral ECA Water Quality Assessment (WQA; Whitall, Bricker et al. 2019, Whitall and Bricker 2021) and the National Coral Reef Monitoring Program Climate and Carbonate Chemistry surveys (NCRMP-CCC; Towle, Allen et al. 2021). The WQA uses a fixed monitoring design focused on inlet canals (Figure 2) and sewage outfalls, but also incorporates a number of randomly selected stations (see Kilborn (2022), Appendix C) that are meant to capture a more comprehensive characterization of the Coral ECA's water quality. Furthermore, the repeated monthly observations across the universe of fixed stations allows the WQA program to evaluate the status of the water quality subsystem and track trends over time (Whitall, Bricker et al. 2019). This design also takes full advantage of the ICA framework (Pickering and Baker 2015) and can be particularly useful in studies that seek to link terrestrial activities to aquatic outcomes. Water samples are collected and analyzed at National Environmental Laboratory Accreditation Conference (NELAC) certified facilities beginning in 2017, continue through the present, and capture data on 14+ different analytes (Table 1).

Beginning operations in 2018, NCRMP-CCC employs a bi-annual, random stratified survey design to monitor a suite of climate-related environmental attributes across the Coral ECA (Towle, Allen et al. 2021). The purpose of NCRMP-CCC is to capture the effects of planetary changes in ocean temperatures and acidification on the vital processes and rates that govern coral reef structure and function (Towle, Allen et al. 2021). Thus, measurements of standard water quality parameters such as temperature, salinity, and depth are captured along with a number of carbonate chemistry characteristics, including total alkalinity, aragonite saturation state value, dissolved inorganic carbon content, partial pressure of CO_2, and pH (Table 1). The NCRMP-CCC survey is performed in conjunction with the reef fish visual census (NCRMP-RVC) and benthic line point-intercept and belt

Table 1. Comparison of Water Quality Attributes Collected Across Programs.

	WQP	WIN	ECA-WQA	NCRMP-CCC
Alkalinity	x			x
Alkalinity ($CaCO_3$)		x		
Ammonia (NH_3)			x	
Ammonia (N)		x		
Ammonia-Nitrogen	x			
Aragonite Saturation State				x
Calcium	x			
Chloride	x			
Chlorophyll-a, corrected for Pheophytin		x	x	
Chlorophyll-a, free of Pheophytin		x		
Chlorophyll-a, uncorrected for Pheophytin		x		
Chlorophyll-a/Pheophytin Ratio		x		
Depth, Secchi		x	x	
Depth, Site	x	x	x	x
Dissolved Inorganic Carbon (DIC)				x
Dissolved Oxygen	x	x		
Dissolved Oxygen Saturation		x		
Enterococcus Group Bacteria		x		
Fecal Coliforms		x		
Fluoride	x	x		
Hardness	x			
Iron	x			
Magnesium	x			
Nitrate (NO_3)	x		x	
Nitrate-Nitrite (N+N)		x	x	
Nitrite (NO_2)			x	
Nitrogen, Total (TN)			x	
Nitrogen, Total Kjeldahl (TNK)		x	x	
Organic Nitrogen	x			
Orthophosphate (as P and PO_4)	x	x	x	
Partial Pressure of CO_2 (pCO_2)				x
pH		x		x
Pheophytin-a		x		
Phosphate-Phosphorous (as P and PO_4)	x	x		
Phosphorus (as P)		x		
Phosphorus, Total (TPO_4)			x	
Potassium	x			

Table 1 (cont.). Comparison of Water Quality Attributes Collected Across Programs.

	WQP	WIN	ECA-WQA	NCRMP-CCC
Residues, Nonfilterable (TSS)	x	x	x	
Salinity, Bottle				x
Salinity, CTD		x	x	x
Silicate (SiO)			x	
Sodium	x			
Specific Conductance	x	x		
Sulfate (as SO4)	x			
Tannin and Lignin	x			
Temperature	x			x
Total Organic Carbon (TOC)		x	x	
Turbidity	x	x	x	
Urea			x	

transect demographic surveys (NCRMP), and the site selection is based on a stratified random subset of the NCRMP-RVC sites. Across all of the NCRMP surveys the inferential scale is best set to the level of the entire Coral ECA, since the sampling designs are intended to capture broad trends within the geographically comprehensive monitoring unit and, in general, data at the site level should be pooled together (Towle, Allen et al. 2021).

In addition to the two *in situ* programs, there are several data warehousing services tailored to water-quality parameters where many short-term or discontinued programs house their results along with other existing programs (e.g., WQA). The U.S. Environmental Protection Agency (EPA) maintains their user submission and retrieval mechanisms, called the Water Quality Exchange (WQX) and Water Quality Portal (WQP), respectively (EPA 2018), where 25+ different federal, state, county and private programs contribute data related to the Coral ECA. Likewise, a Florida-specific version of WQP, referred to as the Water Information Network (WIN; DEP 2018), houses data by DEP and any other program using DEP-approved methods and NELAC certified laboratories. Furthermore, some of the data in WIN may also be housed by WQP, and both systems provide access to many comparable water quality attributes (Table 1). Lastly, the SFWMD also maintains a database of environmental observations related to hydrogeologic, hydrologic, meteorologic, and water quality parameters called DBHYDRO (SFWMD 2020, SFWMD 2020). This effort is a large-scale undertaking that encompasses data from the entire SFWMD. The sampling locations, dates/times, methods, and experimental designs vary across all data warehouses' entries, thus considerable effort will be required to produce holistic datasets from these sources with inferential frames relevant to FDOU-51.

2.3. Monitoring the Benthic Subsystem

Like the other two subsystems, the benthic subsystem is a complex adaptive system embedded within the larger adaptive system that is the Coral ECA. The physical reef structures vary depending on location and their current morphologies are linked to historical rates of coral reproduction and recruitment, growth, and mortality (Toth, Stathakopoulos et al. 2019), as well as the ambient hydrodynamics that contribute to erosion (Lidz and Shinn 1991, Banks, Riegl et al. 2007). These attributes are all measurable and can be used to determine their relationships with other measurable characteristics of benthic communities, such as biodiversity, species composition and abundance, spatial distributions, colony sizes, and percent-cover for benthic functional groups. Additional measurable impacts to the benthic subsystem include: disease presence and mortality rates; mechanical damages due to anchoring or vessel grounding; climate change effects (e.g., temperature, ocean acidification, storm frequency and intensity), and marine construction (e.g., sedimentation, altered circulation). While the fish subsystem measurably affects the health of the benthic subsystem via herbivory, bioerosion, and other ecological interactions (Hixon 1997, Cole, Pratchett et al. 2008), water quality (and movement) is thought to have an outsized effect on the benthic subsystem's structure and function due to its role as the primary physical medium within which the benthos resides. Comparatively, any changes noted to the composition of the fish subsystem would more likely be representative of prior changes to the benthos (or water quality) than *vice versa*.

Within the Coral ECA, there are three benthic monitoring efforts collecting long-term, *in situ* data, NCRMP (see above), the Florida Reef Resilience Program's Disturbance Response Monitoring (DRM; FWC 2020), and the Southeast Florida Coral Reef Evaluation and Monitoring Project (SECREMP; Gilliam et al. 2021). Each program was initialized with their own focus, resulting in unique inferential frames appropriate to their sampling design and survey protocols. However, some programs were designed to coordinate with others; for example, NCRMP conducts concomitant sampling for all three of the subsystems under review here within its program, and the DRM sampling design was made to augment the data collected by NCRMP.

The NCRMP benthic surveys began in 2014 and are conducted on a bi-annual basis in even years, during the late-summer through fall, in up to 30 m water depth. Benthic sampling sites are randomly subsampled from the NCRMP-RVC fish surveys which are randomly stratified by reef zone, depth, and rugosity (Roberson, Viehman et al. 2014, Towle, Allen et al. 2021). Recall that the purpose of the NCRMP's biological monitoring is to assess the status and trends in the benthic community and, in particular, in the reef-building corals and the fishes that utilize the benthic ecosystem (Towle, Allen et al. 2021). Further, it is notable that the scale of inference relative to NCRMP is that of the whole Coral ECA, and substrata-level information should be carefully analyzed and interpreted. Benthic monitoring consists of demographic belt-transect surveys for corals 4+ cm, selected macro-invertebrates, and other endangered species act listed taxa, as well as line point-intercept surveys for other benthic substrates, biogenic habitats, and reef rugosity (Table 2).

The Florida Reef Resilience Program's DRM survey has been sampling the Coral ECA annually since 2005, and this former Nature Conservancy initiative was originally developed to gather information about the effects of water temperature increases (i.e., coral bleaching) on shallow-water reefs (≤ 20 m) from Martin County to the Dry Tortugas (FWC 2020). However, since the discovery in Florida of Stony Coral Tissue Loss Disease (SCTLD) in 2014 (Muller, Sartor et al. 2020), the DRM protocols were altered to collect detailed data on diseased coral colonies throughout the survey's range. The survey was intended to capture information at the FRT scale, but can be used at the sub-regional level that roughly corresponds to the counties in the case of the Coral ECA (FWC 2020). Site selection is derived from a probabilistic experimental design based on factors such as habitat type, density of sensitive corals, coral variability and other coral reef characteristics, and sampling overlaps with the universe and timeframe used for the NCRMP surveys. Belt surveys are performed to collect coral demographic information for all colonies 4+ cm as well additional information for key species that are endangered, notable (i.e., *Diadema antillarum*), or known to be susceptible to SCTLD (Table 2). Furthermore, the disease information that is collected by DRM covers 10+ specific diseases or other disturbances, and incorporates estimates of impact, mortality recency, and predation (Table 2). DRM also collects rugosity data at each sampling location. Lastly, because DRM sampling is performed annually, this program provides a much longer time series to draw from and can be useful for discovering long-term trends in both coral community change, but also disease impacts.

Beginning in 2003, the SECREMP effort was specifically developed to monitor benthic habitat with the aim of documenting reef community changes through time over the entire spatial extent of the Coral ECA in order to better inform management and decision making (Gilliam, Hayes et al. 2021). As of 2013, SECREMP surveys employ a sampling design with 22 fixed sites (Kilborn and Lizza 2022) selected using a random stratified framework designed to fill in known location or habitat gaps (Gilliam, Hayes et al. 2021). The data collected at each station represents a very thorough cataloging of the benthic habitat (Table 2, Table 3) and consist of a belt-transect survey for stony coral (2+ cm) demographics, octocorals, and *Xestospongia muta*, in addition to a photo-transect point-count survey to assess percent-cover for a number of different taxa. Since the SECREMP monitoring is conducted annually at fixed locations the inferential framework is appropriate for capturing long-term trends throughout the Coral ECA. Furthermore, this program deploys data loggers at each station that collect temperature data at the depth of the coral reef every two hours throughout the year. Finally, like the other two benthic monitoring programs, SECREMP collects data related to reef rugosity.

Table 2. Comparison of Measurable Attributes Across Three Major Benthic Monitoring Programs in the Coral ECA.

	SECRMP	DRM	NCRMP	
Coral Demographics				**DRM SCTLD Targets**
Census All Species ≥ 4 cm	2013	2005	2014	*Colpophyllia natans*
Census All Species ≥ 2 cm	2018	-	-	*Dichocoenia stokesii*
Bleaching	x	x	x	*Diploria labyrinthformis*
Disease Presence	x	x	x	*Meandrina meandrites*
Disease Type		x		*Mussa angulosa*
Juvenile Colony Count	x	x	x	*Mycetophyllia aliciae*
Max. Diameter	x	x	x	*Mycetophyllia ferox*
Max. Height	x	x	x	*Mycetophyllia lamarckiana*
Morality Recency	x	x	x	*Pseudodiploria clivosa*
Mortality/Tissue Loss (%)	x	x	x	*Pseudodiploria strigosa*
Other Disturbances	x	x	x	**DRM Diseases/Other Disturb.**
Predation	x	x	x	Stony Coral Tissue Loss Disease
SCTLD Target *spp.*		x		White Plague
***Macro-Inverts & ESA Corals**				White Band Disease
Acropora cervicornis		x	x	White Pox
Acropora palmata		x	x	Rapid Tissue Loss
Dendrogyra cylindrus		x	x	Dark Spot Disease
**Diadema antillarum*		x	x	Black Band Disease
Mycetophyllia ferox			x	Red Band Disease
Orbicella annularis			x	Discoloration
Orbicella faveolata			x	Abrasion
Orbicella franksi			x	Overgrowth
**Panulirus argus*			x	Sedimentation
**Panulirus guttatus*				Clinoid Infestation
**Strombus gigas*			x	Mucus Sheathing
Line Point-Intercept Surveys				
Algae, Coralline Encrusting	x		x	
Algae, Macro	x		x	
Algae, Turf	x		x	
Octocoral/Gorgonian	x		x	
Pavement/Hardbottom	x		x	
Rubble	x		x	
Rugosity	x	x	x	
Sand	x		x	
Sponge	x		x	
Stony Coral	x		x	
Zoanthid	x		x	

Table 3. SECREMP Sponge and Octocoral Survey Details.

Barrel Sponges	Octocoral Demographics
Census All *Xestospongia muta*	Total Count - All Species
Bleaching	Census *Antillogorgia americana, Eunicea flexuosa, Gorgonia ventalina*
Disease Presence	Bleaching
Max. Base Diameter	Disease Presence
Max. Diameter	Max. Height
Max. Height	Other Disturbances
Other Disturbances	Predation
Predation	

2.4. Monitoring the Fish Subsystem

The fish subsystem is also a complex adaptive system, and is the one most dependent on the other two. Many fishes rely on structural habitat for food or shelter, and all are susceptible to changing water quality conditions. As such, the fish subsystem responds to a number of natural drivers and pressures that can act to reorganize the status, structure, and function of fish communities. These natural factors can include those ranging from the very large-scale (e.g., climate change, temperature shifts, acidification, increased storm intensity/frequency), to the very small (loss of spawning habitat, variable local water quality conditions, invasive species). On the other hand, the fish subsystem in the Coral ECA is subjected to heavy anthropogenic influences by way of very high tourism and a vigorous SCUBA diving industry (Johns, Leeworthy et al. 2001, Fletcher, Nuttle et al. 2013), along with strong recreational and commercial fisheries (Johnson, Harper et al. 2007, NMFS 2018). Additionally, the modes of fishery utilization are very diverse and include spear-fishers, private and charter hook-and-line anglers, as well as commercial fisheries for crabs, clams, flounders, groupers, mackerels, oysters, snappers, swordfish, tuna, and more (Johnson, Harper et al. 2007, NMFS 2018). One other notable aspect of this area is that the recreational sector appears to outpace the commercial with respect to both total finfish landings as well as the number of vessels (Johnson, Harper et al. 2007).

Measurable attributes within this subsystem include population statistics (e.g., species census data, biodiversity, age/size structure, growth rates, fecundity, etc.) and catch/yield values that are required for stock assessment and management of populations. Other measurable attributes for the fish subsystem include juvenile abundance, prey availability, habitat variability, fishery utilization; all of which ultimately impact fishery management decisions regarding total allowable catch levels, albeit over larger spatial scales than the Coral ECA itself. Collection of fishery independent monitoring (FIM) data is limited within the Coral ECA, whereas fishery dependent monitoring (FDM) data is much more readily available. However, FDM data collection is highly targeted, economically driven, and does not capture the complexity of the ecological fish subsystem like more scientifically-derived FIM data would. Furthermore, FDM data collection programs are not designed to operate at relatively small scales such as that of the Coral ECA, and so, while the data are readily available, they are not as useful within the context of FDOU-51. The FIM data collection is performed bi-annually by NCRMP-RVC and are, therefore, suitable for FDOU-51.

The NCRPM-RVC effort began as the Southeast Coral Reef Fishery-Independent Baseline Assessment that ran from 2012 through 2016 (Kilfoyle, Walker et al. 2018) and was incorporated into NCRMP in 2018 (Towle, Allen et al. 2021). Thus, there is a sampling gap every odd year starting in 2017. Nevertheless, this reef fish census represents the only comprehensive FIM program operating continuously throughout the Coral ECA. The NCRMP-RVC program within the Coral ECA was designed to fit seamlessly with the existing RVC program that already sampled from Biscayne Bay National Park through the Florida Keys, and uses a stratified random sampling design (Smith, Ault et al. 2011) that was adapted based on local knowledge (Kilfoyle, Walker et al. 2018). Natural hardbottom habitat in < 30 m water depth is targeted, and sampling locations were randomly drawn from a stratified grid system. The strata incorporate five subregions (Broward-Miami, Deerfield, S. Palm Beach, N. Palm Beach, and Martin), three slope relief types (high, low, and n/d), and 17 different benthic habitat classifications that account for reef type (e.g., ridge, patch, spur and groove), depth (deep, shallow), position (inner, middle, outer), or other habitat class (e.g., seagrass, unconsolidated sediment). Data collections are made from May through October. At each sampling site, RVC stationary point-count surveys (Bohnsack and Bannerot 1986) are conducted to record the names, numbers, and size ranges of all species that are present. In addition to fishes, habitat characteristics are also recorded, including GPS coordinates, slope of substrate, maximum vertical relief (hard and soft), surface relief coverage proportion (hard and soft), abiotic footprint, major biotic cover, habitat type, underwater visibility, water temperature, and current strength (Kilfoyle, Walker et al. 2018, Kilborn 2022).

2.5. Data and Monitoring Gaps in the Coral ECA

The data and monitoring gaps elucidated by FDOU-51 can be summarized as the needs to acquire more information in the Coral ECA about: (*i*) the biological constituents utilizing the system and their population dynamics; (*ii*) water quality issues; and (*iii*) the availability of resources and funding to support time in the water, management of the data for existing programs, and/or the expansion of these survey efforts.

2.5.1. Data and Information Gaps

In many cases, data about various attributes of the Coral ECA's subsystems are simply not being collected or, if they are, the spatiotemporal resolution does not match that required for the specific management purposes of SEFCRI or the ecosystem conservation area. The latter issue is the case with respect to FDM across the fish subsystem, such that all of the dependent monitoring data collected throughout the region are used for managing fish stocks at spatial scales far greater than the Coral ECA (Kilborn 2022, Kilborn and Lizza 2022). Therefore, the fisheries removals from only this system are neither readily available nor reliable for management purposes. Nevertheless, several county-level data aggregations can be assembled for various commercially and recreationally important species but, once again, these are of limited value and are missing some desirable attributes such as depredation rates and release condition assessments. Furthermore, there are almost no data regarding rare and reclusive fishes, and there are no regular plankton surveys that were uncovered or discussed in meetings for this project thus far.

Other important biological attributes that are conspicuously absent from monitoring programs are related to the benthic subsystem. In particular it was noted that targeted data regarding the reproductive timing of corals and new recruit success in the Coral ECA were lacking. There are also no standardized data collections on any aspects of coral demographics or cover on artificial reef structures throughout the area. While the DRM program conducts extensive monitoring of the presence and effects of diseases throughout the Coral ECA, areas of interest for which there are little to no data are the potential sources and transmission vectors of the pathogens. Most stakeholder conversations regarding these issues centered around coral diseases, however, this topic is germane to both fishes as well as humans.

A number of data and information gaps were also related to the water quality subsystem, but the interests are generally rooted in the biological responses to water conditions. For example, one area of water quality where data are desired but missing is toxicology. Besides the Mussel Watch program (NOAA 1986), there is very little information about the toxic contaminants in the water of the Coral ECA, and this includes (but is certainly not limited to) heavy metals, polycyclic aromatic hydrocarbons, polychlorinated biphenyls, pesticides, pharmaceuticals, and other organic and inorganic pollutants. In addition, more nutrient attributes could be collected in addition to those already monitored (Table 1), as could environmental-DNA (eDNA) to help understand additional biological characteristics within the water quality subsystem.

Other physical aspects of the aquatic medium of the Coral ECA are also absent from current monitoring programs, such as high-resolution surveys for turbidity and suspended solids, both of which are critical to understanding light environments and depositional rates (or sediment removals). These can both be important to understanding food-web dynamics (Mallin, Cahoon et al. 1999, Radabaugh, Malkin et al. 2014) and coral growth and survival rates (Houlbreque, Tambutte et al. 2003). Hydrodynamic considerations related to circulation patterns, wave energy, and storm events throughout the Coral ECA also have direct impacts to the geomorphology of the reef system and the advection of all waterborne constituents, both good (e.g., nutrients, food) and bad (e.g., pollutants, pathogens). There exists no hydrodynamic models or standardized physical data collection throughout the Coral ECA that was uncovered in this phase of FDOU-51.

2.5.2. Survey Design and Monitoring Program Gaps

In addition to the specific gaps related to data streams and attributes, many discussions eventually turned to availability of resources and funding to improve, augment, or expand existing monitoring efforts in order to enhance predictive capacities and management decision making (Kilborn and Lizza 2022). Thus, in all cases and given the importance and utility that all of the monitoring programs described here have already exhibited for the Coral ECA, there exists a need for permanent funding with regularly scheduled increases for rising costs associated with the highly complex logistical challenges of *in situ* marine sampling. Since many of the conservation area's monitoring programs are designed to complement each other (Kilfoyle, Walker et al. 2018, Whitall, Bricker et al. 2019, FWC 2020, Gilliam, Hayes et al. 2021, Towle, Allen et al. 2021), it is also critical to note that should any one of them be unexpectedly terminated it would create very large surveillance gaps either spatially or temporally. For example, should either the DRM or SECREMP programs cease to collect data, the odd-numbered years would immediately stop being fully represented in the benthic data collection efforts, since the only remaining program operating throughout the Coral ECA would be NCRMP operating bi-annually.

The bi-annual sampling issue is also very prominent in the fish subsystem, where the only data available to represent this system throughout the Coral ECA's full spatial extent are NCRMP-RVC independent monitoring data. While this sampling frequency may be adequate for relatively sessile organisms like corals, it is far less appealing for researchers who aim to investigate and manage fish resources. Indeed, many fishes move regularly throughout the year due to ontological and seasonal factors, and the interannual variability in a number of environmental factors can also lead to large shifts in populations' status, structure, or function (Helfman, Collette et al. 2009, Kilborn, Drexler et al. 2018). Furthermore, fishing activities and disturbance events (e.g., oil spills, hurricane damage) can also disproportionately affect fish populations on relatively short timescales (Clark 1977, Murawski, Kilborn et al. 2021). Therefore, another critical monitoring gap in the area is related to FIM data collection frequency, and at the very least additional resources are desired for annual data collections. Another sampling-design related gap in FIM data are the lack of information from deeper reef structures, and for artificial reefs throughout the region, as only relatively shallow natural reefs are currently surveyed (Towle, Allen et al. 2021). Artificial reefs are known to support different communities of fishes than natural reefs (Thanner, McIntosh et al. 2006, Arena, Jordan et al. 2007, Phipps, Wood et al. 2018), and they can also be instrumental for tracking pelagic or migratory species utilizing the habitats (Paxton, Newton et al. 2020), thus their lack of monitoring is likely a critical gap.

Other sampling resolution design improvements identified were related to water quality monitoring, where incorporating more randomized elements would be desirable since, aside from the NCRMP-CCC survey, primarily fixed-station sampling is currently employed in the Coral ECA. Furthermore, this dovetails with other identified sampling gaps calling for even higher spatial sampling resolution, such as flow-through systems that capture continuous *in situ* observations, and which would be critical for improving water quality models, reporting, and predictions. In addition to spatial improvements, even finer scale temporal sampling (i.e., frequencies < 1 mo.) for water would also be beneficial to management, as it is well known that water characteristics change very rapidly throughout the coastal marine environment. These structural monitoring changes, in conjunction with the addition of new analytes and water clarity indicators, would greatly improve the surveillance and monitoring capabilities of the SEFCRI managers and would likely be even more successful if implemented through the lens of the ICA framework.

Lastly, with respect to water quality monitoring, there are considerable gaps in the data streams resultant from *in situ* monitoring due to method detection limits (MDLs), and the contention by some stakeholders in collaborative meetings was that this is a result of relying only on NELAC certified laboratories for sample processing (Kilborn and Lizza 2022). Furthermore, if greater proportions of the data are reported as "non-detects" that are below the MDLs, then the costs associated with those samples being collected are essentially wasted. Thus, to improve the return on investment for these sampling efforts, it would be better to either reduce the restriction for NELAC certification (if scientifically and legally tractable) or attempt to improve the MDLs in the laboratory setting. Alternatively, there are methods that can be used to help estimate an appropriate value for imputation of those values below the MDL, but these methods are not generally agreed upon within the scientific community (Briceño, Boyer et al. 2022, McEachron, Bohnsack et al. 2022) and challenges remain.

Finally, the last major programmatic gap that was discussed across all subsystems was the concept of coincidental sampling. Only NCRMP conducts observations across all three of the Coral ECA's conceptual subsystems used in FDOU-51, and non-coincident sampling ultimately creates a whole series of problems when attempting to marry together different datasets and monitoring results. However, in order to begin to understand the networks of connections within and among these complex adaptive systems at each of their inferential scales, and to uncover the patterns and trends across the Coral ECA and its resource pools, cross-cutting themes and questions must be investigated across all three subsystems simultaneously. Therefore, it would be very beneficial to increase the overlap both spatially and temporally for regular the monitoring of all of the Coral ECA, and doing so would only improve the ability to manage this conservation area sustainably into the future.

2.6. Cross-cutting Themes and Coordinated Studies

At the first FDOU-51 collaborative meeting, and with a broad spectrum of stakeholders from the Coral ECA, significant effort was spent on developing and ranking research ideas and monitoring priorities (Kilborn and Lizza 2022). Twenty-three of these research ideas were ultimately selected as the most important topics to study for the ongoing management and sustainable utilization of the modern coral reef ecosystem (Figure 4). These ideas

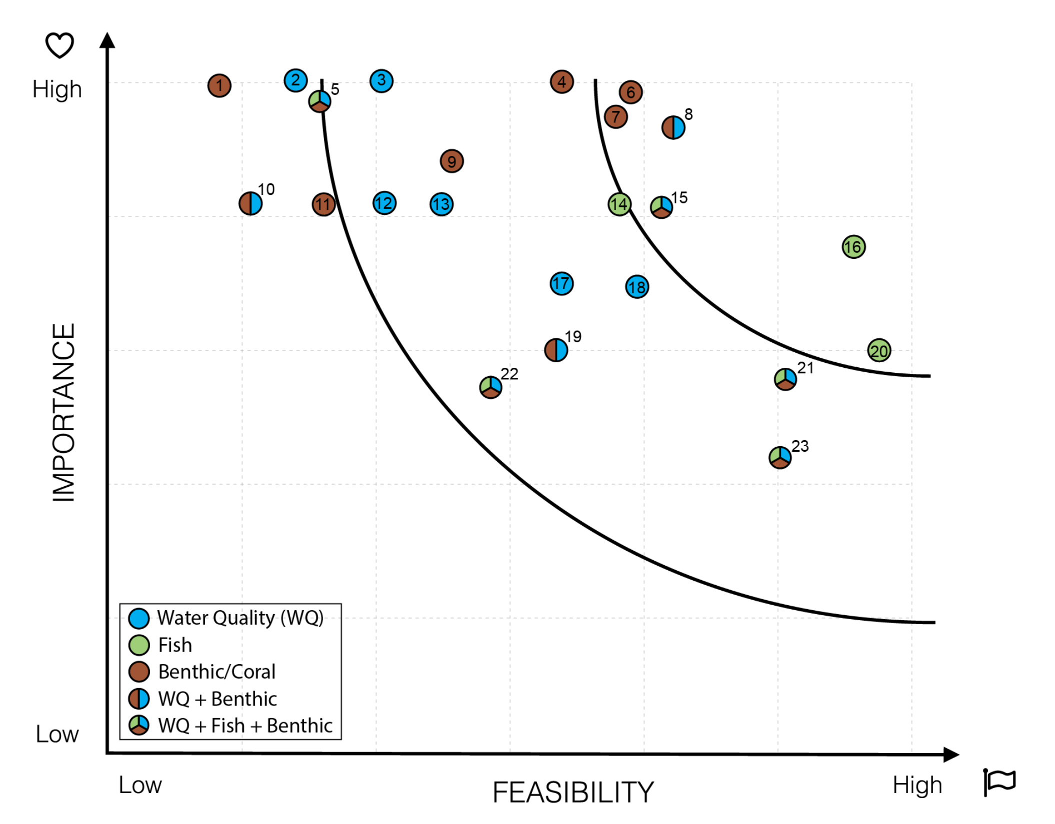
Table 4. Coral ECA Focus Areas for Research. Lists of the research and management priority focus areas that were developed by stakeholders participating in the first collaborative meeting for FDOU-51. Focus areas are listed in order of ranks developed by each group of attendees, and those noted in *italics* (*) represent those areas whose ideas were retained for further review and inclusion in the final research recommendations.

	Water Quality Subsystem	Fish Subsystem	Benthic Subsystem	Coral ECA Scale
1	**Experimental Design*	**FIM Utilization and Assessment*	**Leveraging and Continuing Monitoring*	**Water Quality Habitat Impacts*
2	**Detection Limits*	**FDM Stock Assessment Inputs*	**Nutrients and Turbidity*	**Cross-Discipline Modeling*
3	**Co-Location of Sampling*	**Metacommunity Analyses*	**Coral Recruitment*	**Disease*
4	New Parameters/Methods	Data Needs	Coordinated Sampling	**Indicators and Derived Indices*
5	Goal Setting	Management Uptake	Mapping	Data Acquisition
6	Data Analysis	Socio-cultural Considerations	Triage Mapping	Restoration
7	Hydrodynamics	Miscellaneous	Dedicated Funding	Coastal Construction
8	Miscellaneous	Trophic Interactions	Coral Reproduction	Rugosity
9				Fishing Pressure
10				Fish and Benthic
11				Climate Vulnerability
12				Resilience

comprised several research focus areas that were refined over the course of Phase-I. Eleven priorities became the basis for the four final research themes recommended for future investigation, including the theme ultimately proposed for Phase-II of FDOU-51. However, the details of the individual ideas and the overarching goals and priorities are worth additional discussion here.

2.6.1. Focus Areas for Research

During collaborative meetings (Kilborn 2022, Kilborn and Lizza 2022), stakeholders employed a series of *brainstorming → discussion → ranking* activities to determine sets of research priorities that captured the modern day needs of each subsystem. These ideas were assembled into groups that represented particular research topics, or "focus areas". Each subsystem's stakeholders developed a list of eight focus areas related to their facet of the Coral ECA and then, together, co-developed another twelve to capture those related to the coral reef ecosystem as a whole (Table 4). At the highest level, the focus area topics can be organized into two groups, one that aims to



1. Coral larval supply & recruitment success.
2. Model WQ indicators mechanistic impacts (ex: physiological) across subsystems.
3. Dredging & sediment relations w/ coral disease.
4. Coral disease & LBSP.
5. Monitor coral and fish to measure restoration success, account for population inputs and relate to coral-fish-WQ connections.
6. Role of reefs in coastal risk mediation.
7. Loss of rugosity in coral reefs due to mortality and bioerosion. Measure & compare to predictions.
8. Identify resilient reef areas using multiple data streams and data types (benthic & WQ).
9. SCTLD connection to harbors & boating.
10. Determine effects of coastal construction (near-shore and inshore) on adjacent reef communities and which have biggest impacts on the system.
11. Define what a "healthy" coral reef ecosystem looks like.
12. Evaluate acute vs. chronic impacts from different WQ parameters.
13. Coral ECA eutrophication thresholds & definitions.
14. Identify species or groups of interest for reporting (ex: indicator, ecosystem, fishery target, ESA, etc.).
15. Characterize "keystone" WQ attributes with greatest impact to high fish abundance/density/diversity & high coral cover/relief in space.
16. Fish abundance and density trends in Coral ECA.
17. Sedimentation effects on corals.
18. WQ impacts on coral condition - spatial analysis (near inlets and outfalls vs. background).
19. Determine metrics for key benthic habitat or WQ to assess the health of benthic habitat.
20. Ecologically driven fish assemblage shifts.
21. Compare FIM and FDM indices of abundance to assess fish population health for indicator species (identify species we think help identify health of benthic habitats or preferable water quality).
22. Compile existing monitoring of services over space and time, linking that to an ecosystem model (man-agement relevance + stakeholder buy-in).
23. Track changes in commercial/recreational fishing effort over time. Compare trends in fishing effort to changes in the qulaity of water & benthic habitat.

Figure 4. Importance vs. Feasibility Diagram for Select Coral ECA Research Priorities.

explore ecosystem-based scientific questions (e.g., coral reproduction, fishing pressure, water quality impacts), and another group more focused on areas related to the administration of marine resource monitoring and data collection (e.g., detection limits, experimental design, coordinated sampling). After ranking by the stakeholders, the research and management priorities from the top-three subsystem-scale and top-four Coral ECA-scale focus areas were retained for further discussion and ranking by the group. Ultimately, the best ideas were further scrutinized to determine their feasibility and importance, with 23 retained for development (Figure 4).

2.6.2. Feasibility vs. Importance

After selecting the final set of research and management priorities for consideration, they were plotted on a two-dimensional coordinate system where the horizontal axis represented the relative feasibility of completing the project given the current resources available, and the vertical axis captured the relative importance of each idea (Figure 4). Each idea's placement along either axis was determined by group consensus. Given that the priorities being plotted had already been filtered through multiple group discussions and ranking exercises, it was not surprising that all of the priorities were plotted in the top half of the importance axis, and this reinforces that all of the ideas generated and retained were, in fact, deemed to be important to the various stakeholders assembled.

The feasibility axis, on the other hand, displayed far greater variability in the placement of research priorities (Figure 4) indicating a much lesser degree of certainty from the stakeholders regarding the likelihood of successfully completing many of the tasks developed. In most cases, those ideas that scored lower on this axis did so due to a lack of data required to produce the desired results. Thus, several knowledge and data gaps discussed above were identified due to the development of the FDOU-51 research focus areas and this diagram.

2.6.3. Twenty-three Research and Management Priorities for the Coral ECA

Of the 23 research priorities selected, 15 were predominantly related to either the water quality (6), fish (3), or benthic (6) subsystems. Three more were related to both the water quality and benthic subsystems, and the remaining five addressed concerns that spanned all three of the Coral ECA's subsystems. Closer inspection of (Figure 4) revealed five course groupings of ideas (Kilborn and Lizza 2022) that were used to initialize and aid in the reorganization of eleven research priorities (Kilborn 2022) into the final four stakeholder-derived research themes described in the "Recommendations" section below. The five initial groupings of research ideas were as follows:

Group-1: *Beta-diversity of fishes and fish catches as indicators of Coral ECA, water quality, fish, and/or benthic health, structure, and function.*

Priorities: *16, 20, 21, 23*

This series of priorities was ranked highest of all of the groupings along the feasibility axis and included two of the five ideas addressing concerns spanning all three of the Coral ECA's subsystems. This group emphasized the identification of fish patterns across both FIM and FDM data sectors in order to determine if there are particular assemblages or species that are most indicative of various levels of water quality and benthic condition. Thus, this set of priorities suited the needs of FDOU-51 quite well in that it sought to characterize the changes in all three subsystems and relate those changes to one another in order to highlight potential connections and interactions that could be targeted for future management consideration.

> **Group-2:** *Water quality effects on the fish and benthic subsystems. Characterize indicator species/keystone attributes with the greatest impacts. Specific focus on sedimentation and spatial considerations. Identify benthic indicators of "health".*
>
> **Priorities:** *10, 14, 15, 17, 18, 19*

This group of priorities was tied for the second-most feasible and was the largest collection of ideas identified. Further, Group-2 encompassed priorities that were quite similar to those in Group-1, however, the general focus here was filtered through the lens of water quality rather than fishes. This set of ideas sought to describe the various spatial arrangements of unique water quality states that might affect the distribution and associations of fish resources and benthic habitats. It also aimed to specifically investigate impacts related to coastal construction and sedimentation on the status of water quality, and then ultimately to the nearby benthic communities. This was a very broad set of research priorities that were also well suited to address the requirements of FDOU-51.

> **Group-3:** *Core coral reef population dynamics and functional ecosystem services: larval supply, recruitment success, and resilient area mapping; changes to rugosity and overall coastal risk mitigation services from the reef.*
>
> **Priorities:** *1, 6, 7, 8*

This collection of ideas included three highly feasible priorities as well as another determined to be the least feasible of all (*Obj. #1*; Figure 4). This set of research priorities was built around the idea that coral reefs provide numerous risk mediation benefits to the adjacent coastal areas (Ferrario, Beck et al. 2014, Woodhead, Hicks et al. 2019), but that these services are closely related to the physical attributes of the reefs (i.e., rugosity). Thus, the overall resilience and population maintenance capabilities (i.e., larval supply, recruitment) of the benthic communities are critical to the performance of these ecosystem services over time. Resilience is a fairly complex issue to assess given the need for disturbance events and baseline data for *before vs. after* constrained analyses, and larval supply and recruitment success would be critical for these efforts. Furthermore, the scope of these projects did not include any fish subsystem considerations and may not fully fit the scope of FDOU-51. Nevertheless, this group of research priorities was deemed highly important to the Coral ECA and may still be appropriate for other LAS projects in the region.

> **Group-4:** *Coral disease sources and impacts. Particular focus on LBSP, dredging, and stony coral tissue loss disease (SCTLD).*
>
> **Priorities:** *3, 4, 9*

This set of priorities appeared relatively straightforward in its scope; however, it resided relatively low on the feasibility axis since the objectives are actually quite complex and sought to characterize specific mechanisms related to LBSP, vessel-related pollutants, dredging, and sedimentation that are responsible for the spread and intensity of coral disease outbreaks throughout the Coral ECA. As such, this focus area would require extensive *in situ* fieldwork and laboratory experiments to be accomplished, both of which would fall well outside the scope of FDOU-51. However, disease impacts, particularly SCTLD, have raised the profile of these issues in recent years and, therefore, they rank very high on the importance axis. Lastly, it should be noted that, like Group-3, this set of priorities did not include fish subsystem considerations.

> **Group-5:** *Defining a "healthy" coral reef ecosystem. Define eutrophication thresholds and assess acute vs. chronic impacts of water quality changes in the Coral ECA.*
>
> **Priorities:** *11, 12, 13*

This final group of priorities was also deemed to have relatively low feasibility, likely due to the work required to define what a "healthy" coral reef ecosystem means for the Coral ECA, as well as the focus on the role of eutrophication in that definition. By their nature, tropical coral reefs are often found in relatively oligotrophic waters (Hallock 2002), and in the case of the Coral ECA, the comparison of contemporary nutrient levels relative to some baseline period would be required in order to assign a magnitude of nutrient change over time. This is not trivial, requires extensive historical monitoring data to accomplish, and may not be a realistic objective for the FDOU-51 timeline and scope of work. Furthermore, the addition of the characterization of acute and chronic impacts to the benthos due to differential water quality states is also not trivial and would likely require additional observational work to complete. Once again, it should be noted that, like Group-2 and -3 above, this set of priorities did not include fish subsystem considerations.

3. RECOMMENDATIONS

3.1. Stakeholder Research Themes for The Coral ECA

Approximately half of the research ideas developed by stakeholders (Figure 4) were reorganized into the final-four, independent "research themes" (RT_i) that could each be pursued in a holistic assessment of the Coral ECA and its subsystems in Phase-II of FDOU-51 (Table 5). However, as the themes were explored, the scope of work and depth of the data considerations became clearer for each, and some themes were ultimately restructured. The research themes were largely focused on determining the organizational structures within the networks of resources comprising the Coral ECA's subsystems, and then investigating which aspects of one subsystem or another might have some influence over or help to qualitatively describe any patterns or trends uncovered. While all of the themes are relevant to the entire Coral ECA, they do exist along a relative gradient of ecological generality. Themes #1 and #2 both have broad applicability to the general understanding of large-scale patterns and trends in the Coral ECA and its subsystems (as well as how they relate to one another), whereas #3 & 4 are more specialized.

3.1.1. Theme #1: Fish as Indicators of Benthic Habitat and Water Quality

Vision Statement: *"To investigate the diversity, abundance, and size composition trends in fish resources on natural habitats within the Coral ECA. Examine any relationships between changes to water quality and/or benthic habitat. Identify fish species/functional groups indicative of different environmental conditions."*

Objectives: *16, 20, 21*

This research theme was derived from three stakeholder research priorities and is primarily focused on using fish diversity and other population metrics as indicators of the health, structure, and function for the water quality, fish, and benthic subsystems (Figure 4), and by extension for the Coral ECA. This theme would investigate patterns and trends in the resource pools of all three subsystems and then determine which notable fish species or communities were most indicative of various organizational states detected. This idea extends to other notable aspects of fish population dynamics such as growth rates, age, size, and sex distributions, or recruitment levels. It would also be feasible to utilize the ICA framework for water quality to investigate changes in fishes over space, and to link those changes back to various anthropogenic drivers and pressures. Further spatial subdivisions could be derived from the benthic subsystem based upon existing reef-type classification schemes or from new models derived from existing monitoring data. It is also important to note that this research theme has the flexibility to fully explore the directionality of these relationships among subsystems and with respect to fish specifically. For example, any unique patterns observed within the fish subsystem could be used to then try to understand which water quality or benthic attributes best account for them (*fish → water/benthic*) or *vice versa* (*water/benthic → fish*).

3.1.2. Theme #2: Water Quality Regimes and Benthic Species Indicators

Vision Statement: *"To define the key environmental conditions that associate with benthic assemblages. Determine which benthic species are most indicative of water quality regimes in the Coral ECA."*

Priorities: *14, 15, 19*

This theme was also derived from three stakeholder research priorities and is the only one of the final four research themes that only includes two subsystems: water quality and benthic habitat (Figure 4). During feasibility and research development meetings, stakeholders determined that given the completeness of the proposed investigations for the fish resources in RT_1, inclusion of that subsystem in this theme would be redundant. It was also believed at the time that both RT_1 and RT_2 may be recommended for Phase-II of FDOU-51; however, this was ultimately reconsidered due to the complexity of both themes' required data analyses and estimated workloads. Therefore, if both were to be run concurrently, they should be considered independent projects, but coordination and ample communication across the two would be ideal, as they have similar analytical frameworks and comparable outcomes.

Table 5. Stakeholder Derived Research Themes for the Coral ECA.

Theme	Thematic Focus	Research Ideas
RT_1	Diversity of fishes as indicators of Coral ECA, water quality, fish, and/or benthic health, structure, and function.	#20: Ecologically driven fish assemblage shifts. #16: Fish abundance and density trends in the Coral ECA. #21: Identify fish indicator species for benthic and water quality "health".
RT_2	Water quality effects on the benthic subsystem. Characterize indicator species/keystone attributes with the greatest impacts. Specific focus on spatial considerations. Identify benthic "condition" indicators.	#15: Characterize "keystone" water quality attributes with greatest impact to high diversity, along with high coral cover and relief in space. #14: Identify benthic indicator species or groups of interest. #19: Determine metrics for key benthic habitat or water quality to assess the health of the benthic habitat.
RT_3	Coral reef rugosity and the services that it provides (1) to the reef, and (2) to the adjacent coastal communities (e.g., storm risk mitigation, other?).	#6: Reefs as a coastal risk-mediation service over time. #7: Role of rugosity on reefs.
RT_4	Benthic resilience and resistance to coastal construction and sedimentation.	#8: Reef resiliency (independently and due to water quality changes). #17: Sedimentation effects on corals. #10: Effects of coastal construction on benthic communities.

Like the previous research theme, RT_2 would explore the patterns in one subsystem and then attempt to identify key indicators from another that could be used to describe, monitor, or otherwise account for them. In RT_2, however, the focus is on determining which specific environmental and water conditions might best account for different benthic communities' condition, structure, and function. Therefore, the benthic habitat would be the primary subsystem of interest throughout these analyses and the hypothesis would be that various aspects of the water quality subsystem act as drivers and pressures organizing any patterns or influencing any changes detected within it. This project would also lend itself easily to the ICA framework for water quality, and to many other spatial constraints related to benthic habitat types. Finally, these analyses should also be conducted in both directions, as discussed above for RT_1 (i.e., *benthic → water*; *water → benthic*).

3.1.3. Theme #3: Ecosystem Service Provisions of Reef Rugosity

Vision Statement: *"Examine the varying rugosity and geomorphology of reefs in the Coral ECA, and determine how this impacts the capacity of the system to provide risk-mitigation services to adjacent coastal communities. Estimate any relationships between reef rugosity and fish assemblages and benthic composition."*

Priorities: *6, 7*

In RT_3, the two underlying research ideas (Figure 4) bear relevance throughout the full extent of the Coral ECA. However, this theme focuses on the relatively specific effects of reef rugosity and geomorphology on the provision of coastal risk-mitigation services (e.g., storm protection), and the organization and distribution of fish and other benthic species assemblages. This work should assess the rugosity and structural changes on reefs due to mortality and bio-erosion, as well as estimate independent rates for each within the Coral ECA. Given that previous work suggested that the reefs off of Broward County weren't functioning as effective breakwaters to reduce the impacts from storms and that the verbiage used to describe ecosystem services provided by the reef were inaccurate, it would be appropriate to reassess these claims. There is a reasonable assumption that there is less coral and lower rugosity now than there was 20 years ago, and there is also ample demand for a proper accounting of the ecosystem services provided by the Coral ECA's benthic subsystem. It is also particularly timely given the predictions of increasing frequency and intensity of tropical storms and hurricanes in the region moving forward (Knutson, McBride et al. 2010).

The effects of rugosity and geomorphology on the health, structure, and function of the fish subsystem are important to investigate given the known connections between habitat complexity and fish foraging and sheltering behavior. Furthermore, this could be directly related to the valuation of any in-water services provided by the Coral ECA (i.e., fishing, diving, and other uses), including those indirectly related to the effects of shifting habitat types (e.g., species abundance, distribution, or ontogenetic timing shifts). Lastly, it is important to note that the connection to the water quality subsystem in this theme is primarily with respect to hydrological patterns. However, it could by hypothesized that large-scale changes to the porosity of the physical reef structure, or to the abundance of the relatively large sessile community of filter feeders could result in water quality status changes in some of the more traditional indices used for monitoring that subsystem (e.g., turbidity, nitrogen, phosphorus). Thus, to the extent possible, the influence of and impacts to the water quality subsystem should not be ignored in RT_3.

3.1.4. Theme #4: Coastal Construction and Sedimentation Effects

Vision Statement: *"Investigate the response of the Coral ECA's benthic communities (i.e., resilience and resistance) to coastal construction and sedimentation."*

Priorities: *8, 10, 17*

The final research theme prioritizes an investigation of the resilience and resistance capacities of Coral ECA's benthic (and benthic associated) resources to the effects of the relatively specialized impacts of coastal construction and sedimentation primarily due to dredging activities (Figure 4). In RT_4, suites of attribute indicators representative of different coastal construction pressures (e.g., beach renourishment, hotel construction) and ecosystem drivers (e.g., variability in turbidity, sediment discharge, or pollutant levels) should be assembled to determine the differential risks posed by various activities. Once the set of potential construction- or sediment-related events (or regimes) are identified, the specific effects on corals and other benthic habitats such as sponges, gorgonians, macroalgae, and seagrasses, as well benthic associated fishes, can be assessed. Where higher levels of resilience or resistance are noted, the indicator species associated with those areas would be determined.

Given that RT_{4F} is focused on coastal construction and sedimentation events, outcomes will be heavily geared toward the identification and definition of the "types" of events that create water quality disturbances at levels relevant to local benthic communities. Regardless of the method used to define event types, the description of the spatial (or temporal) footprint for each event type and the severity of impact to the reef system should be developed. Another important area of focus for this theme is to investigate how construction activities impact juvenile diversity, density, and survivability, but this should likely be constrained to the benthic subsystem due to a lack of juvenile fish and recruitment data in the Coral ECA (Kilborn 2022). Desired outcomes also include developing risk metrics for various benthic assemblages, mapping high risk or resilient areas, and updating construction permitting requirements to account for best management practices within this unique coastal ecosystem.

3.2. Management Strategies and Focus Areas

Several research areas were discussed by group members throughout the course of Phase-I for FDOU-51 that are not able to be pursued due to a lack of data or monitoring for the appropriate drivers, pressures, and statuses. In fact, only 11 of the original 23 research ideas prioritized by stakeholders were ultimately reconstituted into the final recommended research themes and, even among those final 11, there exists a gradient of data availability and compatibility considerations (Kilborn 2022). Therefore, there remain several opportunities for the development of new research and monitoring focus areas and strategies. Their inclusion in the future management of the Coral ECA would likely be beneficial, and they are discussed below.

3.2.1. Sources and Transmission Vectors of Waterborne Pathogens

Beginning with coral bleaching (Manzello, Berkelmans et al. 2007, van Oppen and Lough 2018) and increasing after the introduction of SCTLD to Florida's reefs (Hayes 2019, Hayes, Walton et al. 2022), there has been significant effort given to monitoring diseases that affect corals, as undertaken by DRM. However, the monitoring is mostly retrospective in that it only records the presence of active infection, or the aftereffects, and DRM does not record any characteristics of the microbial or genetic aspects related to any one malady or another. Since none of the sampling protocols investigate the potential sources or transmission pathways associated with these waterborne pathogens, predicting and responding to the new or spreading waves of infection are not possible. Some observers have noted a potential connection between diseases and LBSP (Gregg and Karazsia 2013), increased nutrients (Thurber, Burkepile et al. 2014, Lapointe, Brewton et al. 2019), vessel pollutants, and dredging and coastal construction (Pollock, Lamb et al. 2014); therefore, more directed effort into the microbial and toxicological constituents of the water within the Coral ECA, as well as the inputs from land and other anthropogenic sources as expressed through the ICA framework, is recommended. The influence of waterborne pathogens is not limited to the benthos, as fish and shellfish are also susceptible to these problems (Helfman, Collette et al. 2009, Murawski, Hogarth et al. 2014). Therefore, should any specific programs be developed to address these issues, it should not be executed on only one subsystem and observations should be made concurrently across as many subsystems as possible.

3.2.2. Acute vs. Chronic Impacts, Eutrophication, and Condition

In addition to disease and microbial monitoring in the Coral ECA, multiple stakeholders raised the issue of greatly increasing both the spatial and temporal resolution of water quality monitoring. This would have immediate benefits to the predictive and response capacities for the subsystem and would align better with the highly dynamic nature of this particular medium. Furthermore, it would enable studies to determine the quantitative thresholds that define qualitative terminology such as "acute" or "chronic" when discussing the particular impacts to both benthic and fish resources. The same objectives could be applied more broadly to define other ecologically important aspects at the scale of Coral ECA, such as eutrophication, or for making determinations about its overall condition or "health". These goals would likely be more manageable within the ICA framework, as there are a number of important anthropogenic factors that are spatially explicit (e.g., placement of wastewater discharge, proximity to major population centers, agriculture, or shipping). This strategic area would have benefits to both fish and benthic resources, and has relevance for future management given the likelihood of increased nutrient inputs and disturbances moving forward.

3.2.3. Coral Larval Supply and Recruitment Variability

All of the benthic surveys in the Coral ECA are focused on what is already present, and there is no regular monitoring into the supply-side dynamics associated with those communities. Therefore, it becomes very difficult to manage the future of coral resources in the region without understanding what the new inputs to the system are likely to be, and how well those new recruits are expected to do after settlement to the reefs. Thus, the utility of these efforts is reduced to a historical accounting of resources, with the potential to describe retrospective long-term changes over time. While this is useful for describing the qualitative changes observed over a certain period, it has less implications for future planning and management, except to update a sampling footprint or target attributes to observe. Even though it is very time consuming and resource-intensive work, developing comprehensive monitoring of larval supply and recruitment variability would be very beneficial to future management of these resources. In a race against time with these very slow growing animals, there will likely be no stopping coral population declines without fully committing to understanding this aspect of these iconic species' life histories.

3.2.4. Utilization of Additional Fish Monitoring Methods and Data

One of the major monitoring gaps in the Coral ECA is with respect to the fish subsystem, and represents an obvious opportunity for improving the management strategies of the region. Given the importance of commercial and recreational fishing in the area, additional effort must be paid to estimating the removals specific to the Coral ECA, as this is not well understood at this scale due to the sampling frameworks used for FDM data collection at the state and federal levels. Additionally, more attention should be paid to artificial habitats, since these are known to be very important to many fishes (Seaman, Lindberg et al. 1989, Thanner, McIntosh et al. 2006, Arena, Jordan et al. 2007, Phipps, Wood et al. 2018) and because the only full-scale fish monitoring in the Coral ECA is from NCRMP-RVC that is sampling only on natural habitats. Attention should also be given to methodologies that are not exclusively diver-based, as those methods have depth limitations and diver biases (Bohnsack and Bannerot 1986). Much like the missing larval supply information in the benthic subsystem, planktonic sampling would aid in the development of source-sink or recruitment dynamics for many species, and may even lead to new spatial understanding of spawning aggregations or other phenomenon.

3.3. Augmenting Monitoring and Data Collection within the Coral ECA

There are areas where changes or additions to monitoring or data collection efforts would result in better surveillance of the Coral ECA's water quality, fish, and benthic resources (Table 6) and, presumably, would improve the decision-making process for managers. These recommendations derive from conversations with stakeholders, the challenges related to combining existing programs' data streams together for holistic assessments, and other details discussed throughout this report.

3.3.1. Water Quality Monitoring and Hydrodynamic Modeling

Given that the only regular *in situ* monitoring of traditional water quality and nutrient parameters in the Coral ECA is conducted by the WQA program (Table 1), this is the best vehicle for adding new capacity to the water surveillance efforts of the region. Therefore, while the following recommendations are specific to the WQA, they could just as well be developed into a new program that augments the WQA or one of the other *in situ* surveys for another subsystem (i.e., NCRMP/RVC, SECREMP, DRM).

~ Improve analyte method detection limits or abandon analytes that are regularly below the limits as they ultimately consume financial resources that could be applied to other analytes or another recommendation listed below.

~ Increase the spatial coverage and resolution of the survey design, and include more random sampling stations to monitor broad-scale trends in water quality. This would also allow for measuring the downstream impact of water flowing through the inlets and would improve the ability to utilize the ICA framework for analysis and resource management.

~ Increase sampling frequency and/or deploy autonomous monitoring platforms in order to work toward real-time water quality surveillance and prediction.

~ Add more analytes to the program, including nutrients, pollutants, and pathogens. Additional coordination would be required to determine which new parameters to add, as the list of potential candidates is extensive and varied.

~ Upgrade field gear to safely obtain water samples at greater depths, as some stations are not able to be fully sampled due to this limitation. This would also allow for an extension of the spatial sampling frame for data collection.

~ Add flow-through observation systems for water sampling while in-transit between regular monitoring stations. This will also increase the downstream information content for the program.

Table 6. Comparison of the Coral ECA's Monitoring Programs' Analytical Capacities. For each long-term monitoring program identified within the subsystems of the Coral ECA, the associated surveys' sampling design-related considerations are noted in each column. Programs' cells that are noted with symbols indicate the disposition of the column's consideration within the original experimental design, specifically: **x** = included in original design; **+** = fixed sampling locations selected using randomly stratified designs; **•** = analyses potentially adaptable to the ICA framework with careful data quality controls. Cells that are shaded with the subsystem colors (blue = water quality; green = fish; gold = benthic) indicate those areas that would be improved upon if the recommendations in section 3.3 are enacted.

		Instantaneous Status	Temporal Trends	Spatial Trends	ICA Framework	Fixed Sampling	Randomized Sampling	Sampling Frequency	Spatial Inference	Depth Sampled	Original Intent/Notes
Water Quality	**NCRMP - CCC**	x		x	•		x	2 yr	Coral ECA	≤ 30 m	The effects of planetary changes in ocean temperatures and acidification on the vital processes and rates that govern coral reef structure and function.
	WQA	x	x		x	+		1 mo	ICA	< 30 m	Comprehensive characterization of Coral ECA's water quality status and track trends over time.
Fish	**NCRMP – RVC**	x		x	•		x	2 yr	Coral ECA	≤ 30 m	Assess the status and trends in the benthic and reef-associated fish communities.
Benthic	**DRM**	x	x	x	•		x	1 yr	Coral ECA	≤ 20 m	Originally developed to gather information about the effects of increasing temperature and coral bleaching on shallow-water reefs. Later augmented to collect more detailed data on diseased coral colonies.
	NCRMP	x		x	•		x	2 yr	Coral ECA	≤ 30 m	Assess the status and trends in the benthic community and, in particular, the reef-building corals.
	SECREMP	x	x			+		1 yr	Coral ECA	< 17 m	Documenting coral reef community changes through time over the entire spatial extent of the Coral ECA.

Lastly, two additional recommendations are given for general consideration within the context of monitoring water quality throughout the Coral ECA.

~ Develop a hydrodynamic model that can be used to predict near real-time fluid dynamics for the Coral ECA. This is well outside the existing capacity of any of the monitoring programs described in Phase-I of FDOU-51 (Kilborn 2022), and it would likely require additional physical oceanographic observations and monitoring-buoy deployments. However, upon implementation it would be a powerful tool that, when paired with high-resolution water quality and nutrient data, could be used to predict acute and chronic disturbances (e.g., impacts of rainfall related run-off, algal blooms, hypoxic events) as well as the potential fate of sediments or the byproducts of other coastal activities.

~ Perform concurrent water quality sampling with the fish and benthic subsystems to the extent possible. However, lags in the biological response to physiochemical changes is always a consideration, and should the ultra-high-resolution spatiotemporal sampling design recommendations above be enacted to their full extent, concurrent water sampling may become less necessary.

3.3.2. Fish Monitoring

The fish subsystem contains the largest data and monitoring gaps within the Coral ECA. This is due to the lack of FIM data collection and the inaccuracy of the FDM data at the reduced spatial scale of the conservation area. Therefore, the following recommendations would be very beneficial to improving management capacity and decision making for the fish and fisheries resources within the Coral ECA.

~ Perform annual sampling within the NCRMP-RVC program. Since their takeover of the FIM sampling of the fish subsystem after 2016, it has provided regular monitoring of natural hard-bottom and reef habitats on a bi-annual basis in even years. This leaves odd-year gaps in the monitoring of a subsystem that includes species with annual population turnover rates, as well as those that are known to respond to environmental variability at very short timescales. Annual sampling will close these data gaps and improve comparability across the relatively data-rich water quality and benthic subsystems.

~ Monitor artificial reefs across the entire Coral ECA for fishes. This will improve the surveillance of highly migratory species as well as those that are known to aggregate at these unique habitats (e.g., Goliath Grouper, jacks). These habitats are also prized for SCUBA diving, spearfishing, and hook-and-line angling, and monitoring them more closely could be beneficial for estimation of and valuation for the ecosystem services they provide. Lastly, it would also be useful to characterize the proportional contribution of artificial reefs to supporting the local fish populations when compared to the natural systems.

~ Employ more diverse fish monitoring methods. One way to improve both the spatial and temporal coverage of FIM monitoring is to use observation methods other than SCUBA diving-based surveys that are both depth-limited and logistically intensive. In particular, camera-based surveys are quite useful in areas with relatively clear visibility and can be deployed in almost any environment or depth that might be encountered in the Coral ECA. Additional methods that would be beneficial include plankton trawls to capture larval stages of fishes – an area where no regular effort is currently applied – or the use of eDNA.

~ Work with state and federal fisheries data analysts to develop a protocol for downscaling FDM data if possible. In lieu of this approach, a new program that performs FDM only at the scale of the Coral ECA may need to be developed. However, this is a very difficult task and may not have any actual fisheries management value given that those decisions are made at scales related to historical stock ranges and extents.

3.3.3. Benthic Monitoring

Out of the three subsystems within the Coral ECA, the benthic subsystem is, not surprisingly, the most comprehensively monitored. The three programs that survey these resources (i.e., DRM, NCRMP, SECREMP) do so in a way that result in annual observations across the entire range of the conservation area using both random sampling and fixed station frameworks. However, there are still some important aspects of this subsystem that could benefit from updating.

~ Collect high-resolution censuses of non-scleractinian biogenic habitats. While the benthic subsystem is very well monitored, it is mostly with respect to the stony-corals that this is true. Therefore, it would be worthwhile to monitor other living habitats comprising the benthos of the Coral ECA. This type of effort would help to gain a better understanding of the particular nuances and dynamics within these communities, but could also aid in determining if there were historical or contemporary successional changes evident across dominant habitat types and characteristics. This could include species-level data for macroalgae, seagrasses, sponges, octocorals, anthozoans, gorgonians, tunicates, and macro-invertebrates.

~ Develop and implement a larval supply and recruitment success monitoring program in the Coral ECA, or augment an existing program to include this aspect. Given the rate of coral declines previously documented across FCR, it would be wise to begin to scrutinize the sources, magnitudes, and demographics of annual coral larval supplies to the region. Following through on the fate of newly settled recruits provides information about the capacity of the system to support these nascent community members, and may also shed light on the critical tolerances that could limit productivity.

~ Implement large-scale substrate monitoring for erosional and depositional-rate changes across the Coral ECA using stakes and sediment traps at fixed sampling stations. This type of data would complement rugosity and geomorphology data, and could help to tune hydrographic models and provide estimations of habitat loss. These estimations could be tied back to observations made for the fish subsystem since the benthic subsystem serves as essential fish habitat. This type of monitoring would be relatively low-impact and require fewer resources than many other recommendations made here.

4. FRAMEWORK FOR FDOU-51 PHASE-II

The ultimate goal of FDOU-51 is to conduct a holistic analysis of the three primary subsystems that comprise the Coal ECA. Therefore, of the four stakeholder-derived research themes discussed above, Theme #1 is the most suitable for moving forward into Phase-II of this project. Throughout CM_2, statistical experts and Coral ECA monitoring programs' data providers and analysts convened to ascertain what the primary focus of the theme should be and how to perform the analyses (Kilborn 2022). The results of these discussions and subsequent advisory meetings have led to the development of the following framework for the holistic analyses of the Coral ECA and its subsystems.

Recall the general theme and vision statement:

Theme #1: Fish as Indicators of Benthic Habitat and Water Quality

Vision Statement: *"To investigate the diversity, abundance, and size composition trends in fish resources on natural habitats within the Coral ECA. Examine any relationships between changes to water quality and/or benthic habitat. Identify fish species/functional groups indicative of different environmental conditions."*

4.1. Phase-II Project Workflow

4.1.1. Data Compilation

There are a number of data challenges associated with this project (Kilborn 2022, Kilborn 2022, Kilborn and Lizza 2022) broadly due to the complexity of the Coral ECA and its subsystems, as well as variability in the logistical implementations and observational methods across programs. Given the broad scope and vision for this research theme, however, a majority of the data described here should be able to be used for various purposes throughout Phase-II of this project.

4.1.1.1. Temporal Considerations

The focus of this theme on all three of the Coral ECA's subsystems will involve all of the *in-situ* monitoring described in sections 2.2-2.4 above, and the timing of their data collections (Table 7) will ultimately prove to be problematic. Only DRM and SECREMP provide annual data streams longer than 15 years (18-yrs and 20-yrs, respectively),

Table 7. Comparison of the Sampling Frequencies for Coral ECA Monitoring. Reflection of the temporal sampling shema used for monitoring the subsystem resources in the Coral ECA 2003-2022. Each survey's cells are shaded (water quality = blue, fish = green, benthic = gold) in the event that data were collected in that year. White cells represent years in which no data are available. Symbols correspond to a peculiarity of a program's data collection effort in the year noted, specifically: **x** = Only data from non-NELAC certified laborarory available; **+** = Two additional transects added to the sampling protocol due to SCTLD; **•** = All 22 fixed stations implemented and monitored**;** **#** = 50 x 50 m site grid implemented instead of 100 x 100 m grid.

	Water Quality		*Fish*	*Benthic*		
	NCRMP-CCC	WQA	NCRMP-RVC	DRM	NCRMP	SECREMP
2003						
2004						
2005						
2006						
2007						
2008						
2009						
2010						
2011						
2012						
2013						•
2014						•
2015						•
2016		x				•
2017						•
2018	#		#		#	•
2019						•
2020	#		#	+	#	•
2021				+		•
2022	#		#	+	#	•

although the SECREMP data are only available at all 22 stations since 2013 (i.e., a 10-yr timeseries) and DRM's current sampling protocol has only been in effect for the last three years (Table 7). Fish monitoring extends as far back as 2012, but starting in 2017 there are odd-year gaps that correspond across all of the NCRMP surveys. Thus, there is only one set of data that are sampled across all three subsystems concurrently (NCRMP), but they provide only three years of data and will not be informative on their own for trend analyses. Lastly, the water quality data provided by the WQA survey provides a six-year timeseries with NELAC certified data, or seven years if including data from non-certified laboratories. Therefore, the absolute longest data series that could be extracted from these six surveys while including at least one from each subsystem for a paired analysis is seven years. The data warehousing programs may be able to provide some of the missing information for various water quality or hydrological parameters, but this only addresses issues within that subsystem and the other will still remain.

Another temporal data consideration to be mindful of is the potential timing mismatches between water quality or environmental attributes changing and when the correspondent biological or ecological response is noted in fishes. For example, fish community compositional changes may respond to dynamic water quality conditions faster than coral communities can, partially due to differences in the growth rates and turnover times between these taxa (Helfman, Collette et al. 2009, Sheppard, Davy et al. 2018). Therefore, the use of data lags and leads may be beneficial to these efforts, and since the WQA data are collected monthly there is wide flexibility in how they can be organized to suit the objectives of these analyses.

4.1.1.2. Spatial Considerations

Originally, all of the DRM and NCRMP sites are drawn from the same 100 x 100 m gridded sampling universe. However, starting in 2018 NCRMP refined the grid system using a 50 x 50 m resolution (Table 7) such that each original DRM grid cell now contains four updated NCRMP cells. Thus, all of the three subsystems are spatially compatible across both the NCRMP and DRM datasets. The inclusion of the WQA data, on the other hand, is likely to be problematic given that the sampling universe includes a set of fixed stations that are, essentially, point observations at two depths (0.5 m and the maximum observing depth achievable given water depth and gear limitations). Nevertheless, the distributed effort across the nine ICA units will aid in cross-subsystem comparisons since the WQA data are able to be aggregated to that spatial scale (Table 6). Similar challenges exist with respect to the SECREMP data due to the limited number of fixed stations ($N = 22$) employed for this survey. Spatial constraints for these analyses will need to be closely scrutinized according to habitat types, reef morphologies, depth, and rugosity and will need to be explored more completely in the data preprocessing stage. Furthermore, primary outputs for Phase-II should include mapping products related to the patterns and trends discovered throughout the analyses.

4.1.1.3. Preprocessing and Subsystem Indicator Selections

Each monitoring program stores its data according to their own requirements and, as such, some amount preprocessing is always required in order to produce analysis-ready data matrices. Given the complexity and volume of information collected for any survey, “deep dives” into each database (at its native resolution) will be required in order to synthesize the characteristics of each subsystem. These subsystem-specific data explorations will be guided by observational sampling designs and will provide useful information about the trends and patterns that exist within each of the Coral ECA’s complex adaptive subsystems.

One area of flexibility in the ultimate holistic analyses for the Coral ECA is related to the variables (or indicators) that are selected to represent key features of a subsystem, or the critical component of a complex adaptive system. For example, for fishes it may be beneficial to focus on a particular subset of recreationally or commercially important species, as opposed to the full set of 200+ species that are observed throughout the NCRMP-RVC monitoring. Other useful divisions for fishes can be based upon trophic guilds or ecological functional groups, and by collecting only those taxa that are indicative of a certain aspect of interest (e.g., herbivores, groupers and snappers complex), the specific effects of ecosystem drivers and pressures to their status, structure, and function can be tested. In fact, a convenient way of incorporating multiple hypotheses in these holistic inquiries is to utilize different suites of indicators across each of the subsystems in constrained analyses (e.g., reef fishes, nutrients related to eutrophication, shallow vs. deep reefs, stony corals) to represent different investigatory pathways and questions.

Different questions related to water quality or condition will obviously require different indicators (e.g., eutrophication, freshwater effects, climate related phenomena), but it will also be important to remain focused only on parameters that are hypothesized to mostly affect the fish subsystem. Presumably, the fishes in the region are less directly affected by the aragonite saturation state (a variable observed by NCRMP-CCC) than corals are, and if the focus of a study is to determine the impacts of water quality changes on the fish subsystem, then the inclusion of aragonite saturation state is likely not useful. That is, of course, unless the interest is in the indirect effects of coral dissolution on corallivores or to habitat availability. Thus, where water quality regimes are to be described in this theme, the selection of indicators to use for clustering exercises should be carefully made and multiple suites of variables should be investigated.

Similar considerations should be made for benthic regimes as well, since different benthic parameters capture important information regarding the habitat features utilized by fishes as opposed to those that more generally describe the composition, structure, and function of the system. However, there are also other important signals within the benthic data that should likely be accounted for that are unique, and which may also be worthwhile for pattern recognition. Most notably, considerations of benthic communities before vs. after the extensive coral mortality from SCTLD in the Coral ECA (Precht, Gintert et al. 2016, Walton, Hayes et al. 2018, Toth, Stathakopoulos et al. 2019), and from temperature considerations (Jones, Kabay et al. 2021).

Lastly, other derived variables may be important indicators of change to any of these systems. Specifically, percent-change with respect to the previous year in species' mean proportional coverages, sizes, or abundances may be particularly useful data when trying to describe the variability in the complex adaptive systems. Therefore, as the data are acquired from their sources their unique characteristics and variables will help to guide the data compilation, preprocessing, and hypothesis generation efforts.

4.1.2. Pattern Recognition and Indicator Analyses

After compiling the data into the appropriate analytical formats, pattern recognition and indicator analyses can begin. In this case, the water quality and the benthic data are the targets. The general approach (Figure 5) is to first aggregate data from the appropriate programs into suites of indicators related to the questions of interest for each subsystem (e.g., eutrophication states, benthic coral communities). Next, each suite can be examined

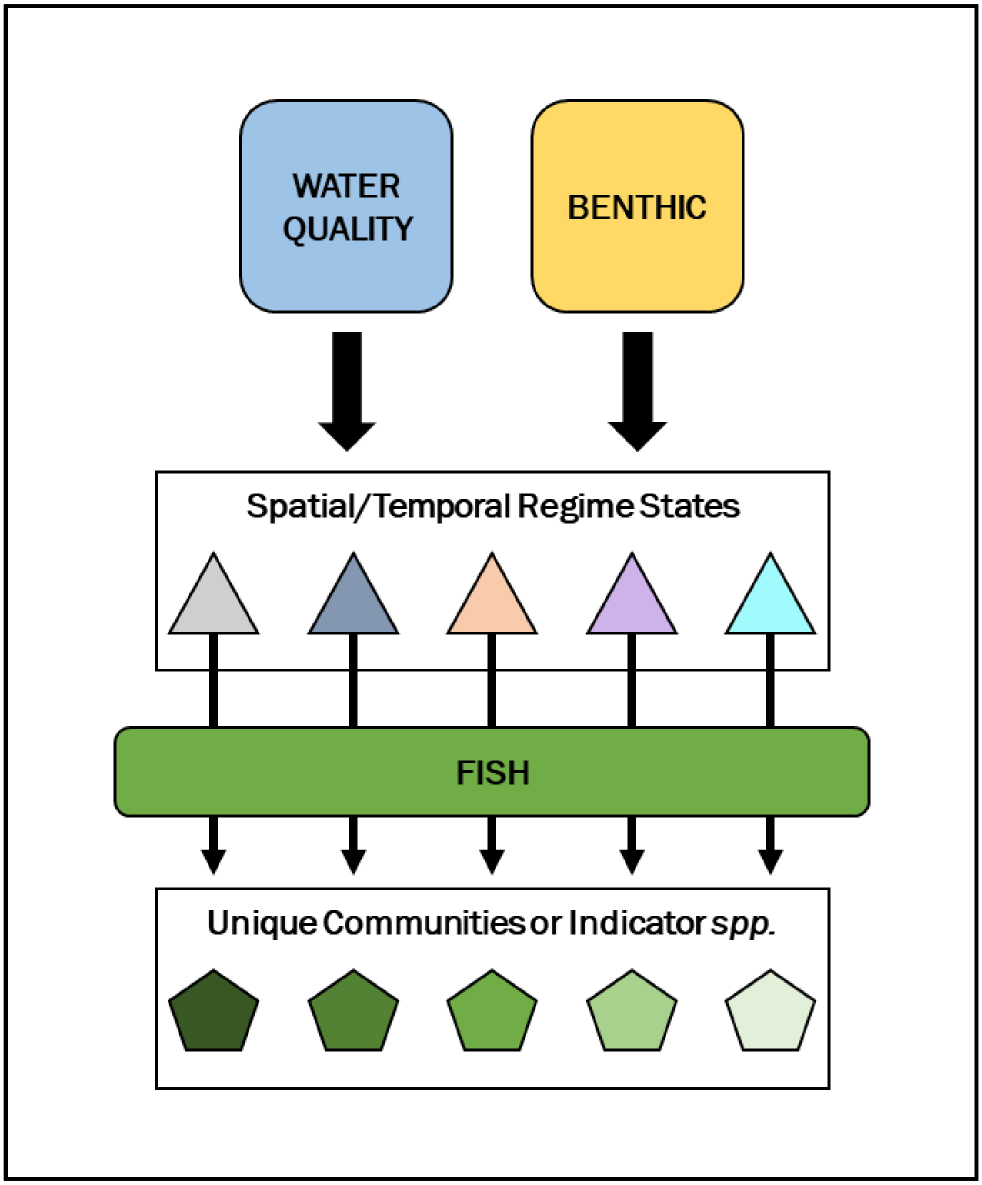


Figure 5. Generalized Approach to Pattern Recognition and Indicator Analyses. Rounded rectangles represent the subsystem-specific data matrices used to represent various important aspects of each. Clustering analyses are performed along either the spatial or temporal axis for water quality and benthic parameters, independently, to determine the unique regimes (multi-colored triangles) that are observed across the Coral ECA. Specific indicator species representative of each regime will be determined and their exclusive communities (green pentagons) described.

using multivariate cluster analysis (Legendre and Legendre 2012) and similarity profiling (Clarke, Somerfield et al. 2008, Kilborn, Jones et al. 2017) to identify spatial or temporal clusters within them. Thus, multivariate representations of these complex adaptive systems will be used to capture and describe their dynamic resource-status changes and the emergent properties and regimes that result from them. The resultant groupings can be used as the primary units for pairing to the fish subsystem, by way of species indicator analysis (IndVal; Dufrene & Legendre 1997), to determine which taxa are most indicative of different water quality or benthic regimes. Once again, this can also be extended into the ICA framework and the differences among (and indicators for) all three subsystems' characteristics can be determined across the ICA experimental units. Other spatially-explicit methods that could be employed involve GIS modeling or eigenvector mapping (Borcard, Legendre et al. 2004, Dray, Legendre et al. 2006, Dray, Pelissier et al. 2012), and in both cases hotspots and other notable spatial (or temporal, in the case of eigenvector mapping) features can be used to explain patterns in the data.

4.1.1. Other Constrained Analyses

In order to investigate the specific dynamics between the fish subsystem and the water quality or benthic habitat characteristics (Figure 6) within each of the regimes where either water quality conditions or benthic habitats are determined to be relatively similar, many other constrained analyses are available. Those appropriate for testing *a priori* grouping factors include analysis of variance (ANOVA) and its multivariate equivalent (MANOVA), along with their distribution-free analog called permutation-based ANOVA, or PERMANOVA (Anderson 2001, McArdle and Anderson 2001). Permutation-based multivariate dispersion tests (PERMDISP; Anderson 2006) can also be utilized for estimating the system-wide variability across spatial/temporal regimes and the underlying parameters used to define them. All ANOVA- and dispersion-based methods mentioned above can be visualized using canonical analysis of principal coordinates (CAP; Anderson & Willis 2003), and which also provides a leave-one-out cross-validation (LOO-CV) product that can be used to explore the predictive capabilities of any model based on grouping factors.

Random forest models (Breiman 2001) represent a link between the categorical and continuous frameworks of constrained analyses, and they function as non-parametric classification and regression trees used to create predictive classifiers and LOO-CVs. Random forests also help to decompose the relationships between independent and dependent variables in a complex multivariate system. Likewise, based on *a priori* categorical groups or the results of classification analyses, within any relevant levels (e.g., a specific ICA unit, a water quality regime, across each benthic subtype) other methods across the continuous-data analytical framework can be applied to uncover relationships between subsystems. These approaches include, zero-inflated regression (Zuur, Ieno et al. 2009) and other distance-based approaches (Legendre and Legendre 2012) which can be

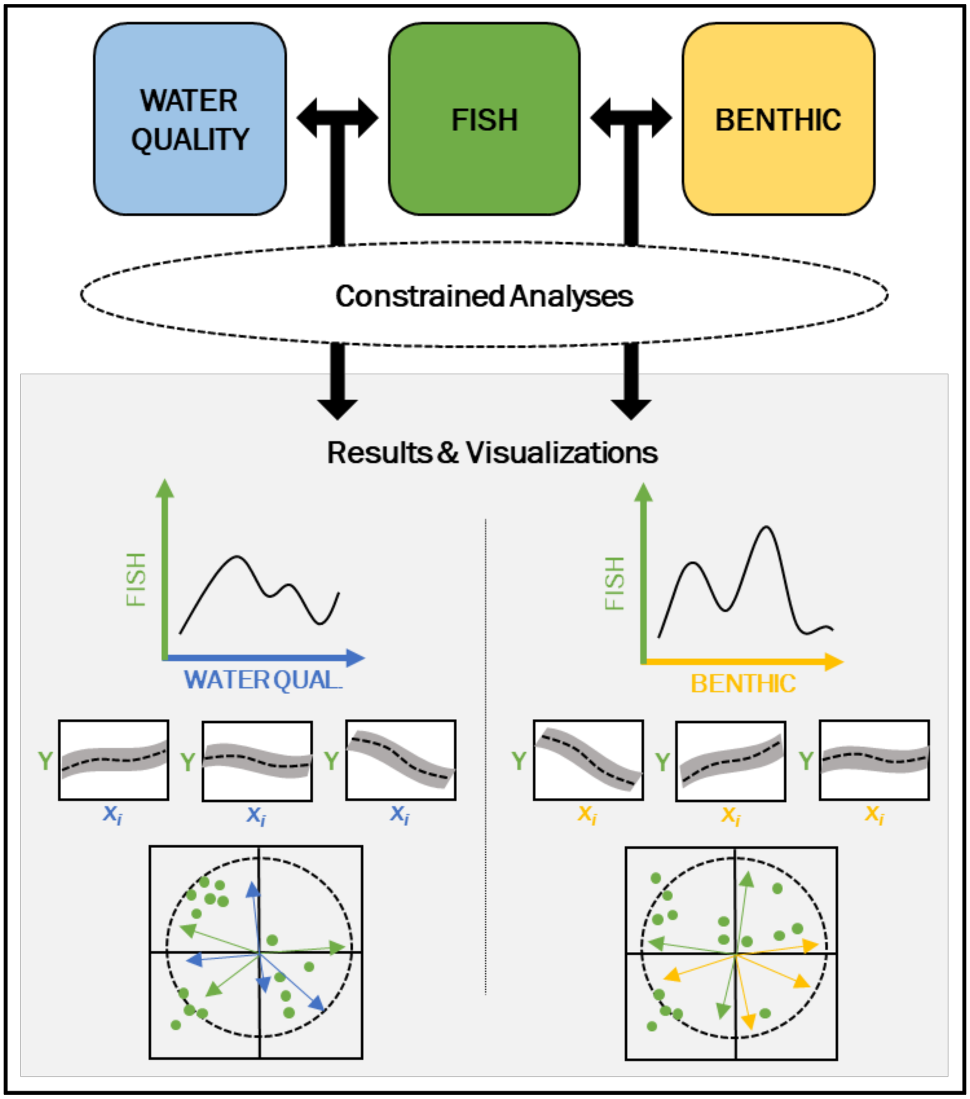


Figure 6. Generalized Approach to Constrained Analyses. Rounded rectangles represent the subsystem-specific data matrices used to represent various important aspects of each, and the thick black arrows represent the pairing of datasets for constrained analyses. Colors correspond to subsystems (water quality = blue; fish = green; gold = benthic) and the results and visualizations are adaptations of those from the various linear analyses and canonical methods described in section 4.1.3 above.

used to account for many predominantly absent species within biological census' data whose distributions are often highly skewed toward zero. More complex forms of linear analysis, such as linear mixed models (Zuur, Ieno et al. 2009) and multivariate statistical approaches like classical redundancy analysis (RDA; Rao 1964) and its distribution-free equivalent dbRDA (Legendre and Anderson 1999, McArdle and Anderson 2001), should all be considered here. These techniques can be used to investigate the complex system of relationships among two (or more) multivariate datasets, and both RDA and dbRDA are capable of providing canonical visualizations similar to those described above for CAP.

4.2. Data Access and Stakeholder Engagement

Upon completion of the holistic analysis of RT_1, there will have been a significant amount of data assembled and a number of derived outputs are also likely. Therefore, it would be advantageous for all products to be made publicly available for future use and to encourage community stewardship. Furthermore, to promote advocacy for the Coral ECA and to educate future ambassadors of this unique ecosystem, a stakeholder engagement process should be developed. The details of such a process would need to be determined by SEFCRI managers. However, the guiding force behind any developments should be that the more engaged and educated the system's everyday users and stakeholders are about the nuanced dynamics within and among the conservation area's subsystems, the more likely they will be to act responsibly in defense of this special region and to encourage others to be as well. Only by doing so, can sustainable, ecosystem-based management be achieved for the Kristin Jacobs Coral Reef Ecosystem Conservation Area.

5. LITERATURE CITED

Anderson, M. J. (2001). "A new method for non-parametric multivariate analysis of variance." Austral Ecology **26**(1): 32-46.

Anderson, M. J. (2006). "Distance-based tests for homogeneity of multivariate dispersions." Biometrics **62**(1): 245-253.

Anderson, M. J. and T. J. Willis (2003). "Canonical analysis of principal coordinates: A useful method of constrained ordination for ecology." Ecology **84**(2): 511-525.

Arena, P. T., L. K. B. Jordan and R. E. Spieler (2007). "Fish assemblages on sunken vessels and natural reefs in southeast Florida, USA." Hydrobiologia **580**: 157-171.

Banks, K. W., B. M. Riegl, E. A. Shinn, W. E. Piller and R. E. Dodge (2007). "Geomorphology of the Southeast Florida continental reef tract (Miami-Dade, Broward, and Palm Beach Counties, USA)." Coral Reefs **26**(3): 617-633.

Bohnsack, J. A. and S. P. Bannerot (1986). "A stationary visual census technique for quantitatively assessing community structure of coral reef fishes." NOAA Technical Report NMFS **41**: 1-15.

Borcard, D., P. Legendre, C. Avois-Jacquet and H. Tuomisto (2004). "Dissecting the spatial structure of ecological data at multiple scales." Ecology **85**(7): 1826-1832.

Bowen, R. E. and C. Riley (2003). "Socio-economic indicators and integrated coastal management." Ocean & Coastal Management **46**(3-4): 299-312.

Breiman, L. (2001). "Random Forests." Machine Learning **45**(1): 5-32.

Briceño, H., J. N. Boyer and I. L. Dryden (2022). "Kristen Jacobs Coral Reef Ecosystem Conservation Area Water Quality Data Analysis: Final Report. FDEP Order # BAA7752. FIU/IoE Contribution # 1459." Florida International University - SERC Recharge Centers.

Caraco, D. and S. Drescher (2011). "Land Based Sources of Pollution (LBSP) Project 21 : overview of programs in southeast Florida to reduce land-based sources of pollution and recommendations to improve these programs : final report." NOAA Coral Reef Conservation Program. Center for Watershed Protection

Carsey, T. P. (2013). Water Column. Integrated Conceptual Ecosystem Model Development for the Southeast Florida Coastal Marine Ecosystem. P. J. Fletcher and W. K. Nuttle. Miami, Florida, NOAA Technical Memorandum, OAR-AOML-103 and NOS-NCCOS-163**:** 41-52.

Christensen, N. L., A. M. Bartuska, J. H. Brown, S. Carpenter, C. D'Antonio, R. Francis, J. F. Franklin, J. A. MacMahon, R. F. Noss, D. J. Parsons, C. H. Peterson, M. G. Turner and R. G. Woodmansee (1996). "The Report of the Ecological Society of America Committee on the Scientific Basis for Ecosystem Management." Ecological Applications **6**(3): 665-691.

Clark, W. (1977). "The lessons of the Peruvian anchoveta fishery." California Cooperative Oceanic Fisheries Investigations Reports **19**: 57-63.

Clarke, K. R., P. J. Somerfield and R. N. Gorley (2008). "Testing of null hypotheses in exploratory community analyses: similarity profiles and biota-environment linkage." Journal of Experimental Marine Biology and Ecology **366**(1-2): 56-69.

Cole, A. J., M. S. Pratchett and G. P. Jones (2008). "Diversity and functional importance of coral-feeding fishes on tropical coral reefs." Fish and Fisheries **9**(3): 286-307.

Collier, C., R. Ruzicka, K. Banks, L. Barbieri, J. Beal, D. Bingham, J. A. Bohnsack, S. Brooke, N. Craig, R. E. e. Dodge, L. E. Fisher, N. Gadbois, D. S. Gilliam, L. Gregg, T. Kellison, V. N. Kosmynin, B. Lapointe, E. McDevitt, J. Phipps, N. Poulos, J. Proni, P. Quinn, B. Riegl, R. E. Spieler, J. Walczak, B. K. Walker and D. Warrick (2008). "The State of Coral Reef Ecosystems of Southeast Florida. The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2008." Nova Southeastern University. Retrieved from NSUWorks: 31 pgs.

DEP (2004). "Southeast Florida Coral Reef Initiative: A Local Action Strategy." Florida Department of Environmental Protection, Office of Coastal and Aquatic Managed Areas, Coral Reef Conservation Program: 31 pgs.

DEP. (2018). "Watershed Information Network." Retrieved March 18, 2022, 2022, from https://floridadep.gov/dear/watershed-services-program/content/winstoret.

Dray, S., P. Legendre and P. R. Peres-Neto (2006). "Spatial modelling: a comprehensive framework for principal coordinate analysis of neighbour matrices (PCNM)." Ecological Modelling **196**(3-4): 483-493.

Dray, S., R. Pelissier, P. Couteron, M. J. Fortin, P. Legendre, P. R. Peres-Neto, E. Bellier, R. Bivand, F. G. Blanchet, M. De Caceres, A. B. Dufour, E. Heegaard, T. Jombart, F. Munoz, J. Oksanen, J. Thioulouse and H. H. Wagner (2012). "Community ecology in the age of multivariate multiscale spatial analysis." Ecological Monographs **82**(3): 257-275.

Dufrene, M. and P. Legendre (1997). "Species assemblages and indicator species: The need for a flexible asymmetrical approach." Ecological Monographs **67**(3): 345-366.

EPA. (2018). "Environmental Protection Agency's Water Quality Data Warehouse." Retrieved March 17, 2022, 2022, from https://www.epa.gov/waterdata/water-quality-data.

Ferrario, F., M. W. Beck, C. D. Storlazzi, F. Micheli, C. C. Shepard and L. Airoldi (2014). "The effectiveness of coral reefs for coastal hazard risk reduction and adaptation." Nature Communications **5**: 9.

Finkl, C. W. and J. L. Andrews (2008). "Shelf geomorphology along the southeast Florida Atlantic continental platform: Barrier coral reefs, nearshore bedrock, and morphosedimentary features." Journal of Coastal Research **24**(4): 823-849.

Fletcher, P. J., W. K. Nuttle, J. S. Ault, J. Browder, B. M. Riegl, D. S. Gillam, D. Lirman, J. W. Fourqurean, F. E. Marshall, K. Banks and C. Bergh (2013). "Integrated conceptual ecosystem model development for the Southeast Florida coastal marine ecosystem : MARine Estuarine goal Setting (MARES) for South Florida." NOAA Technical Memorandum, OAR-AOML-103 and NOS-NCCOS-163: 125 p.

Florida-Senate (2018). HB 53: Coral Reefs. T. F. Senate. Tallahassee, FL. **HB 53**.

FWC (2020). "Florida Reef Resilience Program's Disturbance Response Monitoring Metadata (2005-2020)." Florida Fish and Wildlife Conservation Commission. Environmental Protection Agency cooperative agreement number X7-01D00320-0.: 9 p.

Gilliam, D. S., N. K. Hayes, R. Ruzicka and M. Colella (2021). "Southeast Florida Coral Reef Evaluation and Monitoring Project: Year 18 Final Report." Florida DEP & FWC. Miami Beach, Florida: 82 p.

Gregg, K. L. and J. Karazsia (2013). "Literature review and synthesis of land-based sources of pollution affecting essential fish habitats in southeast Florida." NOAA Fisheries Southeast Region, Habitat Conservation Division.

Hallock, P. (2002). Evolution and function of coral reef ecosystems. Earth System: History and Natural Variability. V. Cilek. Oxford, UK, Developed under the Auspices of the UNESCO, Eolss Publishers. **4**.

Hayes, N. K. (2019). "A characterization of a Southeast Florida stony coral assemblage after a disease event. Master's thesis." Nova Southeastern University. Retrieved from NSUWorks **512**: 44 pgs.

Hayes, N. K., C. J. Walton and D. S. Gilliam (2022). "Tissue loss disease outbreak significantly alters the Southeast Florida stony coral assemblage." Frontiers in Marine Science **9**.

Helfman, G. S., B. B. Collette, D. E. Facey and B. W. Bowen (2009). The diversity of fishes : biology, evolution, and ecology. Chichester, UK ; Hoboken, NJ, Blackwell.

Hixon, M. A. (1997). Effects of reef fishes on corals and algae. Life and Death of Coral Reefs. C. Birkeland. New York, Chapman & Hall**:** 230-248.

Holling, C. S. (1987). "Simplifying the complex: The paradigms of ecological function and structure." European Journal of Operational Research **30**(2): 139-146.

Houlbreque, F., E. Tambutte and C. Ferrier-Pages (2003). "Effect of zooplankton availability on the rates of photosynthesis, and tissue and skeletal growth in the scleractinian coral Stylophora pistillata." Journal of Experimental Marine Biology and Ecology **296**(2): 145-166.

Johns, G. M., V. R. Leeworthy, F. W. Bell and M. A. Bonn (2001). "Socioeconomic study of reefs in southeast Florida: Final Report." Hazen and Sawyer Environmental Engineers and Associates. Ft. Lauderdale, Florida.: 348 p.

Johns, G. M., J. W. M. Milon and D. Sayers (2004). "Socioeconomic study of reefs in Martin County, Florida: Final Report." Hazen and Sawyer Environmental Engineers and Associates. Ft. Lauderdale, Florida.: 120 p.

Johnson, D. R., D. E. Harper, G. T. Kellison and J. A. Bohnsack (2007). "Description and discussion of Southeast Florida fishery landings, 1990-2000."

Jones, N. P., L. Kabay, K. S. Lunz and D. S. Gilliam (2021). "Temperature stress and disease drives the extirpation of the threatened pillar coral, Dendrogyra cylindrus, in southeast Florida." Scientific Reports **11**(1): 10.

Kelble, C. R., D. K. Loomis, S. Lovelace, W. K. Nuttle, P. B. Ortner, P. Fletcher, G. S. Cook, J. J. Lorenz and J. N. Boyer (2013). "The EBM-DPSER Conceptual Model: Integrating Ecosystem Services into the DPSIR Framework." Plos One **8**(8): (8) e70766.

Kilborn, J. P. (2022). Data Discovery for a Meta-Analysis of Water Quality, Fish, and Benthic Data within the Kristin Jacobs Coral Reef Ecosystem Conservation Area. Report prepared for the Florida Department of Environmental Protection, Coral Reef Conservation Program. Saint Petersburg, FL, University of South Florida, College of Marine Science**:** *ix* and 54 pp.

Kilborn, J. P. (2022). Summary of Collaborative Meeting #2 for a Meta-Analysis of Water Quality, Fish, and Benthic Data within the Kristin Jacobs Coral Reef Ecosystem Conservation Area. Report prepared for the Florida Department of Environmental Protection, Coral Reef Conservation Program. Saint Petersburg, FL, University of South Florida, College of Marine Science**:** *viii* and 30 pp.

Kilborn, J. P., M. Drexler and D. L. Jones (2018). "Fluctuating fishing intensities and climate dynamics reorganize the Gulf of Mexico's fisheries resources." Ecosphere **9**(11): e02487.

Kilborn, J. P., D. L. Jones, E. B. Peebles and D. F. Naar (2017). "Resemblance profiles as clustering decision criteria: Estimating statistical power, error, and correspondence for a hypothesis test for multivariate structure." Ecology and Evolution **7**(7): 2039-2057.

Kilborn, J. P. and K. Lizza (2022). Summary of Collaborative Meeting #1 for a Meta-Analysis of Water Quality, Fish, and Benthic Data within the Kristin Jacobs Coral Reef Ecosystem Conservation Area. Report prepared for the Florida Department of Environmental Protection, Coral Reef Conservation Program. Saint Petersburg, FL, University of South Florida, College of Marine Science**:** *ix* and 65 pp.

Kilfoyle, A. K., B. K. Walker, K. L. Gregg, D. P. Fisco and R. Spieler (2018). "Southeast Florida Coral Reef Fishery-Independent Baseline Assessment: 2012-2016 Summary Report." National Oceanic and Atmospheric Administration: 121.

Knutson, T. R., J. L. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J. P. Kossin, A. K. Srivastava and M. Sugi (2010). "Tropical cyclones and climate change." Nature Geoscience **3**(3): 157-163.

Lapointe, B. E., R. A. Brewton, L. W. Herren, J. W. Porter and C. M. Hu (2019). "Nitrogen enrichment, altered stoichiometry, and coral reef decline at Looe Key, Florida Keys, USA: a 3-decade study." Marine Biology **166**(8): 31.

Lee, T. N., J. A. Yoder and L. P. Atkinson (1991). "Gulf Stream frontal eddy influence on productivity of the southeast U.S. continental shelf." Journal of Geophysical Research: Oceans **96**(C12): 22191-22205.

Legendre, P. and M. J. Anderson (1999). "Distance-based redundancy analysis: Testing multispecies responses in multifactorial ecological experiments." Ecological Monographs **69**(1): 1-24.

Legendre, P. and L. Legendre (2012). Numerical Ecology. Amsterdam, The Netherlands, Elsevier.

Levin, P. S., M. J. Fogarty, S. A. Murawski and D. Fluharty (2009). "Integrated Ecosystem Assessments: Developing the Scientific Basis for Ecosystem-Based Management of the Ocean." PLoS Biol **7**(1): e1000014.

Levin, S. A. (1998). "Ecosystems and the Biosphere as Complex Adaptive Systems." Ecosystems **1**(5): 431-436.

Lidz, B. H. and E. A. Shinn (1991). "Paleoshorelines, Reefs, and a Rising Sea: South Florida, U.S.A." Journal of Coastal Research **7**(1): 203-229.

Lubchenco, J. and N. Sutley (2010). "Proposed U.S. Policy for Ocean, Coast, and Great Lakes Stewardship." Science **328**(5985): 1485-1486.

Mallin, M. A., L. B. Cahoon, M. R. McIver, D. C. Parsons and G. Christopher Shank (1999). "Alternation of factors limiting phytoplankton production in the Cape Fear River Estuary." Estuaries **22**(4): 825-836.

Manzello, D. P., R. Berkelmans and J. C. Hendee (2007). "Coral bleaching indices and thresholds for the Florida Reef Tract, Bahamas, and St. Croix, US Virgin Islands." Marine Pollution Bulletin **54**(12): 1923-1931.

McArdle, B. H. and M. J. Anderson (2001). "Fitting multivariate models to community data: A comment on distance-based redundancy analysis." Ecology **82**(1): 290-297.

McEachron, L., K. Bohnsack, A. Bruckner, L. Gentry, C. R. Kelble, D. Kochan, K. Montenero, F. E. Muller-Karger, T. Murray and D. Otis (2022). "Florida's Coral Reef Water QUality Data Compilation, Analysis, and Decision Support Year 2." Florida DEP & FWC. Miami Beach, Florida.

Moyer, R. P., B. Riegl, K. Banks and R. E. Dodge (2003). "Spatial patterns and ecology of benthic communities on a high-latitude South Florida (Broward County, USA) reef system." Coral Reefs **22**(4): 447-464.

Muller, E. M., C. Sartor, N. I. Alcaraz and R. van Woesik (2020). "Spatial Epidemiology of the Stony-Coral-Tissue-Loss Disease in Florida." Frontiers in Marine Science **7**: 11.

Murawski, S. A., W. T. Hogarth, E. B. Peebles and L. Barbeiri (2014). "Prevalence of External Skin Lesions and Polycyclic Aromatic Hydrocarbon Concentrations in Gulf of Mexico Fishes, Post-Deepwater Horizon." Transactions of the American Fisheries Society **143**(4): 1084-1097.

Murawski, S. A., J. P. Kilborn, A. C. Bejarano, D. Chagaris, D. Donaldson, F. J. Hernandez, T. C. MacDonald, C. Newton, E. Peebles and K. L. Robinson (2021). "A Synthesis of Deepwater Horizon Impacts on Coastal and Nearshore Living Marine Resources." Frontiers in Marine Science **7**(1212).

NMFS (2014). Fisheries Economics of the United States, 2012. T. M. NMFS-F/SPO-137. NOAA, U.S. Department of Commerce, Washington, DC**:** 175.

NMFS (2018). Fisheries Economics of the United States, 2016. T. M. NMFS-F/SPO-187. NOAA, U.S. Department of Commerce, Washington, DC**:** 243.

NMFS, R. Cody, L. D. Few, J. Fenner, C. Krikstan, M. Lewis , M. Liddel, A. Litwack, K. Mayo, K. Papacostas, J. Thibodeau and M. Yencho (2022). Fisheries of the United States, 2020. U.S. Department of

Commerce, NOAA Current Fishery Statistics No. 2020**:** 28.

NOAA. (1986). "National Status and Trends: Mussel Watch Program." Retrieved April 4, 2022, 2022, from https://www.fisheries.noaa.gov/inport/item/39400.

Paxton, A. B., E. A. Newton, A. M. Adler, R. V. Van Hoeck, E. S. Iversen, J. C. Taylor, C. H. Peterson and B. R. Silliman (2020). "Artificial habitats host elevated densities of large reef-associated predators." Plos One **15**(9): 17.

Phipps, J., L. Wood, C. Lott and M. Moore (2018). Palm Beach County Long-Term Monitoring of Artificial and Natural Reeds Report 2017 for Florida Fish & Wildlife Conservation Commission Grant No. 16144. Palm Beach County, Florida, USA.

Pickering, N. and E. S. Baker (2015). "Watershed scale planning to reduce land-based sources of pollution (LBSP) for protection of coral reefs in southeast Florida : an overview and data gap assessment." NOAA Coral Reef Conservation Program, Horsley Witten Group, Inc.

Pollock, F. J., J. B. Lamb, S. N. Field, S. F. Heron, B. Schaffelke, G. Shedrawi, D. G. Bourne and B. L. Willis (2014). "Sediment and Turbidity Associated with Offshore Dredging Increase Coral Disease Prevalence on Nearby Reefs." Plos One **9**(7).

Precht, W. F., B. E. Gintert, M. L. Robbart, R. Fura and R. van Woesik (2016). "Unprecedented Disease-Related Coral Mortality in Southeastern Florida." Scientific Reports **6**(1): 31374.

Radabaugh, K. R., E. M. Malkin, D. J. Hollander and E. B. Peebles (2014). "Evidence for light-environment control of carbon isotope fractionation by benthic microalgal communities." Marine Ecology Progress Series **495**: 77-90.

Rao, C. R. (1964). "The use and interpretation of principal component analysis in applied research." Sankhyā: The Indian Journal of Statistics, Series A: 329-358.

Rayer, S., R. Doty, S. Roulston-Doty, J. Teisinger and Y. Wang (2021). Florida Estimates of Population 2021. Gainesville, FL, University of Florida Bureau of Economic and Business Research**:** 61 pgs.

Riegl, B. M., D. S. Gilliam and D. Lirman (2013). Benthic Habitat: Coral and Hardbottom. Integrated Conceptual Ecosystem Model Development for the Southeast Florida Coastal Marine Ecosystem. P. J. Fletcher and W. K. Nuttle. Miami, Florida, NOAA Technical Memorandum, OAR-AOML-103 and NOS-NCCOS-163**:** 63-83.

Roberson, K. K. W., S. Viehman and R. Clark (2014). "Development of Benthic and Fish Monitoring Protocols for the Atlantic/Caribbean Biological Team: National Coral Reef Monitoring Program."

Seaman, J. W., W. J. Lindberg, C. R. Gilbert and T. K. Frazer (1989). "Fish Habitat Provided by Obsolete Petroleum Platforms off Southern Florida." Bulletin of Marine Science **44**(2): 1014-1022.

SFWMD. (1949). "South Florida Water Management District." Retrieved April 1, 2022, 2022, from https://www.sfwmd.gov/who-we-are.

SFWMD. (2020). "DBHYDRO." Retrieved April 3, 2022, 2022, from https://www.sfwmd.gov/science-data/dbhydro.

SFWMD (2020). DBHYDRO Browser User's Guide. West Palm Beach, FL.

Sheppard, C., S. K. Davy, G. M. Pilling and N. Graham (2018). The biology of coral reefs. Oxford, Oxford University Press.

Smith, S. G., J. S. Ault, J. A. Bohnsack, D. E. Harper, J. Luo and D. B. McClellan (2011). "Multispecies survey design for assessing reef-fish stocks, spatially explicit management performance, and ecosystem condition." Fisheries Research **109**(1): 25-41.

Sponaugle, S., T. Lee, V. Kourafalou and D. Pinkard (2005). "Florida Current frontal eddies and the settlement of coral reef fishes." Limnology and Oceanography **50**(4): 1033-1048.

Storlazzi, C. D., B. G. Reguero, A. D. Cole, E. Lowe, J. B. Shope, A. E. Gibbs, B. A. Nickel, R. T. McCall, A. R. van Dongeren and M. W. Beck (2019). Rigorously valuing the role of U.S. coral reefs in coastal hazard risk reduction. Open-File Report. Reston, VA**:** 52.

Thanner, S. E., T. L. McIntosh and S. M. Blair (2006). "Development of benthic and fish assemblages on artificial reef materials compared to adjacent natural reef assemblages in Miami-Dade County, Florida." Bulletin of Marine Science **78**(1): 57-70.

Thurber, R. L. V., D. E. Burkepile, C. Fuchs, A. A. Shantz, R. McMinds and J. R. Zaneveld (2014). "Chronic nutrient enrichment increases prevalence and severity of coral disease and bleaching." Global Change Biology **20**(2): 544-554.

Toth, L. T., A. Stathakopoulos, I. B. Kuffner, R. R. Ruzicka, M. A. Colella and E. A. Shinn (2019). "The unprecedented loss of Florida's reef-building corals and the emergence of a novel coral-reef assemblage." Ecology **100**(9): 14.

Towle, E. K., M. E. Allen, H. Barkley, N. Besemer, J. Blondeau, C. Couch, J. D. L. Cour, K. Edwards, I. C. Enochs, C. Fleming, E. Geiger, S. Gonyo, L. J. Grove, S. Groves, A. Halperin, S. Hile, C. Jeffrey, M. W. Johnson, T. Kindinger, J. L. Koss, C. Langwiser, G. Liu, D. Manzello, K. McCoy, H. Nash, S. O'Connor, T. Oliver, F. Pagan, T. Rankin, S. Regan, J. Samson, L. Siceloff, J. Smith, D. Swanson, B. Vargas-Angel, T. S. Viehman, B. Williams and B. Zito. (2021). "National Coral Reef Monitoring Plan." NOAA Coral Reef Conservation Program,.

Tscherning, K., K. Helming, B. Krippner, S. Sieber and S. G. Y. Paloma (2012). "Does research applying the DPSIR framework support decision making?" Land Use Policy **29**(1): 102-110.

van Oppen, M. J. H. and J. M. Lough (2018). Coral Bleaching: Patterns, Processes, Causes and Consequences, Springer Nature.

Walker, B. K., S. Carpenter, J. Anderies, N. Abel, G. Cumming, M. Janssen, L. Lebel, J. Norberg, G. D. Peterson and R. Pritchard (2002). "Resilience management in social-ecological systems: a working hypothesis for a participatory approach." Conservation Ecology **6**(1): 17.

Walton, C. J., N. K. Hayes and D. S. Gilliam (2018). "Impacts of a Regional, Multi-Year, Multi-Species Coral Disease Outbreak in Southeast Florida." Frontiers in Marine Science **5**.

Whitall, D. and S. Bricker (2021). "Examining Ambient Turbidity and Total Suspended Solids Data in South Florida Towards Development of Coral Specific Water Quality Criteria." NOAA Technical Memorandum NOS NCCOS ; 297.

Whitall, D., S. Bricker, D. Cox, J. Baez, J. Stamates, J. Gregg and F. Pagan (2019). "Southeast Florida Reef Tract Water Quality Assessment." NOAA Technical Memo NOS NCCOS 271: 116 p.

Woodhead, A. J., C. C. Hicks, A. V. Norstrom, G. J. Williams and N. A. J. Graham (2019). "Coral reef ecosystem services in the Anthropocene." Functional Ecology **33**(6): 1023-1034.

Zuur, A., E. N. Ieno, N. J. Walker, A. A. Saveliev and G. M. Smith (2009). Mixed Effects Models and Extensions in Ecology with R. New York, NY, Springer New York.