Living Shorelines for Coastal Resilience

Developing a Decision Support Framework to Analyze Coral Reef Restoration Sites

by

Kris Anderson

Dr. James L. Hench, Advisor

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Executive Summary

Coastal communities around the world experience flooding every day. Increased frequency and intensity of storm events compound local tides with storm surge (IPCC, 2013). Sunny day flooding inundates low-lying areas during extreme high tides, with a confluence of land subsidence and sea level rise (IPCC, 2014). The need for coastal resilience arises as communities and stakeholders seek solutions to remain strong when confronted with destruction from greater coastal hazards, storms, and flooding.

This research strives to strengthen coral reef conservation by identifying research gaps, examine how nature-based shoreline protection from coral reef restoration aids coastal resilience, and broaden public support for natural solutions in coastal defense. The key research question for this investigation is "What criteria prioritize increased coastal resilience from coral reef restoration with living shorelines?"

Through applications with socioeconomic benefit, the main objective of this research is to improve the state of coral reefs and coastal resilience, globally. Focusing on coastal community resilience, this research strives to raise awareness of the benefits and best practices from coral reef restoration.

This research focuses on developing a decision support framework to analyze coral restoration sites and inform coastal resilience decisions. While previous studies investigated the role of coral reefs in shoreline protection, few offer a comprehensive approach to inform effective restoration and resilience decisions. This research concentrates on promoting the ability of communities, stakeholders, and nonprofit organizations to employ the framework to evaluate the protective benefits of coral reefs as living shorelines.

Three primary research objectives guide this analytic review: (1) develop a decision support framework to inform decision making; (2) apply the analytic framework to evaluate coral restoration sites for resilience; and (3) create an information matrix to communicate results that inform restoration and resilience decisions.

The research methods aim to conduct a literature review to develop baseline knowledge, consult faculty and industry advisors to guide the research, compile information to select criteria for decision making, and assemble components to form an analytic framework.

For analysis, the research applies the framework to case study sites with coastal resilience data. An information matrix visually displays analytic patterns and research gaps across the framework. Finally, a report captures a descriptive review of research to analyze reef restoration sites for coastal resilience.

As research findings, interest in natural and nature-based infrastructure solutions highlights the increasing demand to understand and measure the impacts of ecosystem protection and restoration efforts. Application of the framework revealed a lack of consistent data across case study sites and pointed to focus areas for future research. The methodology of the decision support framework offers a general approach, applicable to a broad range of living shorelines and restoration scenarios.

Earlier research found that coral reefs dissipate 97% of the wave energy directed at shorelines and possess the capacity to keep up with sea level rise through the natural accretion of sediment (Ferrario et al., 2014; Temmerman et al., 2013; TNC, 2018). Therefore, coral reefs offer more resilient protective services than built breakwater infrastructure (TNC, 2018). Currently, 75% of coral reefs in the world face threats from local and global stresses (Burke et al., 2011). As degraded reefs absorb less wave energy, opportunity exists to restore reefs and improve coastal community resilience (CORAL, 2016).

Though the information matrix analysis of this research highlighted data quality and availability limitations, the framework offers a holistic view of elements needed for coastal resilience decisions. The framework also encourages communities and stakeholders to identify criteria to measure the impacts of ecosystem protection and coral reef restoration.

Knowledge and information gaps identified through this investigation offer a focus for future research to examine: (a) a closer study of coral reef bathymetry and ecological services at coral reef restoration sites; (b) the need to measure of coastal damage reduction and restoration costs, consistently across sites; (c) and clarify consistent coral reef restoration best practices for coastal protection by reef type.

In conclusion, this research investigated a highly integrated problem across multiple disciplines with input from many areas of expertise. The success of this research built upon the ability to divide the issue into small steps to adapt and upgrade with additional knowledge, information, and data. The flexibility of the decision support framework enables future research to adjust the methodology for application to a wider range of restoration scenarios for societal benefit.

1.0 Introduction

This research began with curiosity about the effectiveness of coral reefs as living shorelines for coastal resilience. More than ever, coastal communities around the world seek solutions to remain strong when confronted with increased coastal hazards, storms, and flooding. This research aims to develop a decision support framework to inform decision making and analyze the efficacy of coral reef restoration.

The vision for this research focuses on improving the state of coral reefs, globally, through applications with socioeconomic benefit. The research concentrates on the ability of communities, stakeholders, and nonprofit organizations to employ this framework and evaluate the protective value of coral reefs across the disciplines of coral reef ecology, marine planning, coastal engineering, and risk management.

Overall, this research strives to strengthen coral reef conservation by identifying research gaps, examine how nature-based shoreline protection from reef restoration may aid coastal resilience, and broaden public support for natural solutions in coastal defense.

1.1 Background

Coastal communities around the world experience flooding daily. Increased frequency and intensity of storms compound local tides with storm surge (IPCC, 2013, p. 7). High tide flooding inundates low-lying areas, adding to land subsidence and sea level rise (IPCC, 2014, p. 23; NOAA, 2020b; Spiegel, 2019).

Scientists anticipate an increase in regional trends of sea level rise (SLR) and heavy precipitation events over the next century across 7mid-latitude and tropical regions (IPCC, 2013, p. 7). Thermal expansion from ocean water warming, along with flow from melting glaciers, contributed to about three quarters of the global mean sea level rise since 1970 (IPCC, 2013, p. 19). Communities seek coastal resilience.

Adaptation offers communities opportunities to adjust and respond to environmental change. Along coasts, communities build the ability to prepare, adapt, and respond to coastal change and hazards. In the United States (US) many organizations actively support coastal resilience. Guidance and tools arise from the National Oceanic and Atmospheric Administration (NOAA) and the United States Geological Survey (USGS) to The Nature Conservancy (TNC), the National Fish and Wildlife Foundation (NFWF), and the RAND Corporation (NFWF, 2018; RAND, 2016; TNC, 2012).

Communities rely on NOAA to establish guidance and fund resilience with living shorelines. NOAA defines living shorelines as the use of “plants or other natural elements to stabilize estuarian coasts, bays, and tributaries” (NOAA, 2018; Reiblich, 2018). Members of the US Congress wrote bills to establish a Living Shorelines Act (2017, 2018, 2019) which, if passed, would authorize NOAA to award from $20-50 million in projects with grants to protect coastal communities by mitigating risk from:

> (i) effects of erosion;
>
> (ii) impact of coastal storms and storm surge;
>
> (iii) shoreline flooding;
>
> (iv) effects of sea level rise and extreme tides;
>
> (v) sustaining, protecting, or restoring functions and habitats of coastal ecosystems; and
>
> (vi) employing other forms of coastal protection as determined by the Administrator
>
> (Living Shorelines Act 2017, 2018, & 2019).

In March 2017, the United States Army Corps of Engineers (USACE) began issuing nationwide permits (NWP54) to streamline permit processes to use living shorelines in erosion control over a five-year period (Lightbody, 2016; Otts, 2017). Within the Corps, districts develop regional general permits (RGP) to reduce the process and timelines to approve projects with living shorelines (USACE, 2019).

In the tropics, coral reefs provide coastal communities protection from flooding and shoreline erosion. Ferrario et al. (2014) investigated coral reef effectiveness in coastal hazard adaptation. Using a meta-analysis, the research found that coral reefs dissipate 97% of wave energy directed at shorelines, as in *Figure 1* (Ferrario et al., 2014; TNC, 2018). Beyond dissipating storm wave energy, reefs reduce daily swell waves and erosion (Ferrario et al., 2014). Reguero et al. (2018) confirmed the coral reef ability to buffer wave action and stabilize shorelines. Note that degraded reefs reduce this capacity (TNC, 2018).

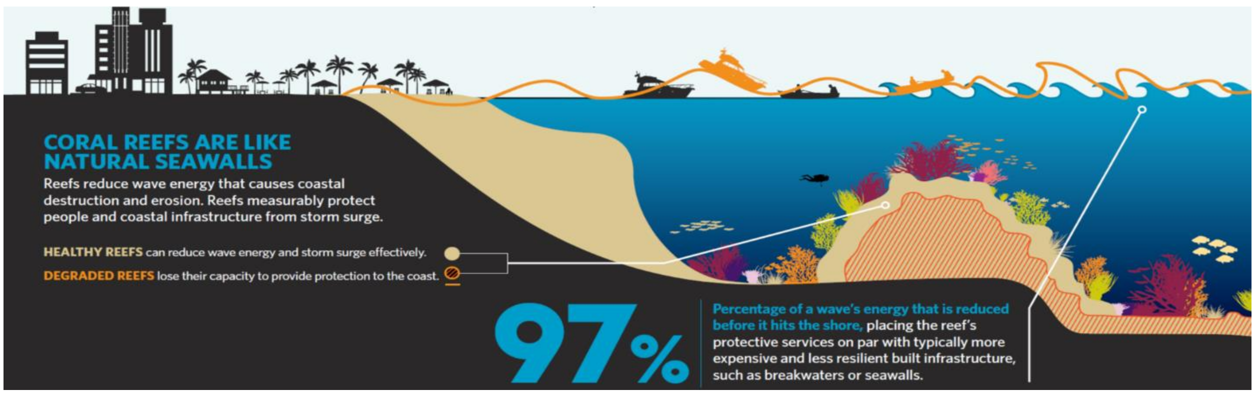


Figure 1. Coral reef protective services (Ferrario et al., 2014; TNC, 2018).

In a coastal resilience review, USACE (2013) highlighted how coral reefs perform nature-based functions to attenuate waves and retain sediment. Similarly, Temmerman et al. (2013) pointed out that coral reefs possess the capacity to keep up with sea level rise through the natural accretion of sediment. As the *Figure 1* graphic displays, research found that coral reefs as natural seawalls offer less expensive and more resilient protective services than the built infrastructure of breakwaters and seawalls (TNC, 2018).

Currently, 75% of coral reefs worldwide face threats from local and global stresses, with effects predicted to reach 90% of coral reefs in the 2030 decade (Burke et al., 2011). Degraded reefs absorb less wave energy, creating a negative feedback loop as protected coastlines become more susceptible to wave damage (CORAL, 2016). Opportunity exists to restore reefs, while improving coastal resilience and the state of reefs globally.

1.2 Key methods

The research design of this study includes scientific literature review, analytic framework development, case study analysis, information matrix presentation of results, and a descriptive research report.

The literature review investigated the baseline level of knowledge in this area of study. The critical comparison of previous studies enabled the research to compile components necessary to develop an analytic framework. The research review also assisted in the collection of knowledge and data on coastal resilience at coral reef restoration sites. Consultation with faculty and industry advisors supported this effort with research recommendations, critical analysis, and guidance.

Assembling the components of the analytic framework into as process flow facilitated analysis, structure, and organization of the framework to assist in decision making. This effort helped to narrow the scope of the research and refine the essential criteria, attributes, elements, functions, and processes of the analytic framework.

Selecting case study sites for analysis and gathering supporting coastal resilience data worked to further analyze the framework. The research considered several major geographic regions for case study sites, based on countries with large populations and built capital near coral reefs. Within these globally representative regions, the research selected specific coral reef study sites to evaluate the framework.

The creation of an information matrix visually displayed analytic patterns and research gaps by comparing compare case study sites across the framework attributes and criteria. The matrix clarified data availability and quality issues across the study sites, as well as decision support framework

Finally, the descriptive analytic review and documentation in this research report further refined the results of this investigation. The key variables of this study resulted from analysis of prior research to define elements, attributes, and criteria for the decision support framework.

1.3 Literature review

This scientific review began by assembling frequently referenced studies on coral reefs for coastal flood protection. After noting leading researchers, this research consulted faculty and industry advisors to confirm the validity of the reference material as secondary research and to identify significant gaps.

Next, this research explored ecosystem services and structure related to coastal protection from coral reefs. To further clarify socioeconomic benefit, the research gathered studies of the value and need of coral reefs for flood protection, coastal resilience, and defense. Finally, this review focused on coral reef restoration techniques to better understand the variety of options at sites around world.

A critical analysis of historical research helped identify trends and gaps in this area of study. Applying a broad perspective from nature-based solutions, this research investigated the role of ecosystems in coastal protection to compare salt marshes, mangroves, seagrass, dunes, oyster beds, and coral reefs.

The research review also sought out coastal resilience and case study site data for coral reefs in tropical and subtropical regions of the world. This information aided the development and analysis of a decision support framework to inform decision making related to coral reef restoration. All the research assisted in populating an information matrix to display data availability and compare sites across the framework.

1.4 Problem statement

As storms increase in intensity and extreme high tide flooding occurs more frequently with rising seas, coastal communities around the world seek coastal resilience solutions. With these changes, demand grows to understand and measure the impacts of ecosystem protection and restoration efforts. While previous studies investigated the role of coral reefs in shoreline protection, few offer a comprehensive approach to inform effective restoration and resilience decisions. The key research question remains, "What criteria prioritize increased coastal resilience from coral reef restoration with living shorelines?"

This research concentrates on promoting the ability of communities, stakeholders, and nonprofit organizations to employ a holistic framework to evaluate the protective benefits of coral reefs as living shorelines. Coral reefs offer services of wave attenuation, sediment retention, and reduced storm damage. By developing a decision support framework to analyze coral restoration sites with coastal resilience data, this research seeks to inform coastal resilience and reef restoration decisions.

2.0 Objectives

Through applications with socioeconomic benefit, the main objective of this research is to improve the state of coral reefs and coastal resilience, globally. Focusing on the resilience of coastal communities and coral reef conservation, this research strives to broaden public support for natural and nature-based solutions. Opportunity exists to develop a decision support framework to inform decision making and analyze coral restoration sites for coastal resilience.

Many studies describe coral reef functions in shoreline protection, yet few offer a comprehensive approach to inform restoration and resilience decisions. Three primary research objectives guide a broader view for this study: (1) develop a decision support framework; (2) apply framework for analysis; and (3) create an information matrix to communicate results. The intent is to raise awareness of coastal resilience benefits from coral reef restoration and to share best practices with partners, internationally.

2.1 Roadmap for research

Opening with a literature review, this research focuses effort on developing two visual, analytic products: (1) a decision support framework and (2) an information matrix to advise resilience and restoration decisions. These products act as tools for coastal communities and researchers to systematically adopt. The analysis for the research applies the decision support framework to case study sites with coastal resilience data, as presented in the information matrix.

The conceptual approach of this research is designed looking to the future to support the analysis of other restoration types and ecosystem challenges facing society. The common elements of ecosystem structure and services consistently influence the society's need and value for environmental protection.

2.2 Develop decision support framework

The decision support framework of this research forms a process flow to assist in decision making.

2.2.1 Structure

In the process flow, decision criteria and attributes characterize each major element of the decision support framework, reference *Figure 2.* The elements are composed of several criteria that identify a smaller number of attributes. For example, this research will consider reef width and roughness as criteria for a bathymetry attribute that defines an ecosystem structure element.

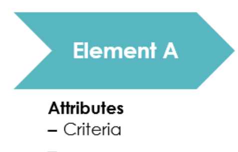


Figure 2. Decision support framework components.

2.2.2 Organization

The elements of the decision support framework operate in sequence, reference *Figure 3*, with each element, attribute, and criteria as distinct. The attributes and criteria, as subordinate components of the framework, characterize the elements. Each element complements preceding elements in the framework building a foundation to substantiate decisions. The literature review sheds light on the each of component of the framework and determines the most appropriate order. Previous research and analysis also assist to narrow the scope of the framework to essential elements, attributes, and criteria.

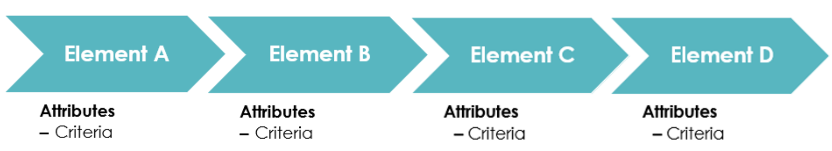


Figure 3. Decision support framework organization.

2.3 Apply framework for analysis

In order to analyze the applicability of the framework, this research considered several geographic areas of interest and numerous data sources to describe coastal resilience.

2.3.1 Case study sites

This research focuses on coral reef ecosystems growing in warm water, tropical regions of the world. As the societal benefits of coastal protection and risk reduction drive this research, this effort examines areas of greatest impact. The geographic scope of this research begins by exploring countries with large populations and built capital infrastructure located near coral reefs. To assess the global applicability of the framework, the research considers several major geographic regions for case study sites.

Within these countries and regions, the research identifies specific coral reef study sites to evaluate the criteria, attributes, and elements of the decision support framework. The research depends on this analysis to ensure the framework supports the selection of coral restoration sites for coastal resilience.

2.3.2 Coastal resilience data

This research views coastal resilience data as an essential factor for evaluating the decision support framework. A known challenge of this research rests in the ability to find sufficient resilience data at each case study site to analyze the framework. A lack of consistency in the level of data detail at each study site led the research to the requirement for an information matrix to visually present the current information and gaps for coral reef restoration and coastal resilience decisions.

2.4 Create information matrix

An information matrix offers a method to analyze elements and attributes of the framework associated with study sites. As in *Figure 4*, the matrix presents study sites horizontally, with framework elements and attributes vertically. Comparing elements and attributes at each site with the matrix offers a flexible approach to show information availability and support comparison across the framework.

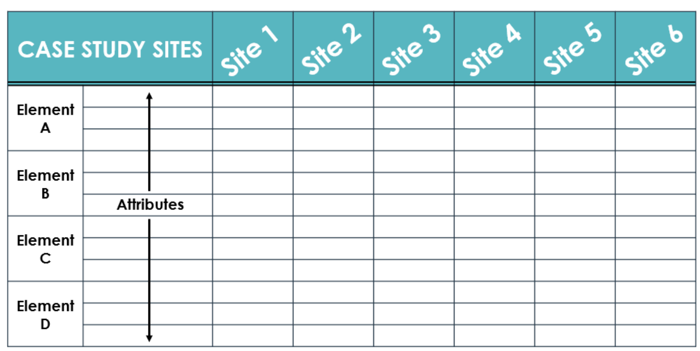


Figure 4. Information matrix template.

2.4.1 Patterns

Visually, the matrix offers a method to present the amount of data available for elements, attributes, and study sites. The benefit of using a matrix resides in the capacity to compare multiple factors at once. With the information matrix, this research compares attributes vertically across the elements, as well as data availability across the case study sites. This information matrix uses color scale, not numerical values for comparison. With the color scale, visual patterns quickly emerge from the data. The research considers both patterns and patchiness in the data.

2.4.2 Knowledge gaps

The information matrix enables the comparison of data across framework elements and case study sites. This research strives to identify data availability and gaps in analyzing the framework. The matrix approach works to inform coral reef restoration and coastal resilience decisions in the future.

3.0 Methods

This research conducted a literature review, consulted with faculty and industry advisors, and identified criteria to evaluate coral restoration sites for coastal resilience. An analysis of alternatives assisted in the selection of the most appropriate criteria and format for the decision support framework. The identification of key knowledge and data gaps, while choosing representative case study sites, bound the scope and extent of this effort to develop a methodological approach to coastal resilience.

3.1 Conduct literature review

A literature review began in the proposal phase of this research with four elements of the framework: (1) ecosystem structure; (2) ecosystem services; (3) need for coastal defense; and (4) value of reefs for resilience, reference *Figure 5*. Duke University Library resources, as well as staff, faculty, and industry advisors facilitated this review. Within the first few months of the literature review, several groups of researchers emerged as major influencers on the body of knowledge for this research.

Figure 5. Elements of the decision support framework.

3.1.1 Baseline knowledge

Within research on ecosystem structure, the predominant analysis of oceanographic and bathymetric data related to reefs and coastal resilience arose from Beck et al. (2018), Ferrario et al. (2014), Reguero et al., (2018), and USACE (2013). Beck et al. (2018) highlighted how wave hydrodynamics, habitat effects, and flood heights heavily affect the flood protection value of coral reefs in damage assessments. Wave energy, height, propagation, and attenuation, all contributed to the Reguero et al. (2018) research on the role of reefs in shoreline protection. USACE (2013) distinguished the complementary impact of wave and reef factors on coastal risk reduction. The meta-analyses by Ferrario et al. established the value of coral reefs for natural hazard protection by reducing wave energy by 97%.

With investigations into the ecological resilience in the Gulf of Mexico and Florida Keys, Cummings et al. (2018) and Rehr et al. (2012) viewed ecosystem services for biotic, abiotic, and social value. The Cummings et al. coral ecosystem summary pointed out some of the ecological, supporting, provisioning, and cultural services that reefs offer. Rehr and colleagues expanded on the range of variables and value that coral reefs contribute to coastal management decisions with coral reef health, fish abundance, and freshwater flow rates. In addition to improved biological productivity, USACE (2013) emphasized the wave attenuation, sediment retention, and coastal storm damage reduction that coral reefs offer.

Increasing storm surges and sea level rise enabled Muis et al. (2016), Reguero et al. (2018), and Temmerman et al. (2013) to identify the need for coastal defense and protection. Muis et al. correlated global tide, sea level rise, and population data to depict extreme exposure to storm surge and flooding around the globe, shown in *Figure 6*. The darkest shaded countries experience the greatest population risk. Temmerman et al. mentioned the natural capacity of coral reefs and other coastal ecosystems to reduce the impact of storm waves and surges on populated areas, by comparing conventional methods to ecosystem-based coastal defense methods. Reguero et al. (2018) offered the historical perspective of shoreline change, climate data, erosion, and sea level rise to the research.

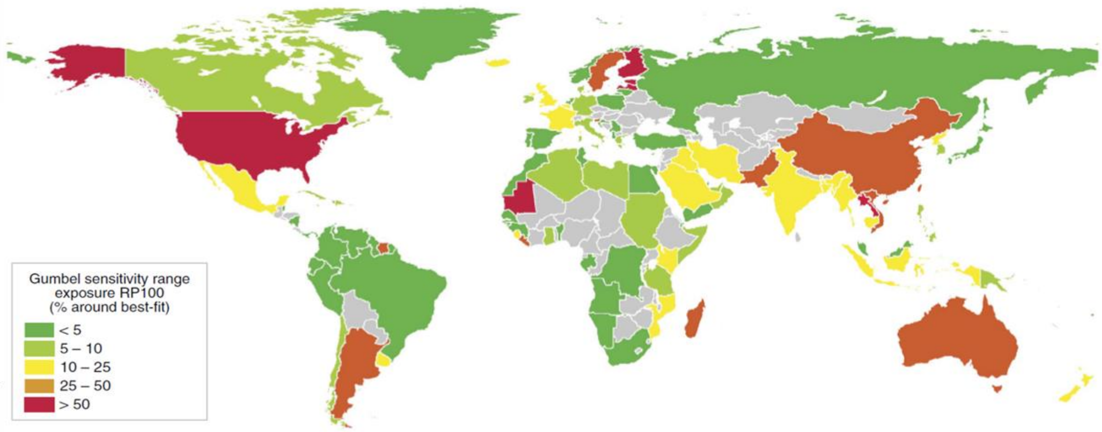


Figure 6. Population exposure to extreme sea levels and flooding (Muis et al., 2016).

Beck et al. (2018) and Constanza et al. (1997) fundamentally shaped the view of this research on the value of reefs for resilience from floods and storms. As mentioned, Beck et al. (2018) assessed flood protection value provided by reefs with estimations of the dollar value of land, people, and built capital averted damages. Though many people may identify reefs for recreational value, research pointed to the value coral reefs play in disturbance regulation as an ecosystem service (Constanza et al., 1997).

3.1.2 Data sources and limitations

The nature of this research centers on the analysis of the decision support framework with available research and data sets. From the beginning, the ability to identify knowledge and data gaps arose as a key factor of the research. Significant investigations already capture the value of coral reefs for flood protection in terms of population and built capital exposure at a large-scale country level (Ferrario et al., 2014; Beck et al., 2018). However, ecosystem structure and ecological services occupy a smaller scale and lack the same consistency across study sites (Reguero et al., 2018).

With this understanding, the literature review proceeded from one research citation to another. The research evolved by exploring ways to capture research trends and data for coastal resilience, as well as case study sites with adequate amounts of data. Collecting data from only one or two study sites appeared to limit the applicability of this research and restrict the ability to identify knowledge gaps.

Using pre-existing secondary research and data on coral reefs from around the world broadened the scope of this primary research to address coastal resilience across a variety of benthic structure and geographic scenarios. However, combining knowledge and data obtained from multiple investigations with different research objectives raised questions about the commonality and relevance for this research. The lack of consistency in scale and detail of data, led this research to move toward an information matrix as an approach to analyze and present the known/unknown information gaps.

3.2 Consult faculty and industry advisors

Throughout the research, this study consulted with faculty advisors and industry experts by phone, video conference, person interview, and email. Dr. James L. Hench of the Duke University Marine Lab (DUML), Mr. Stephen E. Roady, J.D. of the Duke Law School, Dr. Shay Viehman of the National Oceanic and Atmospheric Administration (NOAA) National Ocean Service, and Dr. John W. Virdin of the Nicholas Institute for Environmental Policy Solutions helped focus this research.

Dr. James L. Hench offered constructive feedback throughout this research to refine the scope of criteria, attributes, and the process flow for the decision support framework. Dr. Hench also suggested the information matrix as an approach to display the disparity across data sets to inform decisions. Mr. Stephen E. Roady, J.D., verified the latest developments and organizations involved in coastal resilience. Dr. Shay Viehman provided essential introductions to research focused on coral reef restoration.

Finally, Dr. John W. Virdin supported an investigation into ecosystem services, policies, tools, and practices in action through an independent study review of international policies for marine conservation. This independent study encouraged a deeper dive into the World Bank Wealth Accounting and Valuation of Ecosystem Services (WAVES) partnership for natural capital accounting (Beck & Lang, 2016). Seeking the counsel of Dr. Virdin also assisted to narrow the field of coral reef case study sites resulting in a more regionally representative selection.

Correspondence with The Nature Conservancy's coastal resilience program regarding major data sets for coral reefs in Hawaii, Florida, or globally, reinforced the decision to employ an information matrix for this research. This exchange encouraged the consolidation of data sets discovered, as well as a validation of the breadth of data sources referenced during this research.

3.3 Compile information

During the literature review, this research highlighted key factors in coastal resilience, types of coral reef restoration, and data sets to reference. With each research article reviewed, components of a flow chart began to take shape with criteria for coastal resilience assigned to data input parallelograms and attributes associated with process rectangles. In short order, the need surfaced to group similar criteria.

Compiling information in this manner, facilitated the association of criteria with attributes and ecosystem indicators. Categorizing criteria with attributes and elements from the review of each new research article caused the list of features to quickly expand. Analyzing the criteria, involved finding similar characteristics under each attribute to simplify and narrow scope to the most essential factors.

The research then transitioned to assemble components of the decision support framework into a flow chart. With criteria as inputs and attributes as processes, a detailed process flow strung all elements in sequence. The factors of location risk, ecosystem structure, restoration options, ecosystem services, costs, and benefits became areas to frame and segment the elements, attributes, and criteria.

The next critical analytic step in compiling information involved meeting with Dr. James L. Hench, the research advisor. Dr. Hench offered valuable feedback on ways to simplify the process flow, as well as adding functions and higher-level processes to the decision support framework for clarity.

3.3.1 Framework criteria, attributes, and elements

As stated, the literature review produced many factors to consider as criteria and attributes for the decision support framework. The selection of key criteria began by documenting and analyzing the results of the coastal resilience and reef restoration research to identify patterns and similarities. Consultation with Dr. Hench helped refine the attributes and criteria essential to this research to a smaller subset of the original components. This analysis reduced duplication and ensured clarity in the labeling of each attribute and criteria. Further literature review of previously referenced and new research confirmed the labeling and scope of framework criteria, attributes, and elements.

3.3.2 Decision support framework (DSF) format

The criteria selection caused a careful analysis of the sequence of the decision support framework (DSF). As advisor, Dr. Hench encouraged reordering the elements of the DSF to bound the research by placing the need for coastal defense and value of reefs for resilience at opposite ends of the framework. This new sequence and the research focus on informing restoration decisions, drove the relabeling of the need for coastal defense element as suitability for coastal defense, depicted in *Figure 7*.

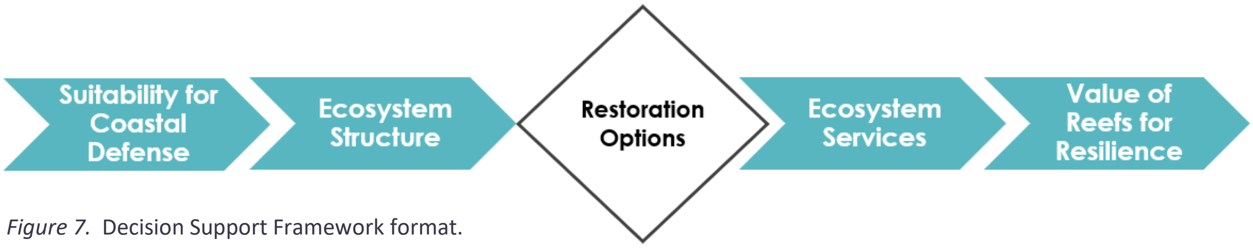


Figure 7. Decision Support Framework format.

Thorough review of the factors within the process flow also led to the addition of a restoration options decision element in the center of the DSF. The research considered the addition of functions and higher-level process steps for each element to clarify what an element offers and how the element applies to the DSF, respectively.

3.3.3 Case study site selection

After assembling the criteria and organizing the decision support framework, this research applied the framework to case study-based evaluations of coral restoration sites. This case study approach enabled the research to assess the applicability of the framework to evaluate sites for coral restoration and coastal resilience. Again, this research focused on coral reef ecosystems growing in warm water, tropical and subtropical regions of the world.

The geographic scope started by exploring countries with coral reefs, and then considered several major geographic regions of the world to demonstrate variety and global representation in the case study sites. Ultimately, the need arose to narrow the scope of the case study sites from a regional or country level to a scale closer to an extent of a coral reef. This refinement better supported the application of the decision support framework to the case study sites. This research pursued the selection of case study sites in parallel with the development of the DSF.

3.3.3.1 Countries and geographic regions

At first, the research plan involved selecting sites from existing Duke University research from the Bass Connections Open Evidence Gap Map, the Duke University Marine Lab, and Nicholas Institute for Environmental Policy Solutions.

The 2018-2019 Bass Connections Open Evidence Gap Map research originally considered sea grass, coral reef habitats, and mangroves, offering potential for this study site selection; the final analysis in that timeframe focused primarily on mangroves (Littlewood, 2019). Dr. John W. Virdin of the Nicholas Institute for Environmental Policy Solutions shared research on the North Brazil Shelf and Tanzania. This consultation encouraged the consideration of Tanzania as a potential study site.

The initial literature review during the proposal phase of this research surfaced studies by Ferrario et al. (2014), Beck et al. (2018), Temmerman et al. (2013), and Muis et al. (2016) and focused the research on the selection of study sites where coral reefs offer the greatest impact to coastal protection and risk reduction, as shown in *Figure 8*. The black outlines along coasts reflect coral reef presence in warm water, tropical regions. Indonesia, the Philippines, Brazil, the United States, and Tanzania clearly displayed the population and built capital proximity to coral reefs that warranted consideration for research (Beck et al., 2018; Ferrario et al., 2014; Temmerman et al., 2013). After closer review, the lack of data for coral reefs off Brazil led to the removal of this country from study site consideration.

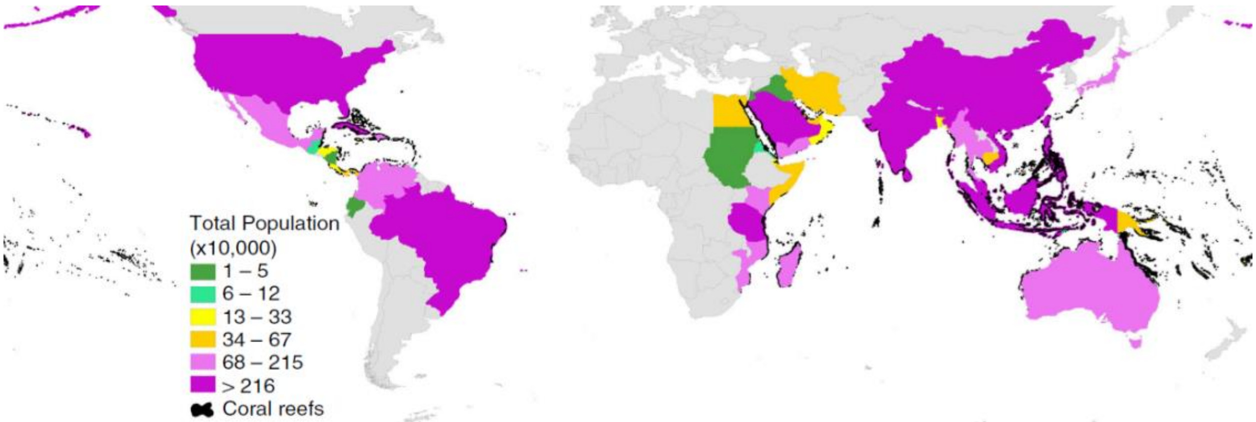


Figure 8. Population risk reduction from coral reefs (Ferrario et al., 2014).

The UNEP (2019) analysis of policies related to the protection of coral reefs reinforced the selection of Indonesia and the Philippines for study sites, as over 40 percent of warm water coral reefs in the world fall within the jurisdiction of Australia and these two countries. The Nature Conservancy (TNC) Mapping Ocean Wealth Explorer validated the large coastal populations protected by reefs in Indonesia, the Philippines, and Mexico (TNC, 2019). Reefs at Risk Revisited (Burke et al., 2011) and Coasts at Risk (Beck, 2014) verified risk to coasts in the Philippines, Indonesia, Tanzania, the United States, and Mexico.

Research by Pendleton et al. (2016) offered a regional view of shoreline protection across ocean provinces. This perspective encouraged a research assessment of the global applicability of the decision support framework across several major geographic regions or ocean basins. The Pendleton et al. (2016) research bolstered support for populations protected by coral reefs in South East Asia and the Caribbean. Based on the countries previously identified, selecting sites in Western Indian Ocean and Central Pacific Ocean provinces supported greater global representation. These regions aligned most with Indonesia, the Philippines, Tanzania, the United States, and Mexico to narrow the focus of this research.

3.3.3.2 Sites

Within these regions and countries, this research needed to further reduce the scope to specific coral reef study sites to better evaluate criteria, attributes, and elements of the decision support framework. The analysis of this research depended on the selection of coral restoration sites with sufficient data and information to ensure the framework supported for coastal resilience.

During the proposal phase, this research recognized the utility of the Mapping Ocean Wealth Explorer to contribute to case study sites and coastal resilience data, specifically for Indonesia, the Philippines, Tanzania, Mexico, and even Florida (TNC, 2019). Around that same time, the Allen Coral Atlas from Vulcan, Inc. showed promise as a resource for case study sites and data, particularly for coverage off the island of Hawaii (Vulcan, 2019).

Research by Spalding et al. (2017) and Burke et al. (2011) further confirmed the results from the Mapping Ocean Wealth Explorer and offered greater scale in the economic value of coral reefs for tourism for Indonesia, the Philippines, Tanzania, and the Caribbean, displayed in *Figure 9*. The warm colors on these maps indicate economic hot spots for specific case study sites. In Reefs at Risk Revisited, Burke et al. (2011) emphasized socioeconomic dependence on coral reefs for these countries.

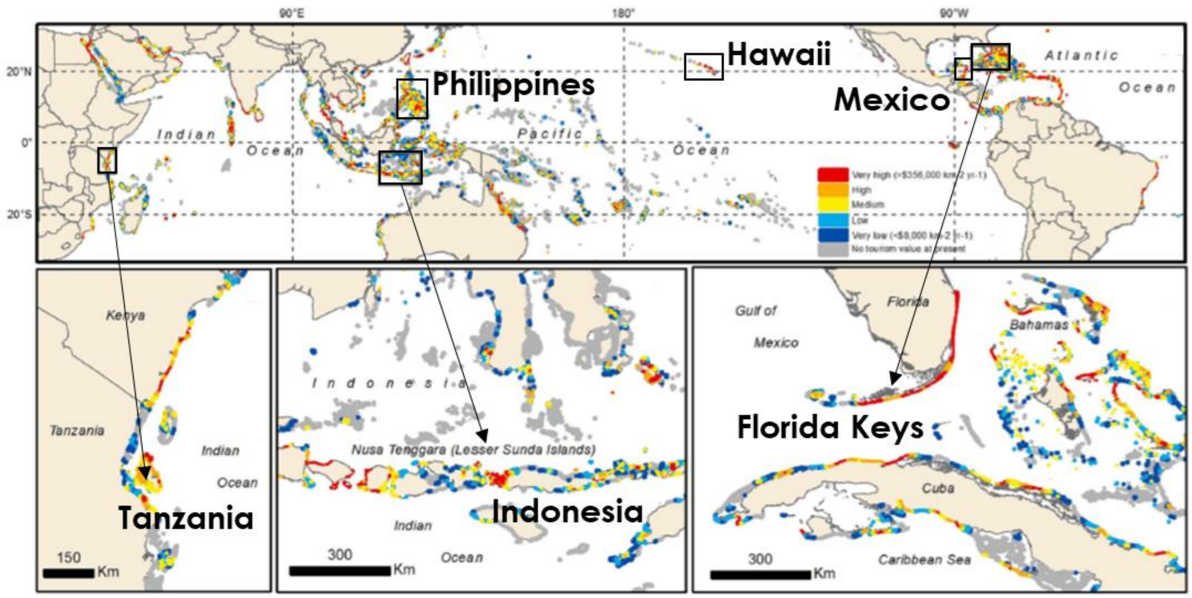


Figure 9. Economic value of reefs for tourism, on-reef & adjacent tourism (Spalding et al., 2017).

Multiple online maps and map explorers assisted in the selection of several coral reef study sites:

(i) Lesser Sunda Islands, Indonesia (ID) (WRI, 2011; Spalding et al., 2017);

(ii) Mindanao to Panglao, Philippines (PH) (WRI, 2011; TNC, 2019);

(iii) Dar es Salaam to Zanzibar, Tanzania (TZ) (TNC, 2019);

(iv) Mesoamerican Reef, Quintana Roo, Mexico (MX) (TNC, 2019);

(v) Key West to Big Pine Key, Florida Keys, United States (US) (TNC, 2019); and

(vi) Kailua Kona to Kawaihae, island of Hawaii, United States (US) (Vulcan, 2019).

Overall, these study sites supported the closer investigation of coastal resilience decisions and coral reef restoration efforts necessary for this research to apply the DSF.

3.4 Develop, review, and refine DSF

The primary task of this research centered on assembling components of a decision support framework to analyze information and data sets for coastal resilience decisions related to reef restoration. This research depended on identification of suitable criteria to evaluate coral restoration sites, based on ecosystem structure and services, as well as value and suitability.

3.4.1 Process

Proceeding with a broader view than previous coastal resilience studies, this research aimed for a more holistic analytic framework. By considering the process steps that each element of the framework represented, this research worked to refine the decision support framework. The addition of these higher-level process steps addressed how each element applies to the overall framework.

In relation to decision frameworks, previous research reviewing decision support tools for marine spatial planning offered a baseline of reference for the higher-level process steps of this framework (COS, 2011; Pinarbasi et al., 2017). This current research reduced the number of steps needed to support decisions and simplified the process flow for this framework, as presented in *Figure 10*.

DEFINE THE PROBLEM	IDENTIFY DESIRED CHANGE & ASSESS EXISTING CONDITIONS	DISCUSS OPTIONS	EVALUATE OPTIONS	PRESENT RESULTS TO CLARIFY VALUE

Figure 10. Framework process flow.

The first element works to define the problem with suitability for coastal defense. The second element identifies existing and desired characteristics from ecosystem structure, in order to answer questions of: What to protect? Why protect? What outcomes to achieve? What prospects exist based on structure? Restoration options, as the third element, encourages a discussion of alternatives. Ecosystem services offers a process step to evaluate options. The final step, the value of reefs for resilience, presents results to clarify value from the framework.

This research found that The Nature Conservancy's coastal resilience program offers a similar approach to hazard mitigation and planning with four steps: (1) assess risk and vulnerability; (2) identify solutions; (3) take action; and (4) measure effectiveness (TNC, 2016a).

3.4.2 Function

As mentioned, this research associated each element of the DSF with a function to capture what each element offers, shown in *Figure 11*. The first element provides a retrospective context of the historical exposure of coastal areas and accounts for location vulnerability as well as viability of coral restoration. Ecosystem structure then captures the natural function ecosystem structure and hydrodynamics.

Retrospective Context	Natural Function	Restoration Options	Protection Value	Balance Sheet

Figure 11. Element functions.

The third element offers generalized restoration options for reefs. The ecosystem services element drives to capture the protective value of reefs for coastal populations, socioeconomic benefit, as well as ecological and biological factors. The final element functions as balance sheet comparing the cost of restoration with resource exposure avoided. All components of the framework work together to deliver context on coral reef restoration efforts for coastal resilience decisions.

3.5 Apply the framework

The analysis for the research applied the decision support framework to coral reef study sites and coastal resilience data to better inform coastal community decisions. This research considered several warm water, tropical study sites and numerous data sources to assess coastal resilience. This research presented the framework analysis in the results section of this report.

3.6 Illustrate information in matrix

From the beginning, this research sought an approach to illustrate information availability to analyze coral restoration sites across the framework. An information matrix became a practical tool to visually present the analysis and communicate the results of this research to inform coastal resilience decisions. The comparison of data across the matrix also helped assess the applicability of the research.

The matrix enabled simultaneous comparison of study sites horizontally and coastal resilience attributes vertically. The information matrix offered a flexible approach to assemble coastal resilience and reef data for analytic comparison. The intent of the using the decision support framework and information matrix, as tools, is to raise awareness of coastal resilience benefits from coral reef restoration in order to share best practices.

The matrix uses a color scale as a key to analyze values across the matrix and enable visual patterns to quickly emerge. Consider the key as one long extended scale in order to cover a wider range from data abundance to scarcity. The color key moves from data abundance values (high to low, as dark to light) and continues with scarcity values (low to high, as dull to bright) to differentiate values across the matrix. The matrix analysis considered availability, gaps, patterns, and patchiness in the data.

4.0 Results

This research aimed to develop a decision support framework to assist in the selection of coral reef restoration sites to sustain coastal resilience decisions. The framework offers the context for this research, outlining the key elements to frame the extent of the investigation, as referenced in the Appendices section 6.1 and *Figure 12*. The information matrix visually presents the analysis of this research, in Appendices section 6.2 and *Figure 14*. Together, these tools enable in-depth examination of the functions and criteria for coral reef restoration that support decision making for coastal resilience.

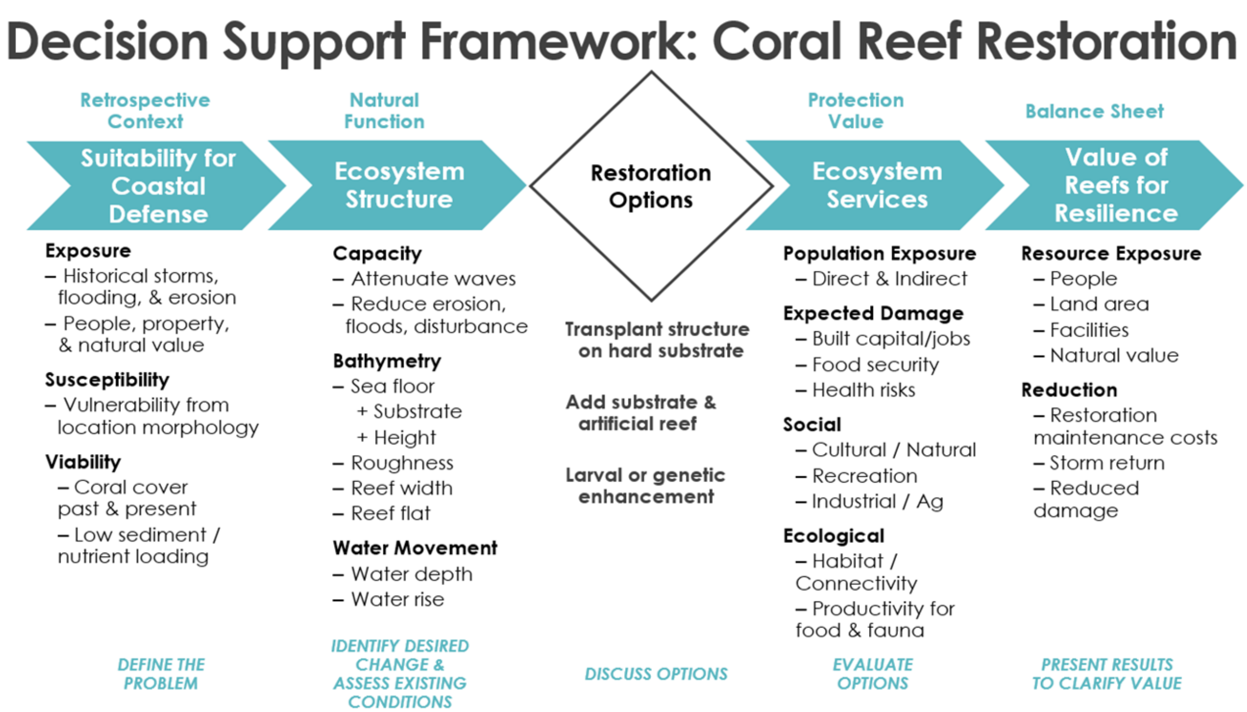


Figure 12. Decision Support Framework (DSF).

4.1 Decision Support Framework (DSF)

The flexible approach of this decision support framework process flow in *Figure 12* offers the ability to adjust the elements and attributes based on the restoration scenario. In coral reef restoration, the type of restoration options become the nucleus of discussions on both sides of the framework. For example, this research quickly recognized coral cover and low sediment/nutrient loading as essential factors for success to identify restoration sites, while a reef's ability to protect communities from resource exposure and reduce damage offer important measures of effectiveness.

4.1.1 Problem – Suitability for Coastal Defense

The first analytic step in the framework defined the problem of coastal resilience by associating the retrospective context of historical storms with location morphology and viability for coral growth. The bold attributes of exposure, susceptibility, and viability all supported the element of suitability for coastal defense. Underneath the attributes, specific criteria enabled the evaluation of this element across the case study sites.

4.1.1.1 Exposure

In terms of the attribute of exposure, significant research volume already considered storms, flooding, and sea level rise as hazards that placed coastal populations at risk (Beck, 2014; Muis et al., 2016; Spalding et al., 2014; Storlazzi et al., 2019; USACE, 2015). Ferrario et al. (2014) noted that coastal property development added to these hazards and suggested that coral reef habitat loss further increases the threat of coastal hazards. A few researchers consistently pointed to the need to reference historical storm and shoreline erosion data, when possible (Reguero et al., 2018; Reguero et. al., 2019b). Other studies investigated inundation from floods with and without coral reefs to assess coastal protection value (van Zanten et al., 2014). Finally, research examining the role of coastal ecosystems in protection suggested quantifying the value of natural systems in terms for natural benefits, non-monetary values, and potential losses in ecosystem services from development and exposure (Spalding et al., 2014). Each of these criteria supported the exposure attribute of the decision support framework.

4.1.1.2 Susceptibility

Many studies, on the coastal protection value of coral reefs, already considered susceptibility and vulnerability as key factors in assessing risk with storm/flood damage and likelihood of harm (Beck, 2014; Reguero et al., 2019b). Flood zones offered a key tool for many studies to assess vulnerability (van Zanten et al., 2014). For this research, susceptibility focused on the vulnerability created by location morphology given the need to identify coral reef restoration sites suitable for coastal defense.

	Ranking of coastal vulnerability index				
	Very low	Low	Moderate	High	Very High
VARIABLE	1	2	3	4	5
Geomorphology	**Rocky, cliffed coasts, fiords, fiards**	**medium cliffs, indented coasts**	**low cliffs, glacial drift, alluvial plains**	**cobble beaches, estuaries, lagoons**	**barrier & sand beaches, salt marsh, mud flats, deltas, mangrove, coral reefs**
Coastal Slope (%)	> 0.2	0.2 – 0.07	0.07 – 0.04	0.04 – 0.025	< 0.025

Table 1. Coastal Vulnerability Index (Thieler & Hammar-Klose, 1999).

Prior research referred to this factor as historical position of the shoreline and nature of adjacent areas (Reguero et al., 2018; Spurgeon, 2001). Refer to *Table 1* for an excerpt from the USGS assessment of a coastal vulnerability index (CVI) to sea level rise which offered practical examples of site location geomorphology associated with the variables of coastal slope, relative sea level rise, shoreline erosion/ accretion, mean tide range, and wave height (Theiler & Hammar-Klose, 1999). The table clarified that coral reefs occupy locations with very high CVI and a very gradual slope equating to greater susceptibility to flooding, storm surge, and sea level rise, as well as suitability for coastal defense.

4.1.1.3 Viability

This decision support framework presented viability of a site to host coral as the last attribute under the element of suitability for coastal defense. In order to sustain long term coral reef restoration, site selection must include past or present live coral as criteria. Research documented that coral cover along with topographic complexity typically contribute to greater reef productivity (Cummings et al., 2018). Benthic community ecosystem structure and habitat supporting ecosystem services both depend on live coral cover (Cummings et al, 2018; van Zanten et al., 2014). Live coral offered the complexity and surface roughness to dissipate the wave energy discussed in this research (Reguero et al., 2018). Studies even suggested adding coral cover decline to flood hazard area sensitivity in Flood Insurance Rate Maps (FIRMS) to account for coastal protection functions of coral reef (van Zanten et al., 2014).

Without hospitable environmental conditions for coral growth, reef restoration remains challenging. Excessive nutrient and sediment loading further complicate coral recovery and management by reducing access to light (Rehr et al., 2012). The mutual symbiotic relationship between shallow, warm water corals and zooxanthellae algae depends on sunlight for algal photosynthesis (LaRoche, 2018; NOAA, 2020a). Therefore, low nutrient and sediment loading must be a criterion when selecting sites for coral reef restoration.

4.1.2 Existing & Desired Conditions – Ecosystem Structure

Next, this research examined the natural functions of coral reef ecosystem structure. While the attributes of bathymetry and wave movement concentrated on existing conditions, the capacity to reduce disturbance and attenuate waves focused on processes to achieve desired change.

4.1.2.1 Capacity

In 2013, the US Army Corps of Engineers described coral reefs in a full array of coastal risk reduction measures (USACE, 2013). In a comparison of natural and nature-based features, the study found that coral reefs perform two primary functions: wave attenuation and sediment retention (USACE, 2013). By breaking offshore waves, coral reefs slow inland water transfer and reduce coastal storm damage (USACE, 2013). As previously referenced, coral reefs dissipate 97% of incoming wave energy and reduce 84% of wave height, considering the whole reef environment with seaward reef crests and reef flats (Elliff & Silva, 2017; Ferrario et al., 2014; TNC, 2018). Elliff & Silva (2017) pointed out research gaps and the need for more studies of shoreline protection capacity from different types of reefs such as fringing, barrier, patch, and atolls.

Providing natural flood and erosion reduction, coral reefs offer the capacity to regulate disturbance (Beck et. al, 2018). The World Bank Wealth Accounting and the Valuation of Ecosystem Services (WAVES) review of protection services from natural solutions referred to many research models and tools in clear tabular layout with brief descriptions for storm surge dissipation, coastal flooding, and erosion (Beck & Lange, 2016). The initial insight on coral reef disturbance regulation for this research arose from a study of the value the world's ecosystem services and natural capital (Constanza et al., 1997). The study offered the examples of storm protection and flood control as natural disturbance regulation responses to environmental instability (Constanza et al., 1997). Prevention of shoreline erosion offered another response to environmental variability (Reguero et al., 2018). Only coral reef recreational services exceeded reef disturbance regulation globally, on a by hectare basis and by less than $760 per hectare, in 1994 US dollars (Constanza et. al, 1997).

4.1.2.2 Bathymetry

Many criteria influenced coral reef bathymetry for the decision support framework. Research consistently highlighted reef elevation, roughness, and width as main factors in the coastal protection functions provided by coral reefs (Spalding et al., 2014; Reguero et al., 2018; USACE, 2013). The bathymetric criteria for the framework began with sea floor substrate in order to better understand the physical structure available for reef restoration. For example, a restoration site might involve hard substrate, sandy bottom, rocky substrate, or even fragmented coral rubble from a recent storm disturbance. These types of substrate significantly impact the ability of different types of coral to thrive. Building up the reef structure one layer at a time, this research considered reef elevation as the height from sea floor. Research emphasized the importance of reef height, noting that a reduction at the top of reef crests by one meter would double annual damages from coastal storms and increase coastal flooding of land by 61% (Beck et al., 2018).

Similarly, rugosity offers a measure of reef structural complexity often associated with reef roughness at different scales. As with reef height in the water column, scientists found that rugosity offers one of the most relevant physical parameters for breaking waves and attenuating wave energy (Beck et al., 2018; Ferrario et al., 2014; Elliff & Silva, 2017). Bottom friction, which causes wave attenuation, is a function of roughness along the reef (Ferrario et al., 2014). The width of reef flats also impacts wave energy dissipation rates from friction (Elliff & Silva, 2017). Though wider reef flats offer greater wave energy and wave height attenuation, narrow flats offer the capacity to attenuate wave energy along the first 150 meters of the reef flat (Elliff & Silva, 2017; Ferrario et al., 2017).

All of these criteria demonstrate morphology within the reef that work together on a structural level to both attenuate waves and retain sediment. However, defining where one factor ends and another begins becomes challenging. Visualizing a coastal profile of reef zones and hydrodynamic parameters aids in understanding the interactions leading up to the shoreline, as presented in *Figure 13*. This figure helps reveal the effects of a steeper forereef downward slope (declivity), a more gradual wave runup area, and narrower reef flat (Elliff & Silva, 2017; Reguero et al., 2018).

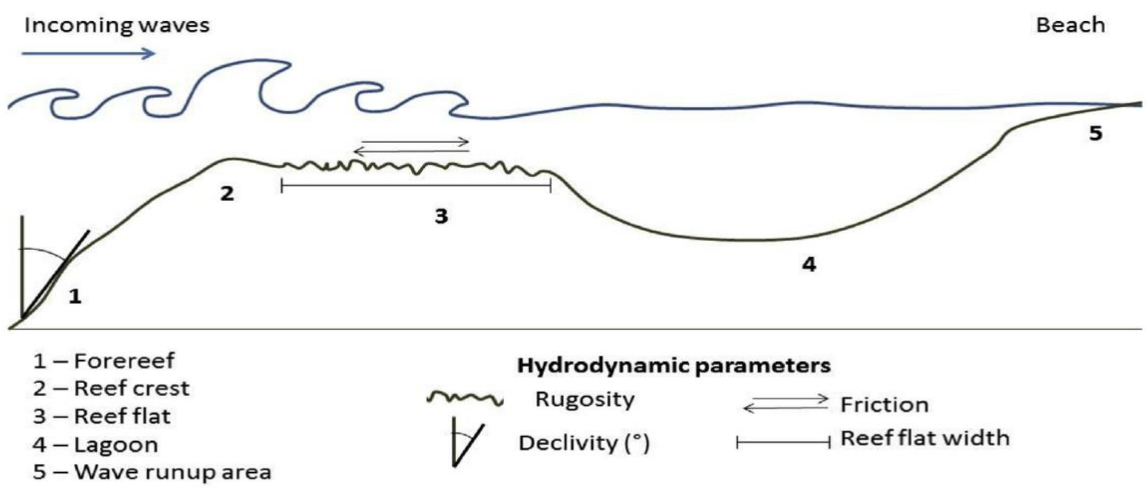


Figure 13. Coastal profile of reef zones and hydrodynamic parameters (Elliff & Silva, 2017).

4.1.2.3 Water Movement

Water moves around and through reef structures. On seaward reef crests, researchers found water depth above the reef as a critical factor in wave attenuation (Beck & Lange, 2016). Many studies applied hydrodynamic wave models to assess wave heights, wave energy magnitude, and direction (Reguero et al., 2018). Shallow water depths yielded the largest relative wave energy dissipation when modeled for 100 year events; shallow high density reefs (95.5% reduced wave energy) and low density reefs (90%) delivered more than deep high density reefs (38%) and low density reefs (32%) (van Zanten, et al. 2014).

Research considered several processes for water rise in coastal protection scenarios. Offshore waves ascend from the interaction between sea level, tides, wind, waves, and storm surge, with estimations from historical storm, climate, and ocean observations (Beck & Lang, 2016). Near shore waves surface when offshore waves approach to interact with the coastal environment observed with bathymetric data sets at the global, regional, and local scale (Beck & Lang, 2016). Though the International Hydrographic Organization (IHO) supports broad access to global and regional bathymetric data sets, locating high resolution bathymetric data from local nautical charts, surveys, and lidar collections for case study sites remains challenging (Beck & Lang, 2016, BODC, 2020).

Finally, onshore flooding and erosion occur from a combination of water movement factors. Mean water level, tides, storm surge, wave setup, and wave runup contribute to coastal flooding (Beck & Lange, 2016). Cross shore and longshore sediment transport from wave action, wind, wave currents, and tidal currents contribute to coastal erosion of land (Beck & Lange, 2016). The World Bank WAVES research offered many models and tools for measuring waves, storm surge, wave runup, flooding, and erosion (Beck & Lang, 2016). These criteria offer useful measures to assess coral reef restoration sites.

4.1.3 Restoration Options

An initial research review did not clearly identify best practices for coral reef restoration in support of coastal protection (Beck & Lange, 2016). Later research offered reef restoration recommendations for risk reduction (Zepeda-Centeno et al., 2018). A few studies summarized major techniques for coral reef restoration based on research reviews (Bayaraktarov et al. 2019; Reguero et al., 2018). By comparing studies, this research settled on three main options for coral restoration.

Transplant Structure - Direct transplantation of coral fragments or colonies on hard substrate, with or without coral gardening growth of coral fragments in a nursery, (Bayarktarov et al., 2016 & 2019; Edwards & Gomez, 2007; Rinkevich, 2019).

Add Substrate & Artificial Reef - Substrate stabilization or enhancement with artificial reefs (Reguero et al., 2018; Zepeda-Centeno et al., 2018).

Larval or Genetic Enhancement - Larval/genetic enhancement by cultivation and planting of juvenile corals (Bayarktarov et al., 2016; Edwards & Gomez, 2007; Zepeda-Centeno et al., 2018).

New research in 2020 confirmed these three main restoration categories as asexual propagation, substratum enhancement, and sexual propagation, respectively (Bostrom-Einarsson et al., 2020). However, case study sites for this research lacked data on reef restoration methods and best practices for coastal protection. A variety of techniques exist within the restoration categories and applicability depends on reef morphology and bathymetric. Reef and adjacent site conditions must be assessed before choosing the most appropriate coral reef restoration option.

4.1.4 Evaluate Options – Ecosystem Services

Under the ecosystem services element, this research focused on protective value offered to population exposure, expected damage, social services from coral reefs, and ecological services.

4.1.4.1 Population Exposure

Based on population levels within 10 kilometers of coral reefs that receive direct and indirect risk reduction benefits, Indonesia, the Philippines, the United States, and Tanzania ranked within the top seven countries of the world, as viewed in *Figure 8* (Ferrario et al., 2014). Population exposure in cities and countries factored into the analysis of extreme sea levels and flooding, as in *Figure 6* (Muis et al., 2016; Pendleton, et al., 2016; Reguero et al., 2019b; Storlazzi et al., 2019; Temmerman et al., 2013).

4.1.4.2 Expected Damage

Indonesia and the Philippines ranked first and second, as countries with the most flood protection value to built capital in averted monetary damages due to reefs; the US ranked tenth (Beck et al., 2018). Expected damages to built capital and residential properties factored into risk protection from reefs (Arkema et al., 2013; Beck et al, 2018; Reguero et al., 2019b; Storlazzi et al., 2019). Some research considered the potential damage to ecosystem provisioning services of fish, food, and fishing jobs (Burke et al., 2011; Constanza et al., 1997; Pascal et al., 2016; Pendleton et al., 2016).

4.1.4.3 Social Services

Several research sources discussed the cultural and recreational ecosystem services of coral reefs (Goodin et al., 2018; Pascal et al., 2016; Rehr et al., 2012; USACE, 2013 & 2015; Whelchel et al., 2018). For recreation, coral reefs ranked the highest of all biomes and across all the reef provided ecosystem services in monetary value (Constanza et al., 1997). As displayed in *Figure 9*, the case study sites for this research displayed high economic value for coral on-reef and adjacent tourism (Spalding et al., 2017).

4.1.4.4 Ecological Services

This research evaluated the ecosystem supporting services in terms of habitat/connectivity and reef food/fauna productivity (Cummings et al., 2018; Edwards, 2010; Goodin et al., 2018; USACE, 2013; Whelchel et al., 2018). Though the research mentioned supporting ecosystem services, few articles quantified or ranked values for these ecological services which created a data gap for this research.

4.1.5 Value – Value of Reefs for Resilience

Finally operating as a balance sheet for the DSF, this research reviewed the value of reefs for resilience.

4.1.5.1 Resource Exposure

Many studies calculated resource exposure from coastal flooding in terms of population, land area, facilities, and property value in dollars (Arkema et al., 2013; Beck et al., 2018; Muis et al., 2016; Pendleton et al., 2016; Reguero et al., 2019b; Storlazzi et al., 2019). Though the Storlazzi research only considered US coral reefs in Florida, Hawaii, and US territories, the study offered values for a broad range of facilities including residential, commercial, industrial, government, educational, agricultural, and religious sites (Storlazzi et al., 2019). Data on natural value resource exposure was not prevalent.

4.1.5.2 Reduction

Research found reduced damage costs/measures challenging to locate. Some storm return data existed. Though only limited case study site reef restoration costs existed, median coral restoration project costs were US $1,290/m per site, much less expensive than $19,791/m for breakwaters (Ferrario et al., 2014).

4.2 Information Matrix

At the start of this research, the method for how to present the results of the analysis was unclear. After careful selection of case study sites and gathering of coastal resilience data for those sites, using an information matrix for analysis and presentation of results became the obvious choice. The selection of multiple study sites validated the data gathered in the literature review and the information matrix utility. Selecting only one or two study sites would have reduced matrix findings, analysis, and utility.

As mentioned previously, the information matrix offered a method to compare elements and attributes of the framework for study sites. The structure of the matrix aligned study sites horizontally for evaluation of the framework elements and attributes vertically, as shown in *Figure 14* and Appendices section 6.2. The matrix grouped attributes with the appropriate elements by sub-row and row.

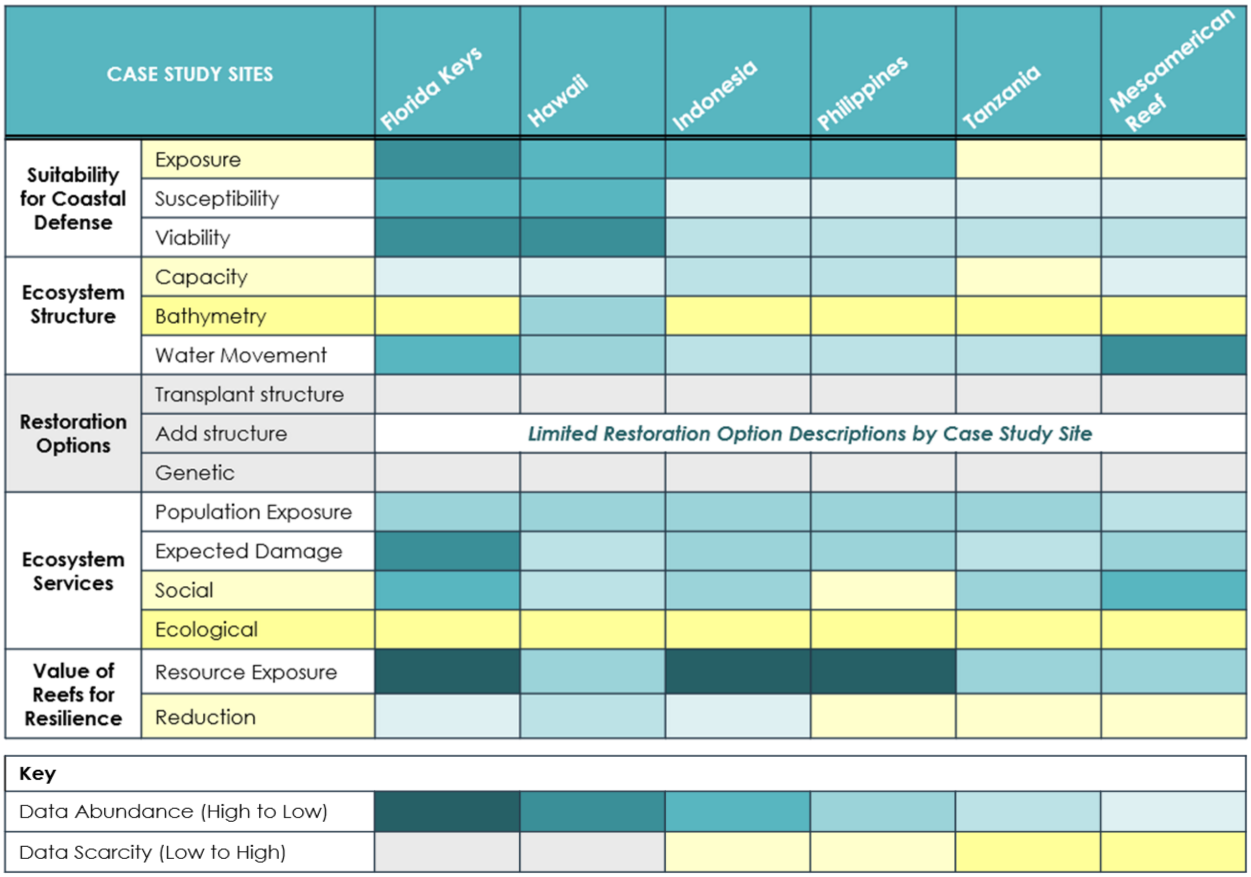


Figure 14. Information Matrix.

The information matrix analysis considered availability, gaps, patterns, and patchiness in the data. A color scale supported analysis of values across the matrix, enabling visual patterns to appear. The key below the matrix presented data abundance and data scarcity, for use as one long extended scale.

Low abundance transitioned to low scarcity, connecting the entire spectrum from abundance to scarcity. The darkest sea blue points to where the most abundant data exists. As study site resilience data decreased, the shade of blue turned lighter. At the opposite end of the spectrum, bright yellow represents data scarcity for coastal resilience attributes and study sites with the least amount of data. When the amount of data available increased, then the brightness of the cell color decreased.

In practice, the darkest sea blue highlighted the most abundant information as resource exposure for Indonesia, the Philippines, and the Florida Keys. Where minimal data existed, bright yellow cell color exposed the lack of data at the study sites for reef bathymetry and reef ecological services.

4.2.1 Criteria by case study site

Visually capturing data and information availability by cell color worked most effectively at the ends of the spectrum. Accurately representing data availability in the middle of the range presented the most challenges. Since the commonality of data sources and units of measure varied across framework criteria and attributes, volumetrically comparing data across study sites became harder to differentiate in the middle range of data availability. Therefore, calculating the number of data sources and research articles contributing relevant and applicable data on specific case study sites became the method to populate the information matrix.

Observing the information matrix notes for cases study sites in the Appendices section 6.2.1, offers a window into how research, online databases, and map services correspond to case study sites by framework attribute. Note the abbreviations used for study site names: Florida Keys (FL), Hawaii (HI), FL and HI as US, Indonesia (ID), Philippines (PH), Tanzania (TZ), and Mesoamerican Reef (MX). Note that almost half of the data sources in the information matrix notes came from scientific research articles, while the majority originated from efforts supported by nonprofit organizations.

4.2.2 Data gaps across study sites

Originally, the research plan involved critically evaluating data from all the case study sites after applying the decision support framework. The literature review and compilation of information on the study sites resulted in substantial information and knowledge gaps needed to apply the framework.

The most abundant data existed for the Florida Keys resource exposure and historical flood/erosion data. However, this research found ecosystem capacity to reduce disturbance, bathymetric structure, values for habitat/connectivity, and reduction damage costs/measures systemically challenging to collect for the Florida Keys. This analysis indicates that even with significant research, databases, and resources for coral reef restoration in the Florida Keys, gaps in data, information, and knowledge exist. These gaps reduce the ability to inform coral reef restoration site selection for coastal resilience.

Consider the case study site columns on the information matrix as a geographic lens for analysis. The most startling aspect of the research came from the analysis and recognition that the Florida Keys offered more data and context for coastal resilience decisions on coral reefs than Indonesia and the Philippines. Even though the data supported significant coastal community resource exposure in the Philippines and Indonesia, the greatest abundance and variety of data for coastal resilience decisions resided with the Florida Keys and Hawaii, both locales in the United States.

This research revealed a growth in research and data across the framework for the Mesoamerican Reef, yet the amount of data openly available for this site remained less than Indonesia and Philippines. Finally, research revealed that Tanzania receives coastal protection value from coral reefs and as a representative niche study site for the West Indian Ocean basin, this site would benefit from more research and data to support reef restoration and coastal resilience decisions.

Overall, this research benefited from seeking globally representative, regional examples of coral reef restoration sites in South East Asia, the Indian Ocean, the Caribbean, and the Pacific Ocean. This geographic selection highlighted how research and data availability related to coastal resilience decisions and coral reef restoration vary greatly around the world.

4.2.3 Data quality & availability

From the proposal phase, this research anticipated that available research and data on the ecosystem services of coral reefs and the economic value for coastal protection may outweigh information on ecosystem structure and suitability for coastal defense, as criteria in the decision support framework.

Employing an information matrix to analyze and present data for this research assisted in overcoming a lack of consistency in data scale and detail. Without generating new primary research data, as the focus remained on developing a holistic decision support framework, much of the data compiled from secondary research focused on applications in other or more specific domains. No global or local databases existed for all the decision support framework components.

This research mitigated the concern for data inconsistency by identifying databases and data sets that applied to as many of the case study sites as possible. The Nature Conservancy (TNC) Mapping Ocean Wealth Explorer and World Resources Institute (WRI) Reefs at Risk Revisited maps offered the most coverage and consistency across the study sites (Burke et al., 2011; TNC, 2019).

Next, as depicted in the information matrix, this research sought out multiple data sets and research articles for each framework attribute and criteria. After confirming data consistency, the availability of numerous data sets per attribute increased the confidence in the analysis.

Finally, although data used in this research originated from secondary research in other domains, many of the sources related closely to this investigation. Examinations of coastal risk and hazards, coral cover, population exposure, coastal ecosystem services, flood protection, and ecosystem service valuation offered data sets closely applicable to this research.

4.3 Analysis

This research presents a descriptive and visual review of the framework presented and an analysis of coral reef restoration sites with the information matrix to support coastal resilience decisions. This research initially anticipated a lack of consistency in the level of detail in data to populate and support the decision criteria of the framework. Therefore, this research devoted time to examine and develop criteria into a similar baseline to rank, prioritize, group, and align with appropriate framework attributes and elements.

The resultant information matrix resembles a patchwork quilt. This appearance reflects the interdisciplinary nature of the coastal resilience problem and variance in research and data across study sites. This research benefited from using the information matrix to compare multiple factors at the same time, across framework attributes and case study sites.

Even though much of the data appeared inconsistent or patchy, patterns arose. First, the information matrix points to a need for future research on reef bathymetry and ecological services at the local level for coral reef restoration sites. Second, many coral reef sites need more measures of coastal damage reduction and cost estimates for coral reef restoration and maintenance. Third, the data availability for coral reef restoration methods and best practices to support coastal protection clearly lacked consistency across all study sites.

In order to raise awareness of coastal resilience benefits from coral reef restoration, the intent is to use this research, the framework, and the information matrix to communicate the results and share best practices with partners working in tropical coral reefs around the world. A focal research aim is to apply the framework and information matrix to advise coastal resilience and coral reef restoration decisions.

5.0 Discussion

While previous studies investigated the role of coral reefs in shoreline protection, few offered a comprehensive approach to inform effective restoration and resilience decisions. This research focused on developing a holistic decision support framework to analyze candidate coral restoration sites and inform coastal resilience decisions with an information matrix.

The intensity of extreme storms and frequency of high tide flooding continues to increase, driving coastal communities to adapt and seek solutions to mitigate environmental pressures. With these threats more communities, stakeholders, nonprofit organizations, and government entities express interest in natural and nature-based infrastructure solutions.

Earlier research found that coral reefs dissipate wave energy directed at shorelines and possess the capacity to keep up with sea level rise through the natural accretion of sediment (Ferrario et al., 2014; Temmerman et al., 2013; TNC, 2018). Therefore, coral reefs offer more resilient protective services than built breakwater infrastructure (TNC, 2018). As degraded reefs absorb less wave energy, opportunity exists to restore reefs and improve resilience for coastal communities (CORAL, 2016).

The comprehensive nature of this research explored many factors in depth. Three primary findings arose from this research:

(1) As communities around the world seek coastal resilience solutions, demand grows to understand and measure the impacts of ecosystem protection and restoration efforts.

(2) Application of the framework revealed a lack of consistent data across case study sites and points to focus areas for future research to investigate:

(a) a closer study of coral reef bathymetry and ecological services at coral reef restoration sites;

(b) the need to measure of coastal damage reduction and restoration costs, consistently across sites;

(c) and clarify consistent coral reef restoration best practices for coastal protection by reef type.

(3) The methodology of the decision support framework offers a general approach, applicable to a broad range of living shorelines and restoration scenarios with socioeconomic benefit.

Though the information matrix analysis of this research highlighted data quality and availability limitations, the framework offers a holistic view of elements needed for coastal resilience decisions. The framework also encourages communities and stakeholders to identify criteria to measure the impacts of ecosystem protection and coral reef restoration. Knowledge and information gaps offer a focus for future research.

This research works to improve the state of coral reefs and coastal resilience, by raising awareness of the framework and expanding public support for natural and nature-based solutions.

In conclusion, this research investigated a highly integrated problem across multiple disciplines with input from many areas of expertise. The success of this research built upon the ability to divide the issue into small steps to adapt and upgrade with additional knowledge, information, and data. The flexibility of the decision support framework enables future research to adjust the methodology for application to a wider range of restoration scenarios for societal benefit.

5.1 Acknowledgements

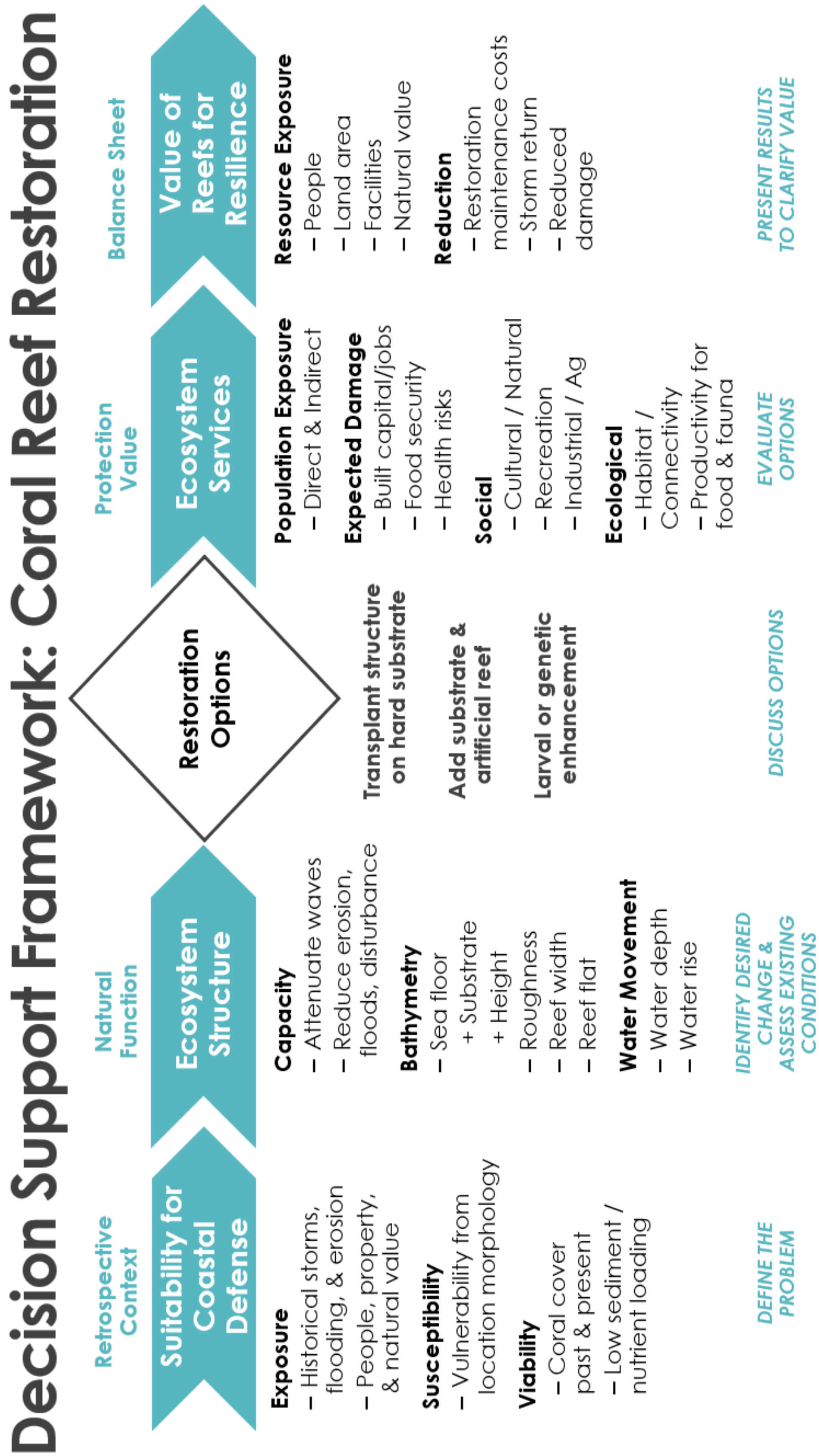
Throughout the research, I consulted with faculty advisors and industry experts by phone, video conference, person interviews, and email. I want to thank Dr. James L. Hench for his patience, constructive feedback, and supportive guidance during this research to narrow the scope, simplify the process, and suggest an information matrix to analyze results. Dr. Shay Viehman graciously offered valuable references to important coral reef restoration research.

I remain grateful to Mr. Stephen E. Roady, J.D. of the Duke Law School, who offered a sounding board to verify organizations and developments in the emerging field of coastal resilience. Dr. John W. Virdin of the Nicholas Institute for Environmental Policy Solutions helped focus this research and refine case study sites to a more regionally representative selection. Colleagues at The Nature Conservancy (TNC) coastal resilience program verified some of the study site data sets, as well as the need for an information matrix.

Thanks to my DEL-MEM cohort members, faculty advisors, and staff, who inspired this work even in the dark of night. Most importantly, I want to thank my family, whose love, patience, and support motivated me while spending long hours behind a desk conducting this research. I remain grateful for everyone mentioned and the silent partners in this research.

6.0 Appendices

6.1 Decision Support Framework (DSF)



6.1.1 Decision Support Framework Notes

Suitability for Coastal Defense	Ecosystem Structure	Restoration Options	Ecosystem Services	Value of Reefs for Resilience
Exposure: Beck, 2014; Ferrario et al., 2014; Muis et al., 2016; Reguero et al., 2018; Reguero et al., 2019b; Spalding et al., 2014; Storlazzi et al., 2019; USACE, 2015; and van Zanten et al., 2014.	**Capacity:** Beck & Lange, 2016; Beck et al., 2018; Constanza et al., 1997; Elliff & Silva, 2017; Ferrario et al., 2014; Reguero et al., 2018; Reguero et al., 2019b; and USACE, 2013.	Bostrom-Einarsson, L. et al, 2020; and Ferrario et al., 2014.	**Population Exposure:** Beck, 2014; Beck et al., 2018; Ferrario et al., 2014; Muis et al., 2016; Pendleton et al., 2016; Reguero et al., 2019b; Storlazzi et al., 2019; Temmerman et al., 2013; Whelchel et al., 2018; and USACE, 2015.	**Resource Exposure:** Beck et al., 2018; Ferrario et al., 2014; Muis et al., 2016; Reguero et al., 2019b; and Storlazzi et al., 2019.
Susceptibility: Beck, 2014; Goodin et al., 2018; Reguero et al., 2018; Reguero et al., 2019b; Spalding et al., 2014; Spurgeon, 2001; Thieler & Hammar-Klose, 1999; and van Zanten et al., 2014.	**Bathymetry:** Beck & Lange, 2016; Beck et al., 2018; BODC, 2020; Cummings et al., 2018; Elliff & Silva, 2017; Ferrario et al., 2014; Goodin et al., 2018; Reguero et al., 2018; Reguero et al., 2019b; Spalding et al., 2014; USACE, 2013; and van Zanten et al., 2014.	**Transplant Structure on Hard Substrate:** Bayarktarov et al., 2016 & 2019; Beck & Lange, 2016; Bostrom-Einarsson et al, 2020; Edwards & Gomez, 2007; Reguero et al., 2018; Rinkevich, 2019; and Spurgeon, 2001.	**Expected Damage:** Arkema et al., 2013; Beck, 2014; Beck et al., 2018; Burke et al., 2011; Constanza et al., 1997; Pendleton et al., 2016; Pascal et al., 2016; Reguero et al., 2018 & 2019b; and Storlazzi et al., 2019.	**Reduction:** Beck & Lange, 2016; Beck et al., 2018; Fabian et al., 2013; Howard et al., 2017; Reguero et al., 2019b; Spurgeon, 2001; Sutton-Grier et al., 2015; USACE, 2013; and van Zanten et al., 2014.
Viability: Cummings et al., 2018; Rehr et al., 2012; Reguero et al., 2018; Spurgeon, 2001; and van Zanten et al., 2014.	**Water Movement:** Beck & Lange, 2016; Beck et al., 2018; Rehr et al., 2012; Reguero et al., 2018; Reguero et al., 2019b; Spalding et al., 2014; Spurgeon, 2001; Thieler & Hammar-Klose, 1999; USACE, 2013; van Zanten et al., 2014; and BODC, 2020.	**Add Substrate & Artificial Reef:** Beck & Lange, 2016; Bostrom-Einarsson et al, 2020; Elliff & Silva, 2017; Fabian et al., 2013; Reguero et al., 2018; and Zepeda-Centeno et al., 2018.	**Social:** Constanza et al., 1997; Goodin et al., 2018; Pascal et al., 2016; Rehr et al., 2012; Spalding et al., 2017; Sutton-Grier et al., 2015; USACE, 2013; USACE, 2015; van Zanten et al., 2014; and Whelchel et al., 2018.	
		Larval or Genetic Enhancement: Bayarktarov et al., 2016; Bostrom-Einarsson et al, 2020; Edwards & Gomez, 2007; Elliff & Silva, 2017; and Zepeda-Centeno et al., 2018.	**Ecological:** Cummings et al., 2018; Edwards, 2010; Goodin et al., 2018; USACE, 2013; and Whelchel et al., 2018.	

6.2 Information Matrix

CASE STUDY SITES		Florida Keys	Hawaii	Indonesia	Philippines	Tanzania	Mesoamerican Reef
Suitability for Coastal Defense	Exposure						
	Susceptibility						
	Viability						
Ecosystem Structure	Capacity						
	Bathymetry						
	Water Movement						
Restoration Options	Transplant structure						
	Add structure	*Limited Restoration Option Descriptions by Case Study Site*					
	Genetic						
Ecosystem Services	Population Exposure						
	Expected Damage						
	Social						
	Ecological						
Value of Reefs for Resilience	Resource Exposure						
	Reduction						

Key	
Data Abundance (High to Low)	
Data Scarcity (Low to High)	

6.2.1 Information Matrix Notes for Case Study Sites

	Case Study Sites: **Florida Keys** - Key West to Big Pine Key, United States - Mapping Ocean Wealth Explorer - TNC, 2019; **Hawaii** - Kailua Kona to Kawaihae, island of Hawaii, United States - Allen Coral Atlas - Vulcan, 2019; **Indonesia** - Lesser Sunda Islands - Spalding et al., 2017; and WRI, 2011; **Philippines** - Mindanao to Panglao - TNC, 2019; and WRI, 2011; **Tanzania** - Dar es Salaam to Zanzibar - TNC, 2019; and **Mesoamerican Reef** - Quintana Roo, Mexico - TNC, 2019.
Suitability for Coastal Defense	**Exposure:** Beck, 2014 (coastal risk exposure; US, ID, PH, TZ, MX); NOAA NCEI, 2019 (storm events, US; 1996-2019);
	Susceptibility: Stanford, 2013 (US coastal hazard index, SLR with & without habitat); and Burke et al., 2011 (ID, PH, TZ).
	Viability: TNC, 2016b (coral & shoreline suitability, FL & HI; depth & sediment, HI); UNEP WCMC, 2018 (coral reefs, US, ID, PH, TZ, MX); Vulcan, 2019 (coral cover, HI); and Goodin et al., 2018 (coral cover, FL).
Ecosystem Structure	**Capacity:** Constanza et al., 1997 (reef services & value, disturbance regulation, food, & recreation, FL, ID, PH, MX).
	Bathymetry: Vulcan, 2019 (geomorphic analysis, HI).
	Water Movement: Stanford, 2013 (US coastal hazards, SLR with and without habitat); TNC, 2016b (SLR, MX & HI); Muis et al., 2016 (extreme SLR & population exposure, FL, HI, ID, PH, TZ, & MX).
Restoration Options	Limited restoration option descriptions by selected case study sites.
Ecosystem Services	**Population Exposure:** Muis et al., 2016 (extreme SLR & population exposure, FL, HI, ID, PH, TZ, & MX); TNC, 2016b (population exposure, FL); Ferrario et al., 2014 (population exposure, FL, ID, PH, & TZ).
	Expected Damage: Constanza et al., 1997 (reef services & value, disturbance regulation, food, & recreation, FL, ID, PH, & MX); Storlazzi et al., 2019 (reef protection of people, buildings, land, facilities, & economic activity, FL & HI); TBD Economics, 2019 (industry & jobs, FL); TNC, 2019 (reef flood protection for people & property, ID, PH, & MX); Burke et al., 2011 (economic, employment, social, & shoreline protection from reefs, FL, HI, ID, PH, TZ, & MX);
	Social: Constanza et al., 1997 (reef services & value, disturbance regulation, food, & recreation, FL, ID, PH, & MX); Spalding et al., 2014 (recreation - reef & reef adjacent tourism, FL, HI, ID, TZ, & MX); TNC, 2019 (social - school & facilities for hazardous material, waste, communications, power, FL) & (recreation - reef & reef adjacent tourism, FL, HI, ID, TZ, & MX); Burke et al., 2011 (economic, employment, social, & shoreline protection from reefs, FL, HI, ID, PH, TZ, & MX);
	Ecological: Limited ecological services for selected case study sites.
Value of Reefs for Resilience	**Resource Exposure:** Arkema et al., 2013 (property value exposure, FL); Muis et al., 2016 (extreme SLR & population exposure, FL, HI, ID, PH, TZ, & MX); Pendleton et al., 2016 (country based population protected by coral reefs, FL, HI, ID, PH, TZ, & MX); TNC, 2019 (people, land area, & built capital, ID & PH).
	Reduction: Ferrario et al., 2014 (reef restoration project costs, FL & ID; breakwater costs, HI); Muis et al., 2016 (extreme SLR, FL, HI, ID, PH, TZ, & MX); and NFWF CREST, 2019 (SLR, storm surge, community threat, & community exposure, FL).

7.0 References

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