A FRAMEWORK FOR INTEGRATING RESILIENCE PRINCIPLES IN CARIBBEAN SMALL ISLAND DEVELOPING STATES

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A Thesis presented to the faculty
of the School of Engineering and Applied Science in Partial Fulfillment of the
requirements for the Degree of
Master of Science in Systems Engineering

University of Virginia
December 2022

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(ABSTRACT)

It is broadly accepted that climate change is associated with infrastructure, economic and societal risk, and vulnerabilities across the globe. Developing island nations are more susceptible to climate change impacts due to the unique location and logistical challenges already faced by these countries, where their geographical isolation drives the need for closed systemic functions. Actions to mitigate climate change require practical, holistic, strategic solutions to enhance the resilience of island nations. Decision-analysis tools are also available for decision-makers to better understand trade-offs within their nation's economic, social, and environmental sectors that will assist with the effective utilization of available economic opportunities and impacts due to climate change. This Thesis describes a framework of resilience principles for Caribbean Small Island Developing States (SIDS) that enhances infrastructure and societal resilience to climate shifts. It presents the application of comprehensive analysis techniques to demonstrate how decision-makers can identify areas of conflict, compare approach options, review stakeholder perspectives, and understand decision impacts and systemic trade-offs, including a detailed discussion of a multi-domain, climate-related issue of Illegal, Unreported, and Unregulated (IUU) fishing. The results of the in-depth analysis confirm the need for policies, project prioritization, and asset management within complex, interconnected systems. Subsequently, the holistic framework and decision-making tools can be adapted for other climate-affected regions with characteristics similar to those of Caribbean SIDS.

Acknowledgments

I would like to thank Professor James Lambert for providing the opportunity to work on a variety of projects during the course of this degree completion. Without his guidance and expertise, the development of this thesis would not be possible. I would like to thank Professor Venkataraman Lakshmi for his guidance in developing research processes and encouraging me to pursue a variety of interests outside of academics. I would also like to thank Professor Robert Riggs, Professor Gianluca Pescaroli, Professor Jose Palma-Oliveira, Professor Miriam Merad, Dr. Igor Linkov, and Dr. Benjamin Trump for their invaluable guidance. Their instruction, insights, collaboration, and lively discussions sparked the conception of system perspectives and interconnection that directed this thesis research. I am grateful to many organizations and individuals for their financial and intellectual support, notably the U. S. Coast Guard Advanced Education Program, the Commonwealth Center for Advanced Logistics Systems, the Army Corps of Engineers, the Society for Risk Analysis, and Mr. Tom Polmateer.

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Chapter 1

Introduction

1.1 Overview

This section describes the motivation for this research, the need to develop a framework of resilience concepts that can be incorporated into the general practice of islands highly impacted by climate change. It describes the purpose, scope and organization for the thesis presentation.

1.1.1 Motivation

Developing island nations, especially those in the Caribbean, are likely to see even greater impacts to the sustainability, economics, and society due to climate change (Bonato et al., 2022; Thomas, Schleussner, and Kumar, 2018). In 2017, hurricanes Irma and Maria devastated the island of Puerto Rico. The physical damage of these storms was compounded by an economic downturn and unreliable infrastructure (Cox et al., 2019). Five years later, global temperatures are predicted to rise another 2° C, increasing sea water levels and affecting normal salinity measurements, and more frequent and intense storms are forecasted. As the climate continues to shift, Caribbean islands must develop effective plans for sustained economic growth and resilience (Mycoo, 2018). Their preparation for continual climate shocks is vital for sustainable, long-term adaptations to various climate-related events anticipated to overwhelm these vulnerable habitats. Despite this, adaptations to climate change require strategic prioritization to identify and implement effective solutions (Bonato et al., 2022; B.D. Trump, Florin, and Linkov, 2018; Ostrom, 2007). To meet these strategic goals, resilience must be considered as part of the system design for infrastructure, economy, and society at large.

As policy initiatives and strategic outcomes are developed, SIDS must consider resilience from climate shifts. The United Nation's Sustainable Development Goals (SDGs) originally promulgated in 2015 state:

> Climate change is one of the greatest challenges of our time and its adverse impacts undermine the ability of all countries to achieve sustainable development. Increases in global temperature, sea level rise, ocean acidification and other climate change impacts are seriously affecting coastal areas and low-lying coastal countries, including many least developed countries and small island developing States (p. 5).

The Union of Concerned Scientists also outlined a framework of 15 principles for decision-makers to consider when determining future courses of action for bridging the climate resilience gap, *i.e.*, "the scope and extent of climate change-driven conditions for which people remain unprepared" (Concerned Scientists, 2016). A principle specifically outlined in the resilience framework is the need for systems approaches to making changes in an interconnected world to understand how seemingly unrelated policies or governance practices can influence the outcomes or processes of related systems and their functions (Concerned Scientists, 2016). Another author specifically describes the needs of Caribbean Small Island Developing States (SIDS) to make preparations to withstand climate change impacts beyond that of the least-impact predictions, including the need to develop adaptation strategies that address social, environmental, and economic capacities (Mycoo, 2018; Biondi and Guannel, 2018). To meet these needs, decision-makers require up-to-date, effective analysis tools that incorporate a variety of reliable sources, perspectives, and outcomes to take appropriate actions in preparing for, and adapting to the impacts of climate change.

SIDS are categorized by the United Nations as islands "that face unique social, economic, and environmental vulnerabilities" due to their geographic locations and high dependence on external trade (Nations, 2022). SIDS are more susceptible to negative climate change impacts because their economic resources are highly dependent on ecosystems due to the limited variety of resources available internally to an island (Nations, 2022). Thus, large fluctuations in predominant industries, like fisheries and tourism, have a significant impact on the function and prosperity of SIDS (Nations, 2022). Incorporating resilience principles across the societal system of SIDS can enhance the capabilities of these vulnerable regions to manage climate change risks.

The totality of this approach, integrating resilience concepts in the design of economic and cultural operating strategies, could be considered the science of resilience. This science would be the application of a systemic approach used to understand the impacts of climate change effects and long-term adaptations in decision-making across policy development, infrastructure design, emergency management planning, project prioritization, and societal attitudes (D. Wu, Olson, and J. H. Lambert, 2022; Bostick et al., 2018). Using this approach, resilience is integrated into all levels of society, thus enhancing a culture of preparedness and resilience.

1.1.2 Purpose and Scope

This thesis describes a framework of resilience principles to be incorporated into various domains of society. The principles herein aim to enhance disaster preparedness, build resilience, and encourage the inclusion of systemic perspectives in decision-making specifically related to Caribbean Small Island Developing States (SIDS). To accomplish this task, supporting information is provided to clarify definitions, introduce societal perspectives necessary for understanding resilience, and outline the challenges typically associated with climate change impacts. The framework is developed as a dynamic methodology for assessing resilience within a modern societal system, derived from the work by Rebar *et al.* (Rebar et al., 2022). It describes a cyclical process for understanding system perspectives, measuring resilience, integrating non-technological and technology-driven resources, providing decision support tools, and testing system processes. Additionally, this review details two analysis tools which are highly applicable for SIDS use.

1.1.3 Organization

Chapter 2 provides background support and a summary of literature review for risk mitigation, resilience applications, climate change, and decision-analysis techniques. Chapter 3 details the steps of the framework for developing resilience as a societal practice. Chapter 4 demonstrates the practicality and viability of a holistic assessment for multi-disciplinary decision-making. The results of a scenario analysis from two perspectives are provided in detail. Chapter 5 discusses the implications of the decision model outputs and reinforces the holistic framework strategy. Chapter 6 summarizes the key arguments and solutions presented in this thesis and presents future directions for this work.

Chapter 2

Background

2.1 Overview

This Chapter reviews literature that supports the basis for this thesis. It provides a discussion of current definitions, theories, and applications that are foundations for establishing the status of current research regarding systemic resilience in areas highly impacted by climate change. This chapter includes a discussion of gaps in current work and describes new application areas for the approaches described.

2.2 Review of Literature

Support for this research is derived from application domains outlined in the subsections below.

2.2.1 Definitions

Understanding the relationship of risk and resilience is vital to adeptly relating the concepts with applicable principles. Risk is most commonly described as the "probability of an event occurring and the severity of the event impact" (Haimes, 2009). The lesser described attributes of risk are the valuation of the event at a specific time, with the current implications of the environment, and within the contexts through which the event is viewed, *i.e.*, the system (Haimes, 2009). This further understanding of risk implies that the valuation of risk is constantly shifting, and is relevant to the time and system state at impact (Aven, 2011; Connelly et al., 2017). Modelling risk is challenging as it includes some degree of uncertainty, which is not a directly measurable variable until the event occurs. This uncertainty and the vulnerability associated with a system prone to risk requires mitigation factors to be included as a method of reducing these two variables. Thus, inherently relating risk and resilience (Berkes, 2007).

Numerous sources outline various definitions of resilience. A widely accepted definition in terms of disaster resilience, provided by the National Academy of Sciences is “the ability to plan and prepare for, absorb, recover from, and adapt to adverse events” (Linkov and Palma-Oliveira, 2017). Another description of resilience is the ability of a system to transform and yet another definition is “the speed of recovery” (Logan et al., 2022). Therefore, to be considered resilient, an entity must identify potential risks, or reduce vulnerabilities, in terms of duration, disruptiveness, or both. Resilience and risk analyses are related to climate change often focus on assets or infrastructure, commodities, or policies (Linkov, B. Trump, et al., 2022; Argyroudis et al., 2022; Huiskamp, Brinke, and Kramer, 2022; J. Lambert, C. Karvetski, and Linkov, 2011). With the increasing complexity and interconnections of technology as a risk mitigation strategy, resilience perspectives must shift to include understanding of how decisions with regard to one risk mitigation domain influence the spectrum of society (J. Lambert, Troccoli, et al., 2011). This drives the need to develop resilience strategies in vulnerable systems facing climate change impacts like Small Island Developing States.

2.2.2 Approaches

The framework introduced in this thesis applies a variety of well-established concepts from applicable literature. The novelty of this new framework is the assembly of the various systems theories, perspectives, and tools applied across a complex system rather than within one area of concern. This approach ensures that a holistic assessment of impacts can be known.

In the understanding of this approach, several background sources must be identified. A key resource describing the nature of a dynamic system is described in the diagram of a modern socio-ecological system (SES) in Figure 2.1 (Ostrom, 2007). This figure adeptly identifies the interplay of various domains within a societal level system and their methods of interaction. Understanding this conceptual relationship allows for the integration of resilience within various sectors of the system. For example, re-

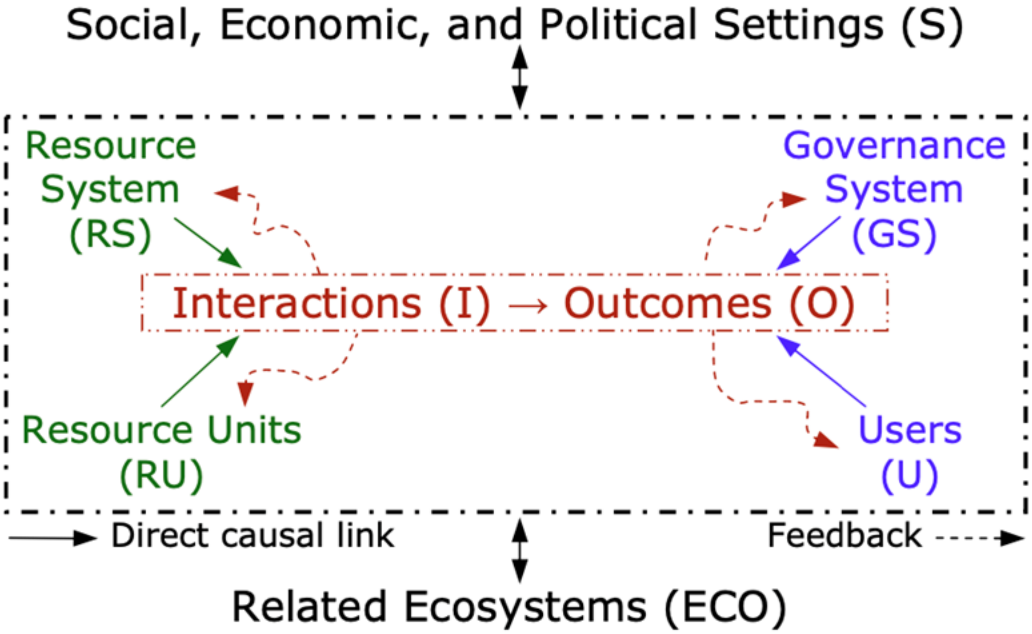


Figure 2.1: A Socio-Ecological System (SES) description proposed by (Ostrom, 2007).

silience in Resource Units could be infrastructure or economic growth. The diagram describes how enhancing resilience in one area provides positive reinforcement and, alternatively, where a lack of resilience can create a negative feedback loop. These interactions are all interrelated within each other and are affected by, and affect, social, economic, political, and environmental domains. Another concept highly applicable to the understanding of system relationships is *panarchy*. Panarchy is a theoretical method of understanding the dynamics of human-nature relationships, noting that they are influenced by scales of space and time (Gunderson, Allen, and Garmestani, 2022). Recent literature describes the dynamics within ecosystems subject to change and how the time and scale of a system, the entire structure undergoes a regime shift; where the system is inherently different than the one that previously existed (Allen et al., 2014). This theory is applicable to the concept of resilience as the aim of a human-driven system is typically to assume its previous structure, but panarchy provides a new perspective for realizing system dynamics with regard to a natural propensity to adapt (Cooper, Willcock, and Dearing, 2020; Pescaroli and Alexander, 2016a). This is especially important given the rate of climate change noted in recent literature.

2.2.3 Multi-Criteria Decision Analysis

Multi-Criteria Decision Analysis (MCDA) technique application is a key focus of this thesis. MCDA techniques are often utilized in the development of risk mitigation strategies. Several resources describe how modern risk governance must be approached using multiple perspectives, input values, and comparative tools to support effective decision-making across a system enterprise (Quenum et al., 2019; Linkov, B.D. Trump, et al., 2018; Linkov, Bridges, et al., 2014). MCDA models are analysed in assessments as viable methods to address decision-making applications regarding environmental processes (G. A. Kiker et al., 2005; I. B. Huang, J. Keisler, and Linkov, 2011; C. Karvetski, J. Lambert, J.M. Keisler, and Linkov, 2011). Quantitative risk methods, such as a Likert scale-based model, have been applied to assess gaps in resilience preparedness, operational capacity, and risk mitigation that can provide policy-makers with a benchmark of their organizational readiness (Pescaroli, Velazquez, et al., 2020; You, J. Lambert, et al., 2014). Critical infrastructure assessment tools aim to classify technical, organizational, economic, and social resilience by networking the various interactions and correlations between the sectors as a method of understanding the systemic impacts of an initiative in a lower- or higher-level system domain (Theocharidou, Galbusera, and Giannopoulos, 2018; Bostick et al., 2018). Various tools are also implemented to measure disaster severity in the immediate aftermath of an event as a decision-support tool for responders to effectively allocate resources (discussed in Section 3.2.2) (Yew et al., 2019). MCDA techniques are often applied specifically to managing risks related to climate change (Hamilton, J. Lambert, and Valverde, 2015; You, Connelly, et al., 2015; J. Lambert, Y. Wu, et al., 2013; C. Karvetski, J. Lambert, J.M. Keisler, Sexauer, et al., 2011). The application of MCDA techniques to analyze and provide decision support for managing risk is a key component of the framework for integrating resilience in a societal system as described in this thesis.

Chapter 3

Technical Approach

3.1 Overview

This Chapter presents the technical framework for the application of resilience principles in developing island states.

3.2 Holistic Framework to Assess Resilience

The compilation of the concepts presented in Chapter 3 is a systematic method for assessing resilience across a socio-ecological system. Figure 3.1 describes the relationship of these principles.

Each step in the assessment process described in Figure 3.1 will be described in detail in the subsections below. The key understanding from this process is that due to the dynamic nature of systems, resilience is a process which must be approached from a holistic perspective in modern systems. Thus, the framework for measuring resilience is cyclical so the results of system testing remain relevant for appropriate response to system shocks. This is especially important for systems highly susceptible to climate change, which drives the application of the framework to Small Island Developing States.

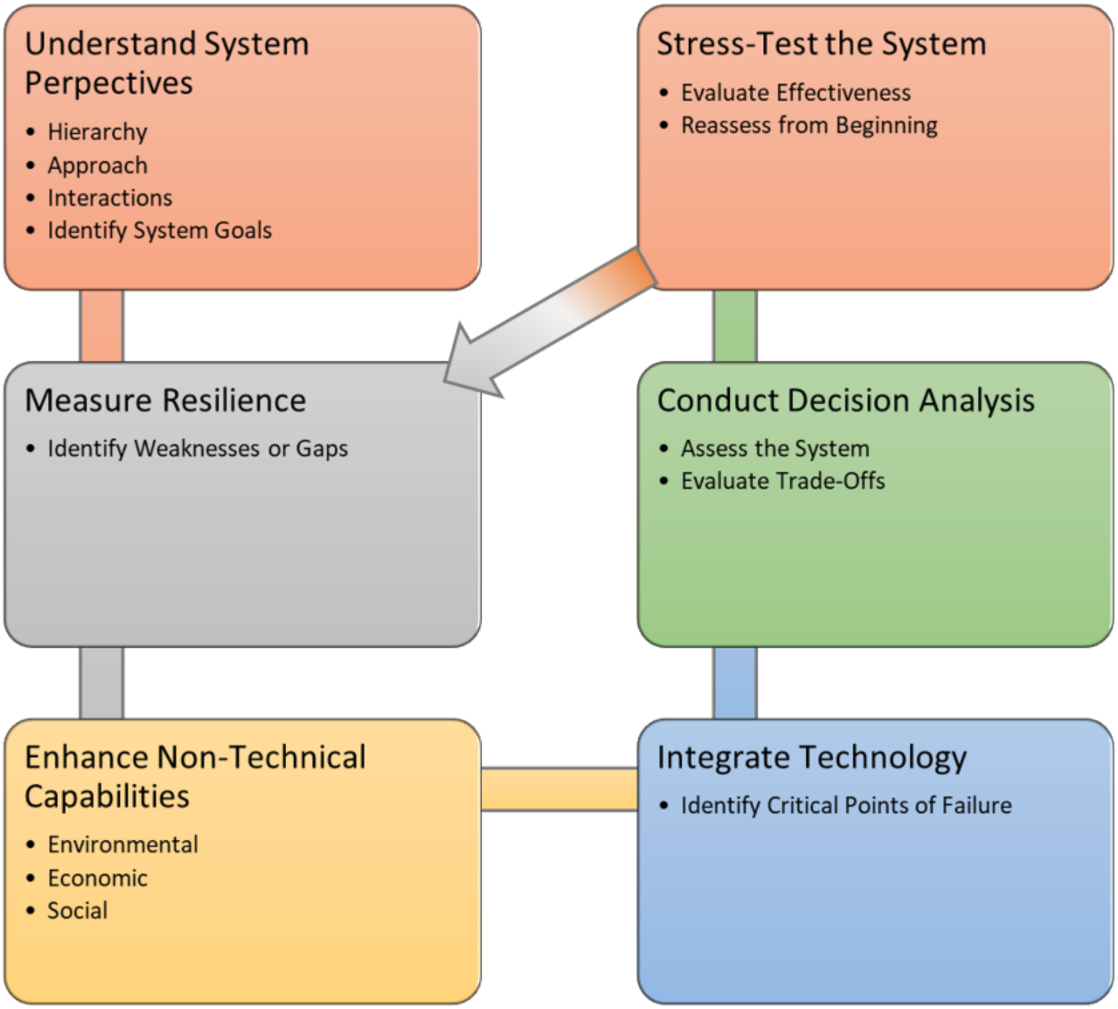


Figure 3.1: Resilience Principles Application Framework

3.2.1 Resilience Perspectives for SIDS

The first step in the Framework for Integrating Resilience into SIDS is to understand the nature of the island from a system perspective. This can be accomplished by reviewing applicable systems theories, including understanding the structure and relationships of a SES and the panarchy model as described in 2.2.2.

The SES model of system, described in 2.1 introduces the concept of phases that can shift the vulnerability of a system. For example, a shock to the ecosystem such as a hurricane or bleaching of coral reefs affects the availability of resources which could result in an economic disruption outcome. The system capability to respond to the incoming stressor, its potential to absorb the impact and retain balance or to undergo a regime shift and change entirely, is inherently related to its structure (Allen et al., 2014). System-wide dynamics are complicated in that these disruptive events occur at various levels, timeframes, and differ in impact severity within or across the system (Palma-Oliviera et al., 2018). In the case of Caribbean SIDS, islands are faced with climate events that each must recover from, through adaptation of the system to a new dynamic or re-absorption of the impact into the existing structure. Thus, applying an adaptive framework to developing island states uncovers systemic interactions key to developing resilience.

The dynamics of various system entities, interactions between levels of system components, causes, cascading effects, and hierarchies of prioritization all affect system stability. For example, sea level rise mainly affects the coastline of an island, with a seemingly small overall impact. But coastal degradation shifts land use near coastlines, plausibly causing infrastructure damage, and increasing the likelihood of more severe weather effects in the area. The combination of these concerns thus alters economic and socio-economic decision-making for affected coastal areas. Island nations that heavily rely on the tourism industry for economic growth should consider shoreline erosion as a critical concern as it will impact shoreside structures such as oceanfront resort destinations, abating economic revenue. Considering sea level rise as an additional climate impact on shoreline degradation, the importance of accounting for both short-term and long-term resilience strategies becomes more crucial. Resource allocation and policy development must scrutinize all climate-related risks and balance immediate emergency response capabilities with longer-term climate adaptation needs.

It can be assumed that each island state is a socio-ecological system (SES) (Ostrom, 2007). The functions of each SES relate to another same-level SES (for example other islands and/or a mainland region with similar socio-economic dynamics) that provides different flows of people and goods to the island, ultimately changing the SES of the island. The SES of each level is also connected with one or more higher-level SES that can make a long-lasting impact on an individual island state. An example of this interaction can be described by the first tourist-colonial occupation of Barbados settled on the east coast of the island because of the specific psychological drives of the initial demand. When those psychological drives changed the demand, the tourism-driven economy shifted to the west coast, which imparted a different array of implications for the SES of an island nation. The shift modified the way the island state responded to the natural hazards, making resilience more costly and difficult.

Also, within an island state SES exists multiple low levels of SES that have different echelons of resources and users and employ different types of governance and regulations. An example of this is that even small islands are distinguished by zones that differ in the characteristics of the coast and human occupation and the regulatory requirements required to manage each (Barbados, 2020). A conclusion derived from comprehending these interconnected SES dynamics is that almost all SES have a set of factors that are permanent and can be described fully at any particular time point. When the permanent state is understood, an almost complete description of the particular SES dynamics becomes apparent. From this SES interplay, it is concluded that resilience, as an emergent property of the system, can be evaluated when the system is confronted with a stressful event. The resulting outcome for the system varies due to the relationship among these variables. Similar systems finding balance after a disruptive event can vary in time to recover, cost to rebuild, or system functions. The variability in this recovery for both systems is a measure of system resilience. In the case of an urbanized area experiencing a disaster compared to the disaster occurring in a natural ecosystem often requires external aid and resources to recover. Thus an external component of the SES exists as a variable and it introduces the concept of a hierarchical structure of dependence for SIDS.

In this systemic view of resilience, the interplay between low level and higher-level SES must be seen from a new perspective. Normally standard societal functions and their relationship with ecological systems are viewed as a hierarchical system. Control in a system is viewed as exerted by the larger entity in a top-down manner (Allen et al., 2014). Though, in the case of SIDS this perception must be viewed in the opposite direction: that the control can be exerted by the small-scale, bottom-up processes. In essence, SIDS systemic resilience impacts are often lower-level system impacts, or singular events, like a pandemic diminishing economic revenue form tourism, disrupting the entire societal system. Applying the concept of panarchy to this power dynamic can elucidate the practical and theoretical consequences of this view.

A panarchy is a nested set of socio-ecological systems in their different evolution points (considered as adaptative cycles) that are operating at different scales (Allen et al., 2014). Sometimes it is a larger-scale system that imposes the reorganization of an SES, such as the need for external support to rebuild damaged infrastructure after a hurricane. For other SES, the modification of a small component within the system, such as the destruction of coral reef barriers decreasing desirability of an island as a travel destination, denotes a regime shift in the structure or function of the system due to economic loss, thus modifying the larger, higher-level SES (Arkema et al., 2013). This is especially impactful in the SES of an island nation and important to note as the timescale for the bottom-up implications on system dynamics are occurring at a rapid pace due to climate shifts.

The implementation of the previously described set of principles is necessary to promote long-term resilience of island nations. SES resilience in general must be viewed from a systems perspective where the critical function of an SES defines its limitations (Linkov, Bridges, et al., 2014). For an island state, this is simplified when the natural SES is assumed to be the island. Thus, the definition of the island's SES hierarchy structure is straightforward and the connection with larger SES is easily identifiable. Using this framework and the identification of the system variables described above, the needs and drives of an island state can more easily be addressed.

Management processes and policies are critical to properly balancing the system. Regulatory bodies must consider response management concepts for both emergencies and long-term projects in terms of funding, resource allocation, and response procedures for the global SES and subs-systems (Linkov and Palma-Oliveira, 2017; Linkov, B.D. Trump, et al., 2018). The system cannot return to an equilibrium that effectively prepares for long-term resilience, the goal, if it cannot respond efficiently to a short-term system shock (Pescaroli, Velazquez, et al., 2020). This can be seen in many variables but is more important in the social and economic sectors.

Building resilience is also not a responsibility solely held by government officials or industrial specialists. Citizens must also build internal resilience and adaptability to withstand regular shocks and the shifting of their livelihoods, especially due to the impacts of climate change. Trust in the decisions made by officials and industry must be established with the local community to avoid a "tragedy of the anticommons" as described by (Palma-Oliviera et al., 2018). To avoid the anticommons tragedy requires that decisions are made in effort to not overly burden one population, constituent, component, etc. of a system despite having a goal that benefits the entirety of the construct (Palma-Oliviera et al., 2018). In terms of climate change resilience, this means that decisions made to build resilient infrastructure, adaptive programs, and economic fortitude should not come at the expense of social and cultural degradation. Considerations for the community, using community-driven and led processes, are critical to successfully establishing a resilient nation through design.

Finally, hierarchical but flexible structures must be developed so that the system can find equilibrium even in dire circumstances, i.e. it should not be so highly regulated or "top-heavy" that actions cannot be taken without a single linchpin or failure halting future progress. Power and influence should be evenly distributed within and across the SES, allowing for multiple sectors to elevate or level others depending on the inputs and events affecting the entirety of the system. Ensuring a hierarchical balance across the variables mitigates the potential for the issues with the anticommons as previously described since it provides a calibrated approach across all sectors affecting the system's continuity.

The subsequent discussions relate to variables within the hierarchal structure of SES that, if enhanced, inherently build resilience at critical junctions. These methods focus on the application of management principles that prepare for system-impact events and their interactions with social, environmental and organizational components. The type of interconnectedness among these system variables defines the system output and its ability to retain operability, and thus be resilient.

3.2.2 Metrics for Measuring Resilience

A key to understanding SES-affected variables is the ability to measure impacts on the system. Doing so requires a dynamic set of metrics that are scalable, broadly applicable, and can provide both an instantaneous value and a predictive or potential value. Specific to SIDS, metrics used to evaluate disaster risk, impact, and resilience are critical to receiving adequate resources for long-term success and achieving balance in the previously described system. In this section, current climate-related metrics for disaster valuation are discussed as they relate to the unique challenges that island nations face.

The scale of impact of climate change-related disasters in island nations is far greater than in larger regions, typically with more varied economic portfolios. In 2020, Hurricane Dorian, a category 5 hurricane, caused 3.4 billion dollars of damage in the Bahamas in less than 48 hours ((IDB), 2020). Another storm of category 5 intensity, Hurricane Michael, hit the Florida panhandle in 2018, causing 25 billion dollars of damage as it swept across the Southeastern United States (Beven II, Berg, and Hagen, 2019). Despite being categorized within the same impact scale, the damage to the U.S. coastline costs more than 6 times that of the Bahamas. Yet the damage in the Bahamas equated to a 25% annual GDP loss while the impact on the United States' annual GDP was less than 1% ((IDB), 2020). The only relatable example of a single event causing this shocking of GDP decline in the U.S. was the second quarter of 2020 when the COVID-19 pandemic cost 32.9% of the annual GDP over the course of three months (Horsley, 2020). As seen in this example, the commonly used metrics of GDP and current dollar value to measure disaster impacts is not adequate to understand and relate the totality of climate-related events and more broad, dynamic, and system component-related measures must be identified.

An accurate evaluation of these climate-related impacts is necessary to ensure proper resource distribution and preparation for climate change events from a global perspective. Appropriate comparisons of impacts across nations must be evenly measured to determine the status of a system's balance across the resilience spectrum. The right metrics also determine the long-term impacts of short-term shocks impact over time. With the scope and complexity of GDP as an appropriate holistic measure for disaster impacts, other broadly applicable metrics must instead be identified. Yew et al. describe 17 vulnerability metrics for determining disaster severity to develop a scoring table that compares disaster impacts across various indicators using the Disaster Severity Index (DSI) (Yew et al., 2019). Various aspects of disaster response are selected for the recoverability to be determined shortly after a system shock occurs. The detailed metrics identified by Yew *et al.* in Figure 3.2 provide a holistic review of the total impact to an area (Yew et al., 2019). In comparison to the GDP metric, the DSI provides a more detailed, area-specific disaster comparison that allows for scalability.

The DSI identifies categories of the most important vulnerabilities to address in a system immediately following an event to ensure quick response and ideally recovery. However, the current metrics do not identify the long-term impacts of the disaster nor are they designed for pre-disaster resilience assessments. But, expanding some of the

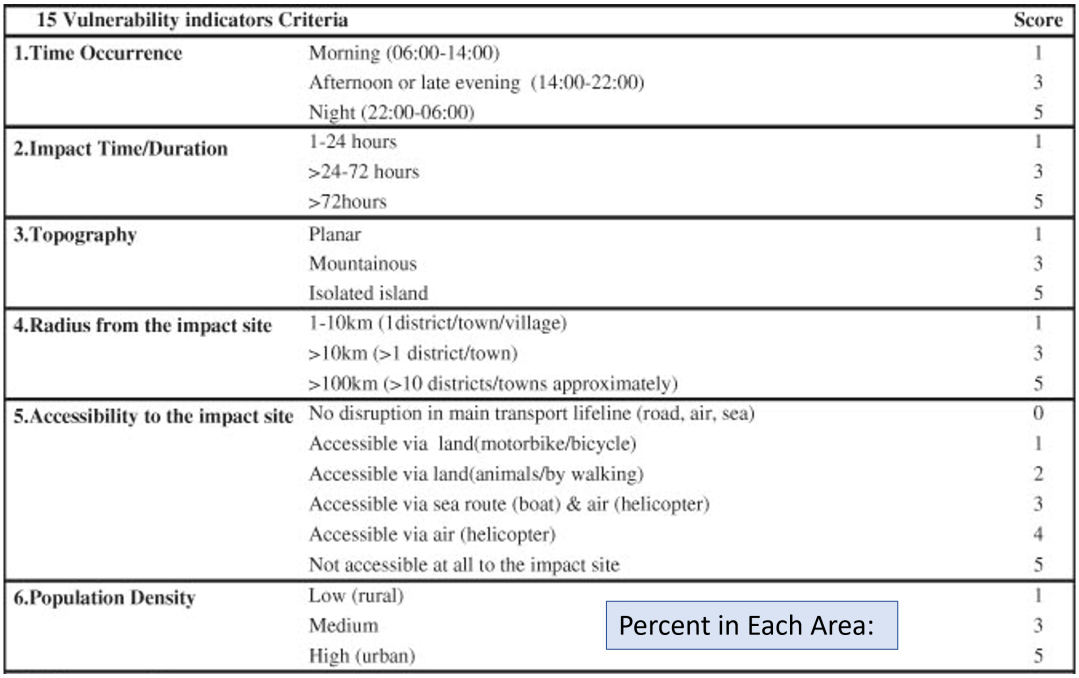
15 Vulnerability indicators Criteria		**Score**
1.Time Occurrence	Morning (06:00-14:00)	1
	Afternoon or late evening (14:00-22:00)	3
	Night (22:00-06:00)	5
2.Impact Time/Duration	1-24 hours	1
	>24-72 hours	3
	>72hours	5
3.Topography	Planar	1
	Mountainous	3
	Isolated island	5
4.Radius from the impact site	1-10km (1district/town/village)	1
	>10km (>1 district/town)	3
	>100km (>10 districts/towns approximately)	5
5.Accessibility to the impact site	No disruption in main transport lifeline (road, air, sea)	0
	Accessible via land(motorbike/bicycle)	1
	Accessible via land(animals/by walking)	2
	Accessible via sea route (boat) & air (helicopter)	3
	Accessible via air (helicopter)	4
	Not accessible at all to the impact site	5
6.Population Density	Low (rural)	1
	Medium	3
	High (urban)	5
7.Main source of economy at impact site	not affected	1
	temporary affected	3
	long term affected	5
8.Public infrastructure	Public infrastructure not affected (no changes before/after disaster)	1
	Public infrastructure <25% affected but still functioning	2
	Public infrastructure <50% affected but still functioning	3
	Public infrastructure >50% affected, need assistance	4
	Public infrastructure totally affected , total assistance needed	5
9.Communication	Communication not affected (no changes before/after disaster)	1
	Communication partially affected, only able to communicate via radio satellite phone	3
	Total disruption of communication network	5
10.Type of country economic	high income country	1
	middle income country	3
	low income country	5
11.Governance *in the case of countries ranking not available, global territories average ranking will be selected. 0= highly corrupt 100=very clean <50=serious corruption problem	**Corruption Perception Index 2015 Ranking (168 countries),to be adapted as per latest ranking**	
	0-20	5
	>20-40	4
	>40-60	3
	>60-80	2
	>80-100	1
	Basic Survival Resources:Water and Sanitation, Food Security, Shelter	
12.Water	No disruption in water infrastructure	0
	Disruption in water infrastructure	1
	Available of water source	2
and	Access to clean water via purification tablets/ceramic filter	3
	Access to clean water via drilling bore hole well	4
	Non-potable water/Not available water source and increased in diarrhea,skin & water related diseases	5
Sanitation Hygiene *Water & Sanitation scoring= (total water +sanitation hygiene scoring) /2 to get the average	No disruption in sanitation infrastructure	0
	Disruption in sanitation infrastructure	1
	Available of mobile/ portable latrines ratio 1:<20	2
	Available of mobile/ portable latrines ratio 1:20	3
	Available of some sort of damaged sanitation	4
	Open defecation & increased in diarrhoea & communicable diseases	5
13.Food Security	Food available & accessible (No changes before /after the disaster)	1
	Food available but needs transport from outside the impact site	2
	Food available but not accessible due to logistical & security issues	3
	Food stocks severely depleted (food scarcity)	4
	Food not available in or to the impact site.	5
14.Shelter	Shelter intact	1
	Shelter <25% destroyed	2
	<50% of the total shelter destroyed	3
	>50% of the total shelter destroyed	4
	All shelter totally destroyed	5
15.Healthcare Capacity	able to cope - all health facilities intact & functioning as normal situation	1
	- <25% of the total health facilities destroyed	2
	- <50% of the total health facilities destroyed	3
	unable to cope - >50% of the total health facilities destroyed	4
	- All health facilities totally destroyed	5
	Total 15 vulnerability indicators score	
2 Exposure indicators	**Criteria**	**Score**
16.Number of Deaths *at least 10 or more= 0 therefore less than 10 = 0 score	10-100	0
	>100-1000	1
	>1000-10 000	2
	>10 000-100 000	3
	>100 000-1 000 000	4
	>1 000 000	5
17.Number of Affected Persons *at least 100 or more= 0 therefore <100=0	100-1000	0
	>1000- 10 000	1
	>10 000- 100 000	2
	>100 000- 1 000 000	3
	>1 000 000- 10 000 000	4
	>100 000 000	5
	Total 2 exposure indicators score	

Figure 3.2: 15 Vulnerability Indicators Criteria (Yew et al., 2019).

identified DSI metrics can expose gaps in preparedness to reinforce local, regional, or national level responses. Application of the expanded metrics pre, or post-event, could be utilized as a semi-quantifiable resilience assessment tool that identifies system risks to be addressed.

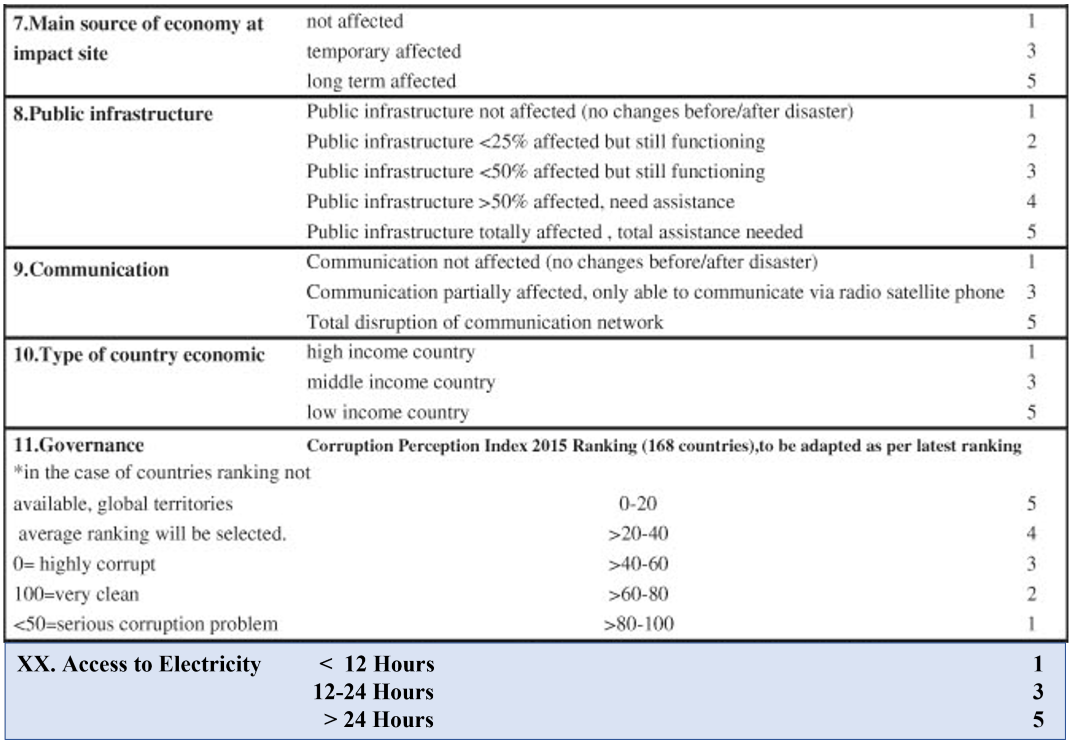
Adjustments to the currently cited DSI would provide more value to examine post-event impacts. One of the ways to adjust this table to better quantify the resilience of island nations is to reevaluate is category *7. Main source of economy impact site*. In the case of SIDS, many nations will have high concentrations of economic importance in one location. There is also high potential that damage could disrupt the entire island. The current metric, as written doesn't take into account these factors. Additionally category *4. Radius from the impact site* should include an option for total devastation or destruction, as could be the case in Caribbean islands due to hurricane or tropical storms (for example the impact of Hurricane Dorian on several islands in the Bahamas). In the population-related categories, a total population count should be added to understand the percent of population affected when determining social impacts in categories *6. Population Density*, *16. Number of Deaths*, and *17. Number of Affected Persons*. A key factor that is not currently considered is the availability of electricity. In modern society, it is a key component of communications, healthcare, and supply chain continuity. This is especially important post-event but can also be a cause for concern in regular business continuity. Updates to the current DSI are adapted in Figures 3.3, 3.4, 3.5, and 3.6.

An additional section could be added to the table to understand the resilience of an island at any time. Another consideration should be in place for noting if the event is part of a compound casualty, for instance, a major hurricane makes landfall during a pandemic, as this can significantly affect the capability to recover in an already



15 Vulnerability indicators Criteria		Score
1.Time Occurrence	Morning (06:00-14:00)	1
	Afternoon or late evening (14:00-22:00)	3
	Night (22:00-06:00)	5
2.Impact Time/Duration	1-24 hours	1
	>24-72 hours	3
	>72hours	5
3.Topography	Planar	1
	Mountainous	3
	Isolated island	5
4.Radius from the impact site	1-10km (1district/town/village)	1
	>10km (>1 district/town)	3
	>100km (>10 districts/towns approximately)	5
5.Accessibility to the impact site	No disruption in main transport lifeline (road, air, sea)	0
	Accessible via land(motorbike/bicycle)	1
	Accessible via land(animals/by walking)	2
	Accessible via sea route (boat) & air (helicopter)	3
	Accessible via air (helicopter)	4
	Not accessible at all to the impact site	5
6.Population Density	Low (rural)	1
	Medium Percent in Each Area:	3
	High (urban)	5

Figure 3.3: Indicators 1-6 of the DSI, adapted from (Yew et al., 2019)

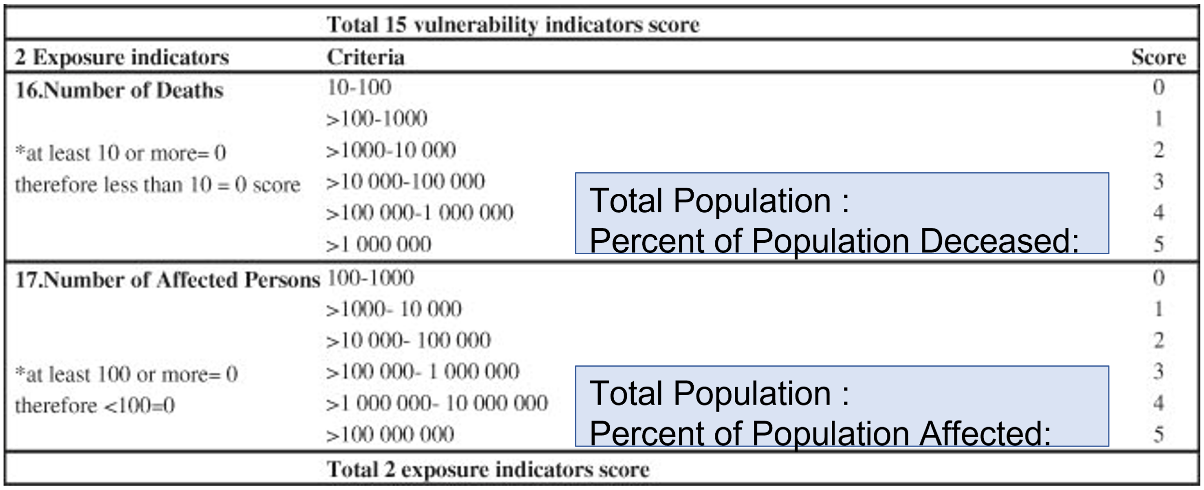


7.Main source of economy at impact site	not affected	1
	temporary affected	3
	long term affected	5
8.Public infrastructure	Public infrastructure not affected (no changes before/after disaster)	1
	Public infrastructure <25% affected but still functioning	2
	Public infrastructure <50% affected but still functioning	3
	Public infrastructure >50% affected, need assistance	4
	Public infrastructure totally affected , total assistance needed	5
9.Communication	Communication not affected (no changes before/after disaster)	1
	Communication partially affected, only able to communicate via radio satellite phone	3
	Total disruption of communication network	5
10.Type of country economic	high income country	1
	middle income country	3
	low income country	5
11.Governance	**Corruption Perception Index 2015 Ranking (168 countries),to be adapted as per latest ranking**	
*in the case of countries ranking not available, global territories average ranking will be selected.	0-20	5
0= highly corrupt	>20-40	4
100=very clean	>40-60	3
<50=serious corruption problem	>60-80	2
	>80-100	1
XX. Access to Electricity	**< 12 Hours**	**1**
	12-24 Hours	**3**
	> 24 Hours	**5**

Figure 3.4: Indicators 7-11 of the DSI, adapted from (Yew et al., 2019) with additional indicator for Electricity Access

	Basic Survival Resources:Water and Sanitation, Food Security, Shelter	
12.Water	No disruption in water infrastructure	0
	Disruption in water infrastructure	1
	Available of water source	2
and	Access to clean water via purification tablets/ceramic filter	3
	Access to clean water via drilling bore hole well	4
	Non-potable water/Not available water source and increased in diarrhea,skin & water related diseases	5
Sanitation Hygiene	No disruption in sanitation infrastructure	0
*Water & Sanitation scoring= (total water +sanitation hygiene scoring)	Disruption in sanitation infrastructure	1
	Available of mobile/ portable latrines ratio 1:<20	2
/2 to get the average	Available of mobile/ portable latrines ratio 1:20	3
	Available of some sort of damaged sanitation	4
	Open defecation & increased in diarrhoea & communicable diseases	5
13.Food Security	Food available & accessible (No changes before /after the disaster)	1
	Food available but needs transport from outside the impact site	2
	Food available but not accessible due to logistical & security issues	3
	Food stocks severely depleted (food scarcity)	4
	Food not available in or to the impact site.	5
14.Shelter	Shelter intact	1
	Shelter <25% destroyed	2
	<50% of the total shelter destroyed	3
	>50% of the total shelter destroyed	4
	All shelter totally destroyed	5
15.Healthcare Capacity	able to cope - all health facilities intact & functioning as normal situation	1
	- <25% of the total health facilities destroyed	2
	- <50% of the total health facilities destroyed	3
	unable to cope - >50% of the total health facilities destroyed	4
	- All health facilities totally destroyed	5
	Total 15 vulnerability indicators score	

Figure 3.5: Indicators 12-15 the DSI, adapted from (Yew et al., 2019)



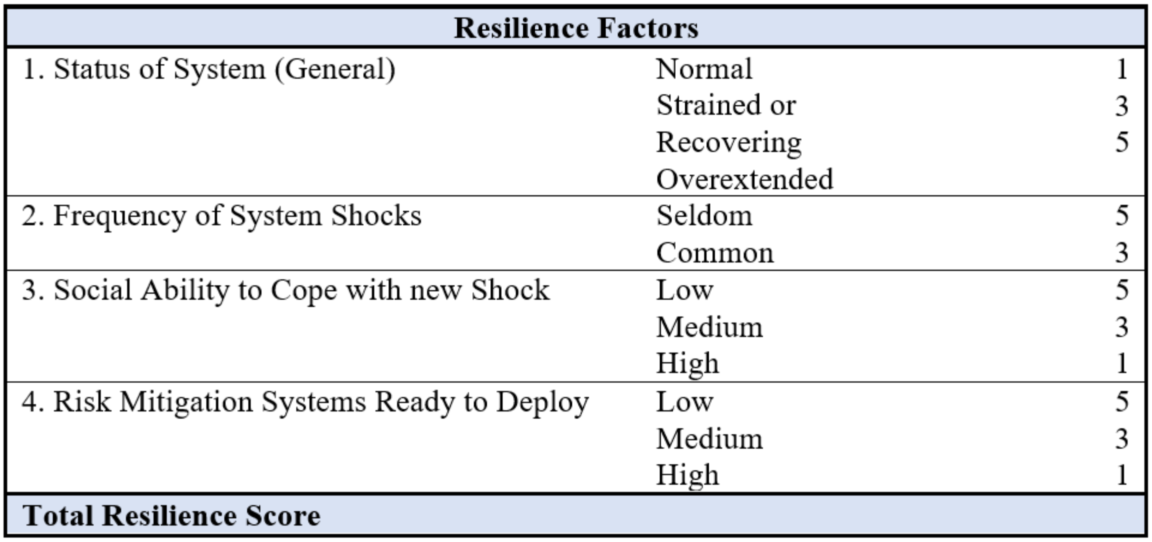
	Total 15 vulnerability indicators score	
2 Exposure indicators	**Criteria**	**Score**
16.Number of Deaths	10-100	0
	>100-1000	1
*at least 10 or more= 0	>1000-10 000	2
therefore less than 10 = 0 score	>10 000-100 000	3
	>100 000-1 000 000	4
	>1 000 000	5
17.Number of Affected Persons	100-1000	0
	>1000- 10 000	1
	>10 000- 100 000	2
*at least 100 or more= 0	>100 000- 1 000 000	3
therefore <100=0	>1 000 000- 10 000 000	4
	>100 000 000	5
	Total 2 exposure indicators score	

Total Population :
Percent of Population Deceased:

Total Population :
Percent of Population Affected:

Figure 3.6: Indicators 16-17 of the DSI, adapted from (Yew et al., 2019)

over-burdened sector of the system (Pescaroli and Alexander, 2016a). This consideration could also include a temporal component for the time elapsed since the last event to measure societal familiarity with the response process and assess the response readiness from a societal aspect. Factors in this category would include relevant and recent response training, disaster management policy familiarity, readiness scenario familiarity, and preparation for an event, i.e., early warning, early resource distribution if assessing resilience post-incident. An example of these measures included in the scale is provided in 3.7.



Resilience Factors		
1. Status of System (General)	Normal	1
	Strained or	3
	Recovering	5
	Overextended	
2. Frequency of System Shocks	Seldom	5
	Common	3
3. Social Ability to Cope with new Shock	Low	5
	Medium	3
	High	1
4. Risk Mitigation Systems Ready to Deploy	Low	5
	Medium	3
	High	1
Total Resilience Score		

Figure 3.7: Resilience Factors Table to include in a Disaster Severity Index

Using the adapted index, new calculations could be conducted. Thus, providing a measure of resilience within disaster metrics. Adapting existing tools to utilize resilience concepts also helps to level response estimates across scales of impact, as discussed in the beginning of this section. Including these factors in the overall scale better identifies the state of readiness within the affected system pre-event, providing a baseline to compare overall impacts to the system at a quick glance, and allowing for easier identification of the most pressing issues for overall resilience.

3.2.3 Non-technical Solutions

Resilience capabilities are often regarded in the preparation for a disruptive event, typically associated with the quantification of resource availability, the capacity of a system to withstand or recover from an event quickly, or the ability to withstand diverse threats (Galaitsi et al., 2021). While these themes resound within resilience concepts for single-event disruptions, resilience on a societal level must include long-term preparations not directly linked to a specific disaster, but broadly appropriate disaster preparedness measures. Considering this concept, the capacity of natural defenses to enhance resilience capabilities must be included. In this context, non-technical solutions and the skills of a population become vital assets for climate change response, preparation and long-term resilience.

Overreliance on technology is a common issue in developing resilience response practices. Though typically advantageous at enhancing societal advancement when properly functioning, no technological solution has a zero percent chance of failure. Oftentimes, a loss of technology causes more disruption to system operations than if it wasn't included as a critical component. Thus, technological solutions cannot be the sole source of reliability for climate change initiatives and alternative solutions that incorporate both technology and non-technological means should be considered.

A top, non-technical function related specifically to climate change preparation would be the inclusion of nature-based solutions (NbS) for building resilient infrastructure. Seddon describes NbS as “actions that involve people working with nature, as part of nature, to address societal challenges, providing benefits for both human well-being and biodiversity" (Seddon, 2022). Integration of NbS as a climate change mitigation strategy has many socio-economic impacts including ecology diversification, climate change impact mitigation, and societal involvement and upkeep for long-term successful implementation in a SES (Turner et al., 2022). Thus, including NbS builds multiple levels of resilience as these solutions include variables that enhance not just physical resilience, but also social, economic, and environmental resilience as well.

In terms of climate change resilience, nature-based solutions provide alternatives to modern shoreline infrastructure designed to protect or shield coastal environments. Guannel *et al.* describe how the interaction of mangroves, coral reefs, and seagrasses provide a natural defense to coastal erosion in a regular environment but also enhances shoreline stability during storm conditions (Guannel et al., 2011). Coastline assessments also show that natural habitat conservation and restoration of natural habitats reduce hazard exposure in coastal communities by half (Arkema et al., 2013).

The importance of utilizing non-technological solutions as a resilience strategy for combating the impacts of climate change is growing as more studies work to understand the role of natural defense strategies. One such study seeks to understand the inundation of tsunami and storm waves using sub-tidal coastal boulder deposits as indicators of past storm impacts and shifts for the future (Kennedy et al., 2021). Natural defense mechanisms can be incorporated to supplement technological solutions in understanding, preparing for, and withstanding the long-term effects of climate change. Sustaining NbS ensures that the success of shoreline protection systems is not hinging on a single point of failure within a technological solution. Rather, NbS allow for the diversification of a climate-resilient society and system.

Societal preparedness is an aspect of resilience that is often overlooked. MacLean *et al.* describe social resilience with six key attributes that are also linked to the economy and environment which describe a balance for system resilience in the context of an SES as previously described (Maclean, Cuthill, and Ross, 2014; Saja et al., 2019). These factors include knowledge, skills and learning, community networks, people-place connections, community infrastructure, a diverse and innovative economy, and engaged governance (Maclean, Cuthill, and Ross, 2014). Tariq *et al.* discuss a framework for preparing communities to withstand disaster at a local level as well (Tariq, Pathirage, and Fernando, 2021). SIDS are especially primed to utilize their people as a force for long-term resilience where alternative climate adaptations, for example diversifying economic output, maybe more challenging given the geographic challenges of island economies.

Relating the concept of social resilience to the SES described in Figure 2.1, these attributes can be incorporated into the system of resources, governance principles, and users. Examples of implementing social resilience can be seen in a variety of methods already employed. One application of this is education. The Virgin Islands Established Program to Stimulate Competitive Research (VI-EPSCoR) establishes climate-focused education opportunities for students to develop a foundational understanding of climate-related issues affecting the Virgin Islands and encourages community engagement in implementing and sharing climate resilience information, projects, and planning (Stimulate Competitive Research, n.d.). Additionally, student outreach and activities help to understand climate impacts more thoroughly (Vanderlinden et al., 2015).

Another application of societal resilience is preparing for emergency situations through policy development; conducting mock scenarios to understand the effectiveness of policy requirements and resource availability. Linkov *et al.* describe a similar approach as stress testing of critical infrastructure, a concept described and applied as the last step in this framework (Linkov, B. Trump, et al., 2022). Learning the limitations of system resilience requires engaged governance which enhances understanding and connectedness of interrelated components, thus increasing social resilience factors. Preparing society for climate-related adaptations and developing coordinated, effective responses ensures society can regain balance across the SES faster for long-term continuity and operability. It shifts the resilience focus to a long-term sustainability ethos. It also enhances resilience by expanding the impact of tools and resources already available within the system.

3.2.4 Technology Integration

Early Warning System Effectiveness

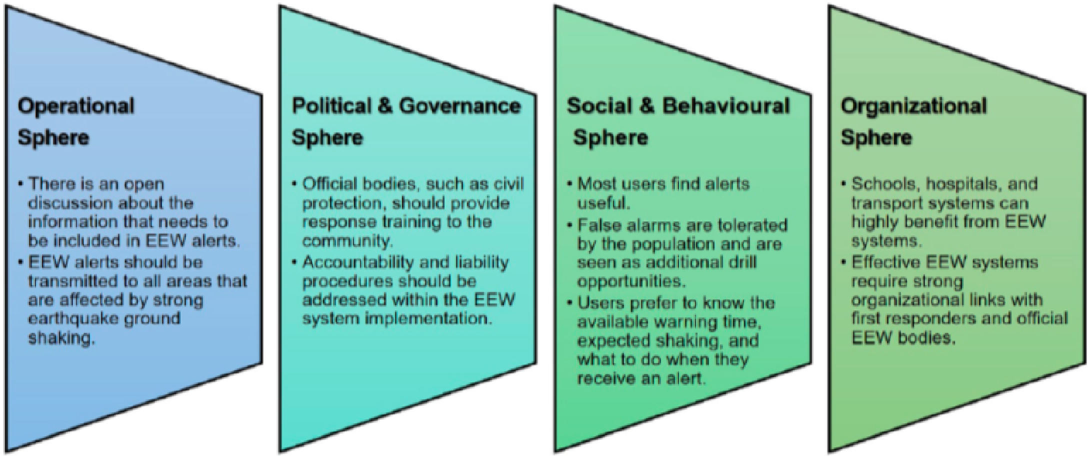
As islands cope with the climate change crisis from an economic perspective, building climate change deterrents into the system cannot completely negate the potential for unforeseen natural disasters or failures within the individual systems. To this end, some technological implementations are critical to island communities and must be addressed. One such climate-related technological solution is the effectiveness of Early Warning Systems (EWS) in the Caribbean islands.

Weather-related early warning systems continue to expand in as scientific research discovers earlier warning signs for many natural phenomena as climate shifts alter expected weather patterns. While many Americans are familiar with hurricane warnings via news and other sources, other EWS focus on a variety of natural disasters associated with a region. In the context of islands, several EWS are in place to identify the onset of earthquakes, landslides, tsunamis, coastal flooding, wildfire spread, and droughts (Argyroudis et al., 2022). Although these tools can be useful in emergencies, reliability, familiarity, and trust of these systems must be developed to ensure the tools are properly employed.

To ensure the successful management of disaster preparedness, a strong understanding of the risks of the event, and/or impact of an actor, and an understanding of the vulnerabilities of the impacted region are critical (Hissel et al., 2014). The risks to Caribbean SIDS are similar across islands: Climate change impacts, exposure to severe weather, higher risks of isolation from external resources, and high potential for catastrophic impacts from one major weather-related event. Each Caribbean island has distinctive terrain, agricultural, and coastal profiles as well as its own government policies, social practices, and economic strengths and weaknesses. Thus, each island is unique in the procedural deployment of EWS and its structure for implementation.

The relative importance of an EWS is described by Velazquez *et al.* in terms of four impact domains: operational, political and governance, social and behavioral, and organizational, which can be expanded from the context of earthquake-specific warnings to the broad category of EWS in general (Velazquez et al., 2020). In application, this relates to parameters of the system, how the system is tested and employed, the public understanding and response to the system once enacted, and the utilization of the system in the disaster response.

Encouraging EWS effectiveness in each of these domains can be extensive. Figure 3.8 shows how several parameters encourage system effectiveness of one type of early warning system for earthquakes. Involvement in the local community and an assessment of the attitude and persuasiveness of an EWS in the region must be known. Culturally, an attitude of resistance can impede the effectiveness of EWS regardless of the data that supports its need. Typically this can be addressed through education and involvement of the community in the EWS execution process. Awareness of the social perception toward EWS and other technological eco-support systems can help to avoid anticommons concerns within an island's communities. Supporting this concept of system trust, an EWS must be accurate and effective at communicating the impending hazard. This requires allocating resources to implementing new technologies, adopting new methodologies into preparedness research, and adapting the system to new incorporate new threats. Finally, system deployment must be well-understood and exercised to ensure success. This relates to the concept of stress testing the system (Linkov, B. Trump, et al., 2022). For example, the last hurricane to significantly affect Barbados struck in October of 2010 bringing heavy rain and damaging winds ((NASA), 2010). Earthquakes are a regular occurrence in the Caribbean due to the proximity of Caribbean islands to an active tectonic plate boundary (Rodríguez-Zurrunero et al., 2020). Tsunamis impacting Hispaniola were recorded in the mid-1900s, however no major events have occurred in the past century (Rodríguez-Zurrunero et al., 2020). As urbanization, tourism, and economic growth have altered the situations of Caribbean SIDS since then, the need to regularly exer-



Operational Sphere

- There is an open discussion about the information that needs to be included in EEW alerts.
- EEW alerts should be transmitted to all areas that are affected by strong earthquake ground shaking.

Political & Governance Sphere

- Official bodies, such as civil protection, should provide response training to the community.
- Accountability and liability procedures should be addressed within the EEW system implementation.

Social & Behavioural Sphere

- Most users find alerts useful.
- False alarms are tolerated by the population and are seen as additional drill opportunities.
- Users prefer to know the available warning time, expected shaking, and what to do when they receive an alert.

Organizational Sphere

- Schools, hospitals, and transport systems can highly benefit from EEW systems.
- Effective EEW systems require strong organizational links with first responders and official EEW bodies.

Figure 3.8: Earthquake Early Warning (EEW) implementation challenges across several domains (adapted from (Velazquez et al., 2020)).

cise these systems and prepare residents for the impacts, and to do so effectively, is essential to building social resilience. A lack of preparedness, training, and practical response applications is vital to maintaining a resilient posture.

Plan for System Failures

Despite the traditional thinking that SIDS typically rely on lower-technology initiatives and self-reliance, their incorporation into the global economy has significantly evolved their organizational and technological implementations. Because of this new reality, it is important to highlight and assess the strengths and weaknesses of these interactions.

The incorporation of technology initiatives into infrastructure, operations, and standard business practices has reduced the isolation of SIDS from the global economy. This provides these island communities the opportunities to develop their own sense of identity and integration into the international market. Although this integration affords SIDS the opportunity to expand their economies, providing competitive sources of supply and alternate sources of demand on a global scale, the inclusion of technologies into critical components of regular operations also increases the vulnerabilities to business continuity by expanding external dependencies onto critical networks such as electrical grids, information and communication technology (ICT), transportation, and navigation capabilities. These dependencies are now essential for continued supply chain operations and quality of life.

Overreliance on certain technologies, though, can have devastating effects. For instance, if emergency management of a SIDS relies heavily on satellite or internet communications for disaster response at a time when those capabilities are not available, the entire response system could collapse. In island nations, where logistics and response for emergency management must be self-reliant, underestimating the impacts of disruption or not identifying critical weaknesses could devastate a region or population. Misidentification of critical points of failure within a system without preparation for system continuity without the availability of technology or vital system components inhibits systemic resilience. This is especially true during times when the SES is already in a state of stress due to non-climate-related concerns such as a pandemic or economic recession.

Though critical infrastructure risks and resilience strategies have been studied internationally, the dependencies of SIDS on these integrated technologies have yet to be thoroughly examined. In terms of climate change impacts, the long-term effects of the extended losses of these key technologies are poorly understood, though indicators of potential outcomes are present from various examples of Caribbean SIDS.

An example is the extended power outages and unstable power supply grid and its effect on the ability of Puerto Rico to cope with extreme climate-related events. In 2017, Hurricanes Irma and Maria made landfall in Puerto Rico, less than two weeks apart, compounding challenges for emergency response, but causing catastrophic damage to the power grid. Impacts of island-wide power outage after these storms included more than 2000 deaths not directly related to the causal event (Puerto Rico, 2018). Another example is the limited transportation capabilities in Haiti due to the frequency of natural disasters devastating the island (Ndambuki and Al Hitmi, 2022). Lastly, a recent internet outage in Tonga demonstrates the extent of societal impacts that can be triggered by the ICT failures of an island nation that heavily relies on international communications to conduct regular business (News, n.d.). Similar issues could result from malfunctions, or reception, of global navigation satellite systems; where an unseen utility affects all other services, such as the ability to conduct regular trade like maritime shipping or air travel.

Island nations also have the additional burden of understanding interrelated casualty factors. The connectedness of extreme weather events and potential technology disruptions makes Caribbean SIDS especially vulnerable to cascading casualties. Understanding the impacts of the incorporation of technology deeply within a vulnerable system can have grave consequences, especially if occurring in conjunction with or because of, another unrelated casualty. Pescaroli and Alexander describe this phenomenon as cascading casualties or "… the manifestation of vulnerabilities accumulated at different scales, including socio-technological drivers. The possible environmental triggers… can be associated with compounding and interconnected risk, while critical infrastructure and complex adaptive systems may be the drivers that amplify the impacts of the cascade" (Pescaroli and Alexander, 2016b). The assessment of possible gaps, identification of singular points of failure, and the impacts of either being exploited must be conducted during the development of a contingency planning procedure (Suppasri et al., 2021). As SIDS economies heavily rely on tourism and regular trade for economic prosperity, these two areas should be scrutinized for weaknesses and alternative measures for spanning potential gaps put in place to enhance the system's overall resilience.

Routine contingency management practices fail to incorporate cross-border, multi-hierarchical scenarios. Takeda *et al.* describe the necessity for local agents to be trained and able to make rational, decisions regarding resource allocation, the needs of the community, and information gathering to effectively respond to emergencies with complex interactions and high uncertainty (Takeda, Jones, and Helms, 2017). Response methodologies and standard practices for overlapping technological and nature-based disasters are not readily available which also limits understanding of how different types of casualties can affect one another, directly or indirectly. Building disaster response plans, which can be "stress-tested" with these "unusual" circumstances can recognize the resilience and robustness of a region. Pescaroli *et al.* describe this scenario as the massive, overwhelming, disruption of operations (Mo.OR.D.OR.) during which accumulated vulnerabilities between natural and man-made risks can escalate a cascading disaster (Pescaroli, Wicks, et al., 2018). Preparing for this kind of contingency response requires significant planning, investment in resources, and strong understanding of the interconnectedness of critical systems to build organizational resilience and continuity. Thus identifying critical points of failure in system connections and integrating technological solutions as risk mitigation factors must be done meticulously so as to enhance resilience rather than introduce new vulnerabilities.

3.2.5 Decision Analysis Tools

The importance of utilizing decision analysis processes has been described in countless studies related to risk mitigation and discussed in 2.2. With the emergence of new technology and the ever-increasing complexities of modern systems, the challenges surrounding the assessment of potential strategies, decisions, and approaches become more difficult to delimit. Thus, the need for a variety of new tools and applications of known tools that assess issues from a systemic approach is vital to decision-support processes.

Systemic decision-making complexities have resulted in the need for policy analytics. This concept is described as the development of policy in a data-driven age with multiple stakeholders, including the broad public, from which decision-makers must assess enormous amounts of data, making the process socially complex (Tsoukias et al., 2013). This process becomes even more complex for the application of environmental policy (Meinard et al., 2021; G. A. Kiker et al., 2005). Thus, four normative properties of policy analytics, specifically related to environmental decision-making, were described by a team of experts in this field to identify valuable functions of decision-support tools. These properties include analyses being conducted with demand and purpose (demand-oriented), results of the interventions leading to notable improvements in the situation (performativity), clarification of underpinnings and how leaders arrived at the decisions made (normative transparency), and emphasis on quality and context of data (data meaningfulness) (Meinard et al., 2021; Logan et al., 2022). Policies regarding decisions should include these priorities in the tools utilized for decision-making processes.

Several tools are already available for resilience analysis and semi-quantification techniques for risk reduction and disaster impacts or preparedness. Two specific decision-support tools that incorporate the four properties described above, including in a multi-perspective scenario analysis, will be described and demonstrated in Chapter 4.

3.2.6 Stress-Test the System

Evaluating the results of this framework requires a method of assessment. Rather than waiting for an impactful event to disrupt the system and understand its dynamics, methods of reviewing system performance must be implemented. A highly applicable concept for this method would be *stress-testing*.

Linkov *et al.* describe the importance of stress-testing as a measure of understanding impacts to critical infrastructure to better model system dynamics, categorize affected systems, and encourage prioritization of resources (Linkov, B. Trump, et al., 2022). Stress-tests can be done by running system tests, for example a mock-evacuation scenario for an EWS. Other examples of stress-testing could include testing cyber-system integrity by attempting to "hack" into the system, conducting simulation model trials to assess impacts of component failures in technological systems, etc. The results of these tests and trials identify vulnerabilities, weaknesses, coverage and knowledge gaps that can exacerbate negative event impacts. Stress-testing allows system testing to identify areas for improvement.

The complexities of the system outlook described in Section 3.2.1 can be overcome with a heuristic perspective that allows for the possibility of stress tests. And the perspective can make much clear the understanding of the timing of a system(s) shock, the prioritization of needs, the presence and process of hierarchical structures with their real value and implications, and the overall coordination of resources. Temporal system shocks will have various levels of impact on the overall system balance depending on the status of other variables in the system. For example, if a hurricane devastates the eastern shore while an island is experiencing extreme drought conditions, the priority for response will likely be different than in a normal condition. Thus, a strong overview of the vulnerabilities at the time of an event must be considered to ensure the proper resources are provided. Minimizing the affects of a disruptive event to allow a system to reestablish equilibrium is the crux of resilience principles.

Cyclical stress-testing ensures that system dynamics are well understood and decisions can be made with regard to the current system state. Thus this principle in the framework is triggers the necessity to re-evaluate the system. If the system goals or a regime shift has occurred, the entirety of the framework, from understanding the dynamics and resilience principles in Section 3.2.1. If minimal shifts to the system have occurred, the process should begin from Section 3.2.2.

3.3 Summary

The sections identified in this Chapter outline a framework of resilience principles in application. The process described in this Chapter is summarized in Figure 3.1. Section 3.2.1 provides a review of system dynamics and the importance of decision-makers understanding system interactions and interplay specific to SIDS SES structure. Section 3.2.2 provides a tool to measure disaster preparedness and system capacity for resilience. Section 3.2.3 provides details on solutions for building internal resilience for SIDS founded in natural solutions such as ecosystem and social applications. Section 3.2.4 describes how technology integration both enhances and encumbers system resilience and should be considered carefully. Section 3.2.5 discusses the importance of utilizing MCDA or other analyses, in conjunction with other references, for policy-making. Applications of these tools are described in detail in Chapter 4. Section 3.2.6 identifies the need to implement stress-testing for enhancing resilience and describes the cyclical nature of the framework described in this Chapter. The framework application will also be discussed in more detail in Chapter 5 and Chapter 6.

Chapter 4

Demonstration

4.1 Overview

This Chapter introduces two tools for decision analysis and support that utilize multiple criteria, incorporate perspectives, and details alternative solutions for decision-making as described in Section 3.2.5.

4.2 Spatial Awareness Tools

4.2.1 Background

Planning for climate change requires foresight and resources directed toward understanding and planning environmental resource allocation, including land-use distributions and development. Island land masses are typically small- of the 13 Caribbean islands SIDS, the median size is 750 square kilometers (465 square miles) and 8 of the islands have a land mass of less than 5,200 square kilometers (3,224 square miles). Island landscapes vary from mountainous and rocky, hilly, prone to soil erosion, or flat and sandy. The variety of topographies within developing islands necessitates effective land-use planning that optimizes social and economic growth within the limitations of available, usable land. This is even more true for islands experiencing sea level rise and coastal erosion, forcing infrastructure and resource shifts farther inland.

A novel approach to address this issue is the integration of spatial awareness tools in land use decision-making. Spatial tools can support decisions regarding land parceling because they are able to assess land availability and potential usages for enterprises. For example, one parcel of land might be ideal for urbanization, but is also a prime for agricultural or industrial development, depending on the nation's economic priorities. Spatial analysis tools can assist in the identification of these contention areas and understanding land use opportunities and areas of potential dispute can help government officials prioritize development projects that meet their needs. This early planning is essential to effectively allocate resources across island communities with limited land availability.

4.2.2 Method

The effectiveness of using spatial awareness tools is evident in the Ghana Land Use Project (GALUP). GALUP is a collaboration of multiple resources that developed a workshop for various land use decision-making agencies in Ghana for how to use GIS-type resources. These resources can be used to map current and future land-use, utilizing the results of the training in tradeoff studies and decision analysis processes (Chen, Judge, G. Kiker, et al., 2021). The modeling techniques taught in the workshop have been saved to a GitHub repository for future training, discussion, and further analysis as Ghana's land use choices and priorities change. The GALUP tools are open source, including the modeling software, training modules, and multi-criteria decision analysis (MCDA) from the results. Similar assessments of Caribbean SIDS land use potential should be completed by each island state using the tools available from GALUP and the code repository.

A key resource in the GALUP toolkit is PyLUSAT (Python-based Land Use Suitability Analysis Tools), an open-source modeling tool directed toward land-use suitability analysis. PyLUSAT incorporates functionalities that assess current land use and can identify land parcels that could lead to future conflict for various resource uses (Chen, Judge, and Hulse, 2021). It can also model the changes in land areas due to climate change effects, such as sea-level rise. Chen *et al.* also note that the PyLUSAT system is unique because it models transportation and hydrologic data while maintaining the capability to be operated without special computing equipment or extensive GIS training (Chen, Judge, and Hulse, 2021). For smaller industries or governments with limited resources available to focus on land use planning, it makes the PyLUSAT tool even more significant. PyLUSAT has proven to be as accurate with vector-based GIS modeling as its GIS counterparts (Chen, Judge, and Hulse, 2021). But the key difference is that the processor significantly decreases the computational run-time required to model similar data, allowing the user to utilize an average computing system to develop detailed GIS models (Chen, Judge, and Hulse, 2021). The system is also customizable and imports open-source, readily available data. Thus, all 16 SIDS in the Caribbean could develop their own modeling systems specific to the geographic, logistical, and resource allocation challenges associated with each island nation. As an open-source, downloadable system, PyLUSAT can be used with no extra cost to the user other than the time required to download files, complete the training modules, and develop pertinent models for the area(s) of concern.

The MCDA function within PyLUSAT is called the *Land-Use Conflict Identification Strategy*, or LUCIS. The LUCIS model is based on suitability analysis theories from the GALUP training modules; its goal is to replicate likely patterns of land use in future scenarios to identify stakeholder conflicts and address them (Chen, Lyu, and Yang, 2021). This tool uses a weighted overlaying technique within the software to combine the importance of variables of concern and show the aggregate results in a spatial representation (Chen, Lyu, and Yang, 2021). Input weights and criteria can be adjusted based on stakeholder or decision-maker priorities and/or limitations. As such, the results can be reviewed and compared to ensure that decision-makers are aware of opportunities for success and can mitigate the negative or undesirable impacts of their decisions. Figure 4.1 details the LUCIS framework.

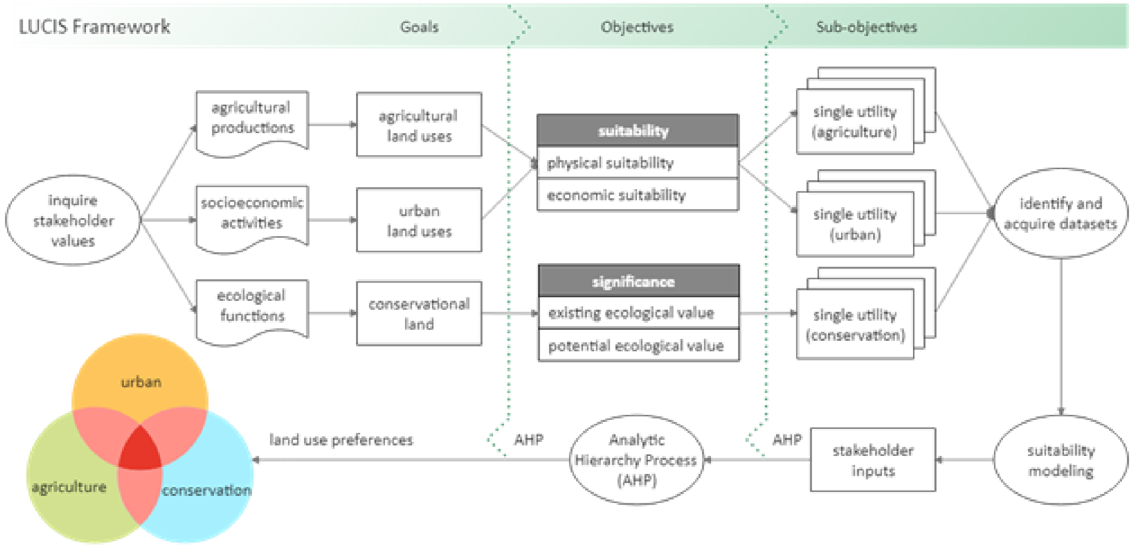


Figure 4.1: LUCIS Workflow (Chen, Lyu, and Yang, 2021).

LUCIS utilizes a common decision-analysis method of ranking a variety of options using weighted values called an Analytical Hierarchy Process (AHP). AHP utilizes a quantitative comparison method that allows a decision-maker to assess options against each other rather than in an absolute manner (Logan et al., 2022; G. A. Kiker et al., 2005). This method is ideal when considering pairwise solutions. Stakeholder perspectives are a strong driver for choosing AHP in this analysis which is key to understanding tradeoffs associated with decisions land usage with competing interests.

4.2.3 Application

The method utilized by GALUP would be an outstanding resource for SIDS. Because the training, equipment, and products designed by GALUP require minimal resource allocation, SIDS could individually build models for their island's specific needs. Decision workflows provided by the LUCIS process would allow land-use priorities to be assessed, a vital part of building resilience in the structure of a society. Examples of this would be to design efficient transportation networks for emergency response and preparing agriculture and urbanization areas less likely to be impacting by sea-level rise or coastal degradation. The model and its outputs provide applicable, timely, and relevant information for decision-makers that also includes stakeholder inputs. As a decision-support tool, the GALUP products would be excellent resources for SIDS to incorporate into the decsiion-making process of their resilience framework.

4.3 Illegal, Unreported, and Unregulated Fishing Risk Analysis

4.3.1 Background

Enterprise risk analysis is a technique available to review the impacts of socio-economic and interrelated environmental concerns. One methodology described by Hassler *et al.* allows for the integration of success criteria (system goals) to be evaluated using initiatives, emergent conditions, and scenario forming to determine which policies, assets, or initiatives best address particular system goals (Hassler et al., 2020). This methodology can be adapted for various stakeholder perspectives and the goals, criteria assessed, and comparative measures are easily adjustable, making the tool vital for decision-makers to understand which priorities are the best investments, or pursuits, that support system objectives. The outcome of this method is a baseline scenario where the most impactful situation(s) can be identified and decision-makers can adjust their course of action, planning processes, or investments as appropriate to manage the development of the situation. The tool has proven successful for a broad array of applications such as managing socio-technical resilience following the COVID-19 pandemic and prioritization of infrastructure initiatives that address climate change (Bonato et al., 2022; Loose et al., 2022; C. W. Karvetski, J. H. Lambert, and Linkov, 2011; Almutairi et al., 2019). This methodology is applied herein to cross-correlate the impacts of Illegal, Unreported, and Unregulated (IUU) fishing across the social, environmental, and economic domains by assessing the impact of global practices and policies devised to deter the prominence of IUU fishing. The results of the analysis can help to identify priority pursuits to discourage this crime, and multiple stakeholder perspectives can be analyzed to de-conflict potential decision contentions. Results from this assessment are highly applicable to SIDS as the islands depend on marine resources for food, economic revenue, culture, and community.

IUU fishing is a complex legal, economic, and social problem that requires a multi-criteria decision analysis approach to effectively deter its prevalence. Catch from IUU fishing is not directly measurable, making fish stock assessments even more difficult with the shifting of fisheries biology and management practices due to climate change effects (*United Nations Fish Stock Agreement .:. Sustainable Development*

Knowledge Platform 1995; Möllmann and Diekmann, 2012; Atmaji, Purnomo, and Fathani, 2021). Economic impacts are also felt by regions losing IUU-caught species as they are unable to properly tax fishing vessels, nor do they receive the direct benefits of the lost goods in local or regional markets (Park et al., 2022; He, S. Huang, and Tang, 2022). Socially, IUU fishing can detract from legal job opportunities and often is an avenue for other maritime crimes including piracy, human trafficking, and drug smuggling (Mackay, B. D. Hardesty, and Wilcox, 2020; Stefanus and Vervaele, 2021). Regulations to deter IUU fishing are also convoluted as criminal offenses vary across regions and nation-states, making it difficult to prosecute offenders based on authority, jurisdictions, and applications of various criminal laws (Rosello, 2022; Tsamenyi et al., 2010). Understanding the systemic view of IUU fisheries impacts and trade-offs can help devise proactive, efficient, and actionable regulatory and management actions to enhance overall socio-economic and socio-ecological issues (Woods et al., 2022; FAO, 2001). Specific to SIDS economically, the island's major sources are highly impacted by climate change, including tourism, agriculture, and fisheries (Mycoo, 2018). These concerns are exacerbated by climate change, such as rising sea temperatures shifting marine resource spatial patterns and fishermen looking for alternate sources of income due to the potential unsustainability of their livelihoods (Desai and Shambaugh, 2021; Galappaththi et al., 2022; Mackay, B. D. Hardesty, and Wilcox, 2020; Lee, 2019). SIDS are more susceptible to these impacts due to the nature of their geographical isolation and current economic structures.

Unfortunately, scenario frameworks regarding climate change effects on future conditions are delayed compared to the rapid nature with which nations are facing climate shifts (Vuuren and Carter, 2014; Möllmann and Diekmann, 2012). The complex nature of IUU fisheries impacts requires a holistic analysis of the vulnerabilities, risk mitigation options, and solutions to meet resilience goals in the rapidly changing seascape of climate risks (Vince, B. Hardesty, and Wilcox, 2021; Donlan et al., 2020). An enterprise risk analysis can meet these demands in a timely manner that provides decision-makers with tools to validate perspectives, evaluate initiatives, identify solutions, and provide transparency in the policy-making process.

4.3.2 Method

In this example assessment, the enterprise risk register tool will be used to identify priority initiatives to combat IUU fishing from a selection of global approaches employed to counter its prevalence. The novelty of this assessment is that it can be adapted in a relatively short time frame, ensuring its ability to retain relevance more appropriately than previously described models. The assessment cross-references system goals (criteria), risk mitigation factors, assets, or policies (initiatives), and potential system shocks (emergent conditions) to identify correlations between variables that could negatively impact the system, shown in Figure 4.2. Relative to the SES described in Figure 2.1, this assessment tool integrates the external relationship factors to the internal factors to identify potential outcomes given the interactions. It can also be analyzed using various perspectives that would influence decisions, as will be demonstrated in the following subsections.

4.3.3 Application

The risk register process scores groups of variables in rank order of priority under the given circumstances. Criteria were selected via relevant literature analysis and application to IUU fishing deterrence and are provided as the set, $C = \{c_1, c_2, c_3, ...c_k\}$,

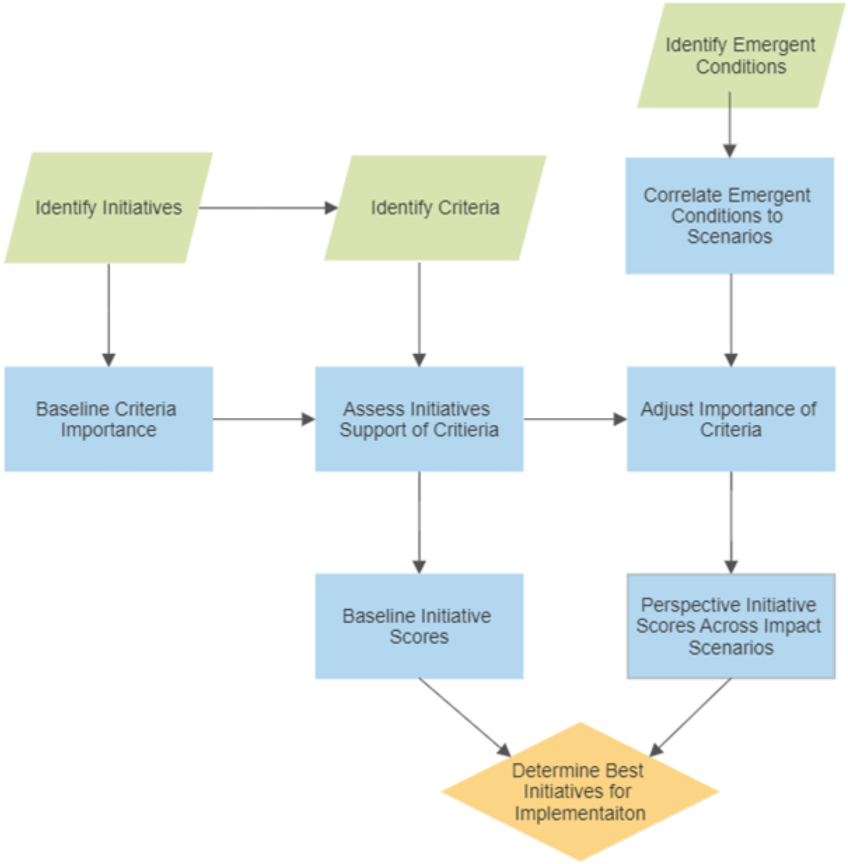


Figure 4.2: Relationship between Risk Enterprise Analysis Variables

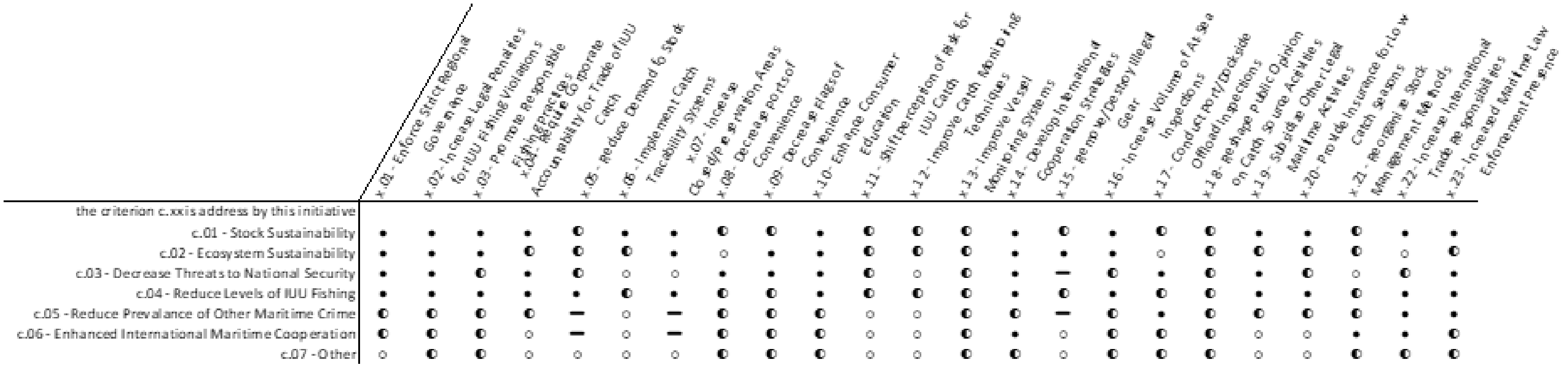
listed in Table 4.1. Criteria are specific to the perspective of the analyis. In this case, the first perspective under review is from that of an Enforcement Agency. The set of initiatives, $X = \{x_1, x_2, ...x_k\}$ that affect criterion success were also derived from literature review. A criterion-initiative (C-I) assessment was completed to understand to what degree the initiative(s) support each criterion. Indicators within literature from law enforcement perspectives provide input as to the level of support as neutral, somewhat agree, agree, or strongly agree for each initiative as it related to a specific criterion. The table of Initiatives and the C-I Assessment are included as Table 4.2 and Figure 4.3 respectively.

Table 4.1: Criteria (system goals) for decreasing IUU fishing from a law enforcement perspective

Index	Criterion	Source
c.01	Stock Sustainability	Vince et al., 2020
c.02	Ecosystem Sustainability	Vince et al., 2020
c.03	Decrease Threats to National Security	Mackay et al., 2020
c.04	Reduce Levels of IUU Fishing	FAO, 2001
c.05	Reduce Prevalance of Other Maritime Crime	Mackay et al., 2020
c.06	Enhanced International Maritime Cooperation	PSMA, 2016
c.07	Other	

Table 4.2: Initiatives are policies or practices that deter IUU fishing.

Index	Initiative	Source
x.01	Enforce Strict Regional Governance	Vince at al., 2021
x.02	Increase Legal Penalties for IUU Fishing Violations	Stefanus and Vervaele, 2021
x.03	Promote Responsible Fishing Practices	He et al., 2022
x.04	Require Corporate Accountability for Trade of IUU Catch	Vince at al., 2021
x.05	Reduce Demand for Stock	Mollmann et al., 2012
x.06	Implement Catch Tracability Systems	FAO, 2022
x.07	Increase Closed/Preservation Areas	Mollmann et al., 2012
x.08	Decrease Ports of Convenience	Park et al., 2022
x.09	Decrease Flags of Convenience	Park et al., 2022
x.10	Enhance Consumer Education	Woods et al., 2022
x.11	Shift Perception of Risk for IUU Catch	Woods et al., 2022
x.12	Improve Catch Monitoring Techniques	Vince at al., 2021
x.13	Improve Vessel Monitoring Systems	Vince at al., 2021
x.14	Develop International Cooperation Strategies	Stefanus and Vervaele, 2021
x.15	Remove/Destroy Illegal Gear	Atmaji et al., 2021
x.16	Increase Volume of At-Sea Inspections	Donlan et al., 2020
x.17	Conduct Port/Dockside Offload Inspections	Donlan et al., 2020
x.18	Reshape Public Opinion on Catch Source Activities	Woods et al., 2022
x.19	Subsidize Other Legal Maritime Activities	Lee, 2019
x.20	Provide Insurance for Low-Catch Seasons	Lee, 2019
x.21	Reorganize Stock Management Methods	FAO, 2022
x.22	Increase International Trade Responsibilities	Stefanus and Vervaele, 2021
x.23	Increased Maritime Law Enforcement Presence	Woods et al., 2022
x.i		



the criterion c.xx is address by this initiative	x.01 - Enforce Strict Regional Governance	x.02 - Increase Legal Penalties for IUU Fishing Violations	x.03 - Promote Responsible Fishing practices	x.04 - Require Corporate Accountability for Trade of IUU Catch	x.05 - Reduce Demand to Stock	x.06 - Implement Catch Traceability Systems	x.07 - Increase Closed/Preservation Areas	x.08 - Decrease ports of Convenience	x.09 - Decrease Flags of Convenience	x.10 - Enhance Consumer Education	x.11 - Shift perception of Risk for IUU Catch	x.12 - Improve Catch Monitoring Techniques	x.13 - Improve Vessel Monitoring Systems	x.14 - Develop International Cooperation Strategies	x.15 - Remove/Destroy Illegal Gear	x.16 - Increase Volume of At Sea Inspections	x.17 - Conduct port/Dockside Offload Inspections	x.18 - Reshape Public Opinion on Catch Source Activities	x.19 - Subsidize Other Legal Maritime Activities	x.20 - Provide Insurance for Low Catch Seasons	x.21 - Reorganize Stock Management Methods	x.22 - Increase International Trade Responsibilities	x.23 - Increased Maritime Law Enforcement Presence
c.01 - Stock Sustainability	●	●	●	●	◐	●	●	◐	◐	●	◐	◐	◐	●	◐	●	◐	◐	●	●	◐	●	●
c.02 - Ecosystem Sustainability	●	●	●	◐	◐	◐	●	○	●	●	◐	◐	◐	●	●	●	○	◐	◐	◐	◐	○	◐
c.03 - Decrease Threats to National Security	●	●	◐	●	◐	○	○	●	●	●	◐	○	◐	●	—	◐	●	◐	●	◐	○	◐	●
c.04 - Reduce Levels of IUU Fishing	●	●	●	●	●	◐	●	◐	◐	●	◐	◐	◐	●	◐	●	◐	◐	●	●	◐	●	●
c.05 - Reduce Prevalance of Other Maritime Crime	◐	◐	◐	◐	—	○	—	◐	◐	◐	○	○	◐	◐	—	◐	●	◐	◐	◐	◐	●	●
c.06 - Enhanced International Maritime Cooperation	◐	◐	◐	○	—	○	—	◐	◐	◐	○	○	◐	●	○	◐	◐	◐	○	○	●	●	◐
c.07 - Other	○	◐	◐	○	○	○	○	◐	◐	◐	○	○	◐	◐	○	◐	◐	◐	○	○	◐	◐	◐

Figure 4.3: Criterion-Initiative (C-I) Assessment Table for Enforcement Agency perspective. Strongly Agree is represented by a filled circle, Agree is represented by a half filled circle, Somewhat Agree is represented by an unfilled circle, and Neutral is represented by a dash.

Next, a set of Emergent Conditions, $E = \{e_1, e_2, e_3, ...e_k\}$, are then identified as potential disruptors to reaching system goals. These are identified in Table 4.3.

Finally, scenarios are derived from the combinations of emergency conditions as that could affect the system's performance, listed in Figure 4.4 as set $S = \{s_1, s_2, s_3, ...s_k\}$.

Table 4.3: Emergent Conditions are existing or potential events that effect enterprise risk.

Index	Emergent Condition
e.01	Loss of Viable Habitat
e.02	Shifts in Stock Location/Migration
e.03	Multiple Climate Shocks in Same Season
e.04	Changes in Fishery Management Processes
e.05	Increase of Closed or Protected Areas
e.06	Rezoning of Maritime Domains
e.07	Reorganization of RFMOs
e.08	Changes to Economic Systems
e.09	Increased Market Demand
e.10	Increased International Collaborations
e.11	Increased Criminal Laws or Penalties
e.12	Increased Operating Costs
e.13	Lack of Enforcement
e.14	Governance or Policy Shift
e.15	Fiscal Stress
e.16	Lack of Laborers
e.17	Population Increase
e.18	Social Unrest
e.19	International Health Crisis
e.20	Cyber Attack on Vessel Monitoring Technologies
e.21	Vessel Data Leak
e.i	Others

Scenarios (*s.xx*)	e.01 - Loss of Viable Habitat	e.02 - Shifts in Stock Location/Migration	e.03 - Multiple Climate Shocks in Same Season	e.04 - Changes in Fishery Management Processes	e.05 - Increase of Closed or Protected Areas	e.06 - Rezoning of Maritime Domains	e.07 - Reorganization of RFMOs	e.08 - Changes to Economic Systems	e.09 - Increased Market Demand	e.10 - Increased International Collaborations	e.11 - Increased Criminal Laws or Penalties	e.12 - Increased Operating Costs	e.13 - Lack of Enforcement	e.14 - Governance or Policy Shift	e.15 - Fiscal Stress	e.16 - Lack of Laborers	e.17 - Population Increase	e.18 - Social Unrest	e.19 - International Health Crisis	e.20 - Cyber Attack on Vessel Monitoring Technologies	e.21 - Vessel Data Leak
s.01 Economic Recession or Collapse		x	x					x		x		x		x	x	x	x	x	x	x	
s.02 Climate Shift	x	x	x	x	x	x	x	x		x				x							
s.03 International Health Crisis								x	x	x	x	x	x	x	x	x		x	x		
s.04 Maritime Boundary Disputes	x	x		x	x	x	x				x	x		x			x	x		x	x
s.05 Maritime Law Development				x	x	x	x			x	x	x	x	x		x				x	x
s.06 Worldwide Food Shortage		x	x						x	x			x	x	x		x	x			
s.07 Cybersecurity Breach											x	x	x					x		x	x

Figure 4.4: Scenarios (S) formed from combinations of emergent conditions identified in Table 4.3

The tables outlining the derivation of a scenario and a list of the emergent conditions it encompasses are included as Table 4.4 and Table 4.5. Scenario-building ensures that various conditions that impact multiple outcomes are considered ensuring that the overlap and differences between component vectors impacts of emergent conditions is accounted for in the final analysis.

Table 4.4: List of Scenarios and the applicable Emergent Conditions that comprise the disruptive event.

Index	Scenario	Emergent Conditions
s.01	Economic Recession or Collapse	*e.02* - Shifts in Stock Location/Migration *e.03* - Multiple Climate Shocks in Same Season *e.08* - Changes to Economic Systems *e.10* - Increased International Collaborations *e.12* - Increased Operating Costs *e.14* - Governance or Policy Shift
s.02	Climate Shift	*e.01* - Loss of Viable Habitat *e.02* - Shifts in Stock Location/Migration *e.03* - Multiple Climate Shocks in Same Season *e.04* - Changes in Fishery Management Processes *e.05* - Increase of Closed or Protected Areas *e.06* - Rezoning of Maritime Domains
s.03	International Health Crisis	*e.08* - Changes to Economic Systems *e.09* - Increased Market Demand *e.10* - Increased International Collaborations *e.11* - Increased Criminal Laws or Penalties *e.12* - Increased Operating Costs *e.13* - Lack of Enforcement
s.04	Maritime Boundary Disputes	*e.01* - Loss of Viable Habitat *e.02* - Shifts in Stock Location/Migration *e.04* - Changes in Fishery Management Processes *e.05* - Increase of Closed or Protected Areas *e.06* - Rezoning of Maritime Domains *e.07* - Reorganization of RFMOs

Table 4.5: List of Scenarios and the applicable Emergent Conditions that comprise the disruptive event (cont.).

Index	Scenario	Emergent Conditions
s.05	Maritime Law Development	*e.04* - Changes in Fishery Management Processes *e.05* - Increase of Closed or Protected Areas *e.06* - Rezoning of Maritime Domains *e.07* - Reorganization of RFMOs *e.10* - Increased International Collaborations *e.11* - Increased Criminal Laws or Penalties
s.06	Worldwide Food Shortage	*e.02* - Shifts in Stock Location/Migration *e.03* - Multiple Climate Shocks in Same Season *e.09* - Increased Market Demand *e.10* - Increased International Collaborations *e.13* - Lack of Enforcement *e.14* - Governance or Policy Shift
s.07	Cybersecurity Breach	*e.11* - Increased Criminal Laws or Penalties *e.12* - Increased Operating Costs *e.13* - Lack of Enforcement *e.18* - Social Unrest *e.20* - Cyber Attack on Vessel Monitoring Technologies *e.21* - Vessel Data Leak
s.i	Others	

Once the described data is modeled by the analysis tool, the various initiatives that best meet the overall objectives of the system are ranked according to the effectiveness in the current state of operations and under the influence of the described scenarios. Initiative values are scored using a linear additive value function $V(x.i)_k = W_k X_i$, where W is the weight vector of impact scores by a scenario. The scores are then sorted by higher or lower values which indicate the priority of the initiative and is represented mathematically to mean IF $V(x_i)_k > V(x_j)_k$ THEN $x_i > x_j$, higher values (indicated to the left of $>$) designate an initiative with stronger priority (Hassler et al., 2020). Initiatives can then be ranked under alternate scenarios as $R(x_i)_k$ which defines the rank of an initiative x_i is influenced by scenario S_k. Using these values, a disruptiveness score can be measured as $D(s_k)$. The correlation of these variables is described in Equation 4.1.

$$D(s_k) = \sum_{i=1}^{n} (R(x_i)_b - R(x_i)_k)^2 \tag{4.1}$$

Where $R(x_i)_k$ is the ranking of an initiative x_i under a scenario s_k and $R(x_i)_b$ is the baseline initiative rank applied across all initiatives n. Once the scores are derived, they can be normalized and compared, thus demonstrating various scenario impactfulness on the enterprise system.

4.3.4 Results: Enforcement Agency

Figure 4.6 shows the ranking of the initiatives, based on the scenario of the government's enforcement agency. The red and blue bars indicate the relative importance of each initiative and whether it becomes more important (blue) or less important (red) under various scenarios. The black bar indicates its importance in the baseline (status quo) situation. Using the results of this analysis, decision-makers can understand the relative importance of initiatives and compare which initiatives will be more resilient given the impact of scenarios on the baseline situation.

Figure 4.5 shows that from this perspective, the most important scenarios that disrupt system goals are *s.02* Climate Shift and *s.04* Maritime Boundary Disputes.

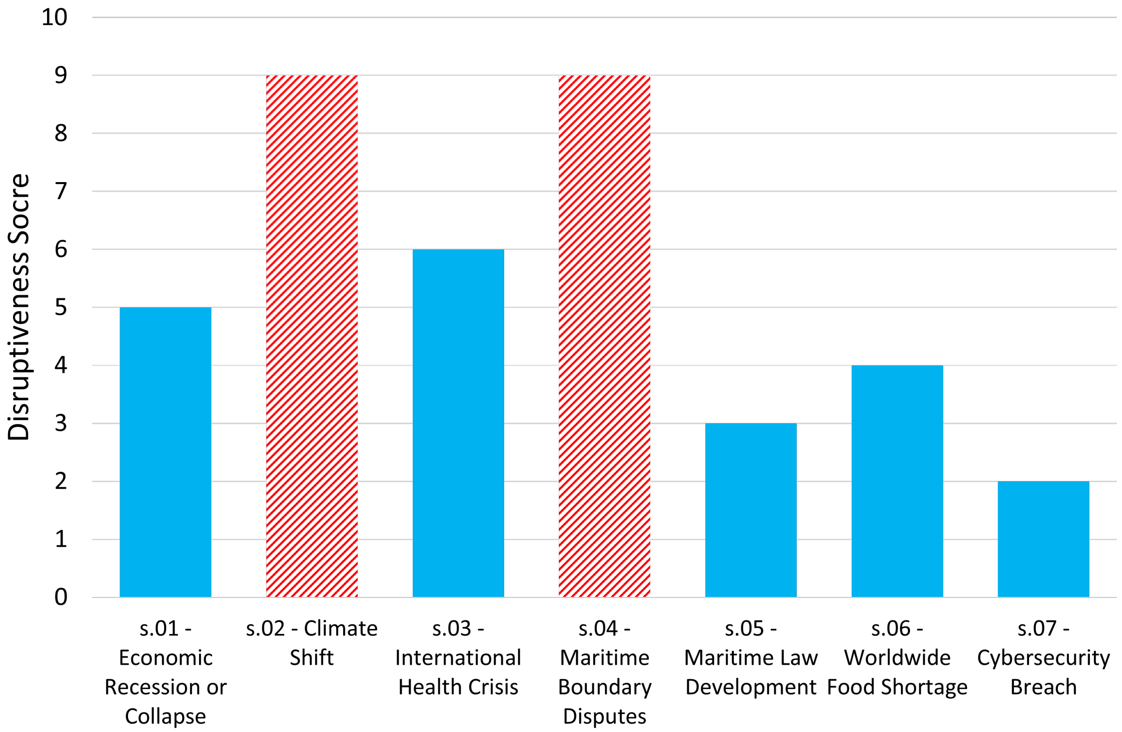


Figure 4.5: Disruptive scenarios for enterprise risk analysis of IUU fishing from the law enforcement perspective.

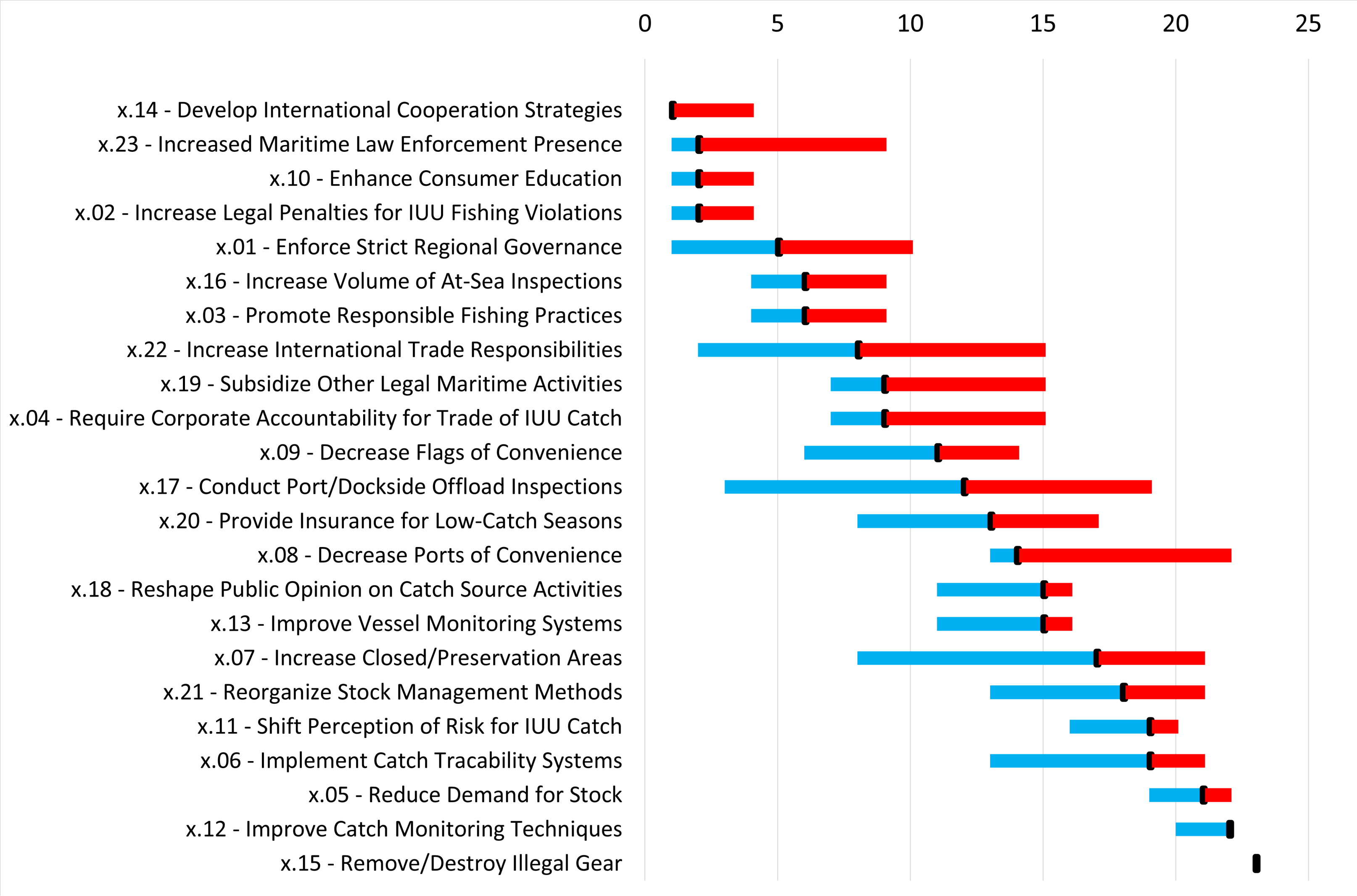


Figure 4.6: Ranking of initiatives priority across enterprise including disruptive scenario effects.

The results of this assessment, from the perspective of an Enforcement Agency, the initiative *x.14* Develop International Cooperation Strategies is the highest priority initiative in all scenarios. Initiative *x.15* Remove/Destroy Illegal Gear is the least strategic initiative because its impact does not have a significant effect in the status, nor does it increase as a strong objective due to disruptive scenarios. Other initiatives that increase in priority with the disruption caused by the highlighted scenarios are *x.17* Conduct Port/Dockside Offload Inspections, *x.07* Increase Closed/Preservation Areas, *x.22* Increase International Trade Responsibilities, and *x.06* Implement Catch Traceability Systems. It is key to note that each of these initiatives identified impacts different societal sectors, showing that the prioritization of initiatives isn't limited within one impact area across society.

4.3.5 Results: Economic Growth

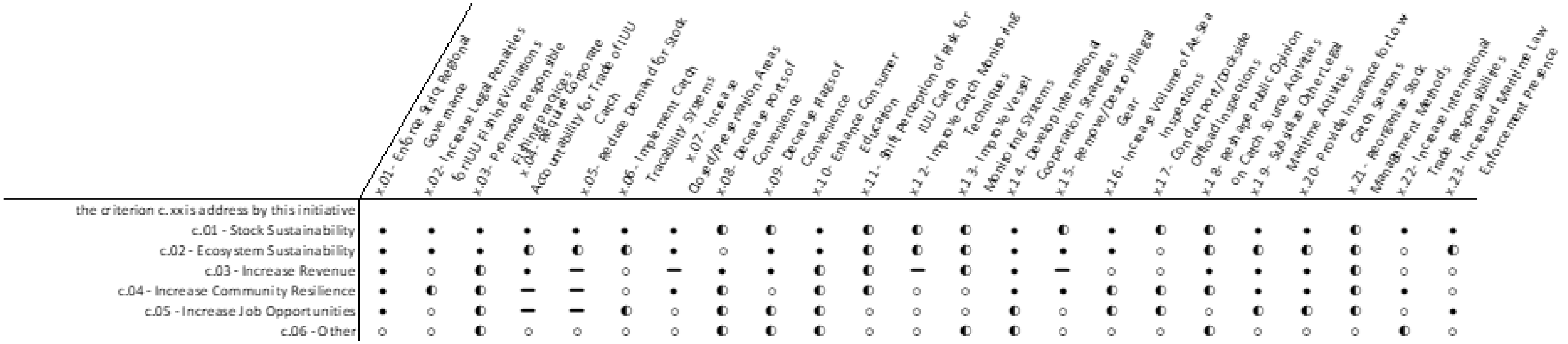
The first analysis conducted using this method was completed using the law enforcement perspective. The IUU fisheries scenario can be analyzed from various stakeholder perspectives using the same methodology. It is important to conduct this type of analysis using multiple perspectives as the stakeholder preferences will change the system goals (Criteria (C)) in each analysis.

To highlight the significance of stakeholder variance in perspective for decision-making, a second assessment of the same scenario is conducted. The new perspective is one that focuses on Economic Growth. A new perspective is assessed by the risk enterprise tool through the lens of the previously described initiatives, emergent conditions, and disruptive scenarios. This ensures that the evaluation tools, such as policies, assets, or future projects, being considered are the same for all stakeholder perspectives being assessed. The new Criteria for a perspective focused on economic growth are included in Table 4.6.

Table 4.6: Criteria (system goals) for decreasing IUU fishing from an economic growth perspective.

Index	Criterion	Source
c.01	Stock Sustainability	Vince et al., 2020
c.02	Ecosystem Sustainability	Vince et al., 2020
c.03	Increase Revenue	Vince et al., 2020
c.04	Increase Community Resilience	He et al., 2022
c.05	Increase Job Opportunities	He et al., 2022
c.06	Other	

Stakeholder input would be utilized to determine the degree to which the entities involved agreed with the initiatives and their alignment with the stated Criteria from Table 4.6. The results of this assessment would be from the same Initiatives identified in Table 4.2. Cross-correlation of the previous Initiatives with the new Criteria results in a new Criteria-Initiative (C-I) Table for this perspective, provided in Figure 4.7.



	x.01 - Enforce Strict Regional Governance	x.02 - Increase Legal Penalties for IUU Fishing Violations	x.03 - Promote Responsible Fishing practices	x.04 - Require Corporate Accountability for Trade of IUU Catch	x.05 - Reduce Demand for Stock	x.06 - Implement Catch Traceability Systems	x.07 - Increase Closed/Preservation Areas	x.08 - Decrease Ports of Convenience	x.09 - Decrease Flags of Convenience	x.10 - Enhance Consumer Education	x.11 - Shift Perception of Risk for IUU Catch	x.12 - Improve Catch Monitoring Techniques
the criterion c.xx is address by this initiative												
c.01 - Stock Sustainability	●	●	●	●	●	●	●	◐	◐	●	◐	◐
c.02 - Ecosystem Sustainability	●	●	●	◐	◐	◐	●	○	●	●	◐	◐
c.03 - Increase Revenue	●	○	◐	●	—	○	—	●	●	◐	◐	—
c.04 - Increase Community Resilience	●	◐	◐	—	—	○	●	◐	○	◐	◐	○
c.05 - Increase Job Opportunities	●	○	◐	—	—	◐	○	◐	◐	◐	○	○
c.06 - Other	○	○	◐	○	○	○	○	◐	◐	◐	○	○

	x.13 - Improve Vessel Monitoring Systems	x.14 - Develop International Cooperation Strategies	x.15 - Remove/Destroy Illegal Gear	x.16 - Increase Volume of At-Sea Inspections	x.17 - Conduct Port/Dockside Offload Inspections	x.18 - Reshape Public Opinion on Catch Source Activities	x.19 - Subsidize Other Legal Maritime Activities	x.20 - Provide Insurance for Low Catch Seasons	x.21 - Reorganize Stock Management Methods	x.22 - Increase International Trade Responsibilities	x.23 - Increased Maritime Law Enforcement Presence
the criterion c.xx is address by this initiative											
c.01 - Stock Sustainability	◐	●	◐	●	◐	◐	●	●	◐	●	●
c.02 - Ecosystem Sustainability	◐	●	●	●	○	◐	◐	◐	◐	○	◐
c.03 - Increase Revenue	◐	●	—	○	○	●	●	●	◐	○	○
c.04 - Increase Community Resilience	○	●	●	◐	◐	◐	●	●	◐	●	○
c.05 - Increase Job Opportunities	○	◐	○	◐	◐	○	◐	◐	◐	○	●
c.06 - Other	◐	◐	○	○	○	◐	○	○	○	◐	○

Figure 4.7: Criterion-Initiative (C-I) Assessment Table for Economic Growth perspective. Strongly Agree is represented by a filled circle, Agree is represented by a half filled circle, Somewhat Agree is represented by an unfilled circle, and Neutral is represented by a dash.

The Emergent Conditions and Scenarios formed from those conditions would remain the same when assessing a new perspective against the same criteria. Thus, the next step in enterprise risk assessment is to identify the priority initiatives and the disruptive scenarios from the perspective of focusing decision-making principles on economic growth. The initiative prioritization chart is included in Figure 4.8 and the disruptive scenarios are identified in Figure 4.9.

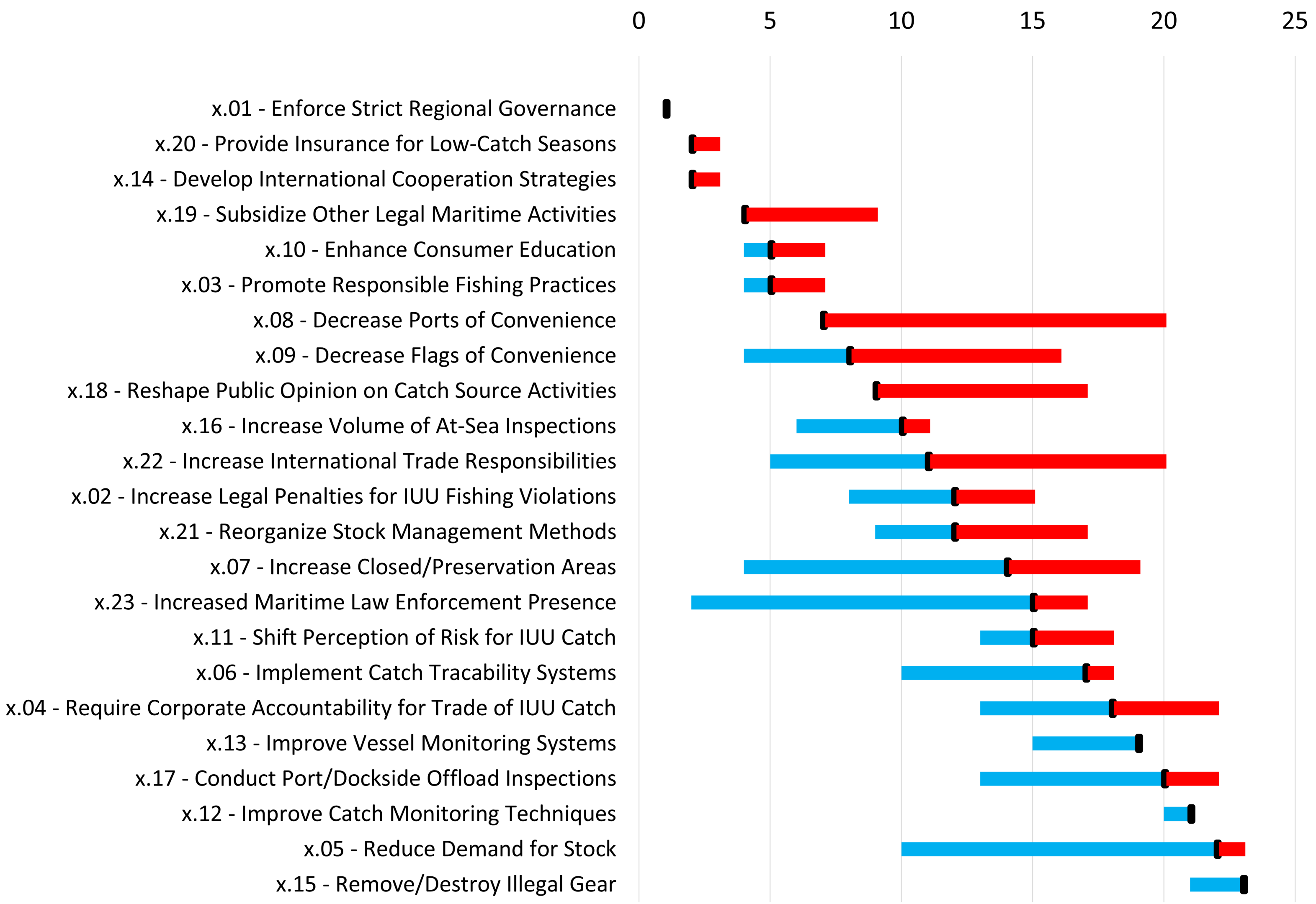


Figure 4.8: Ranking of initiatives priority across enterprise including disruptive scenario effects.

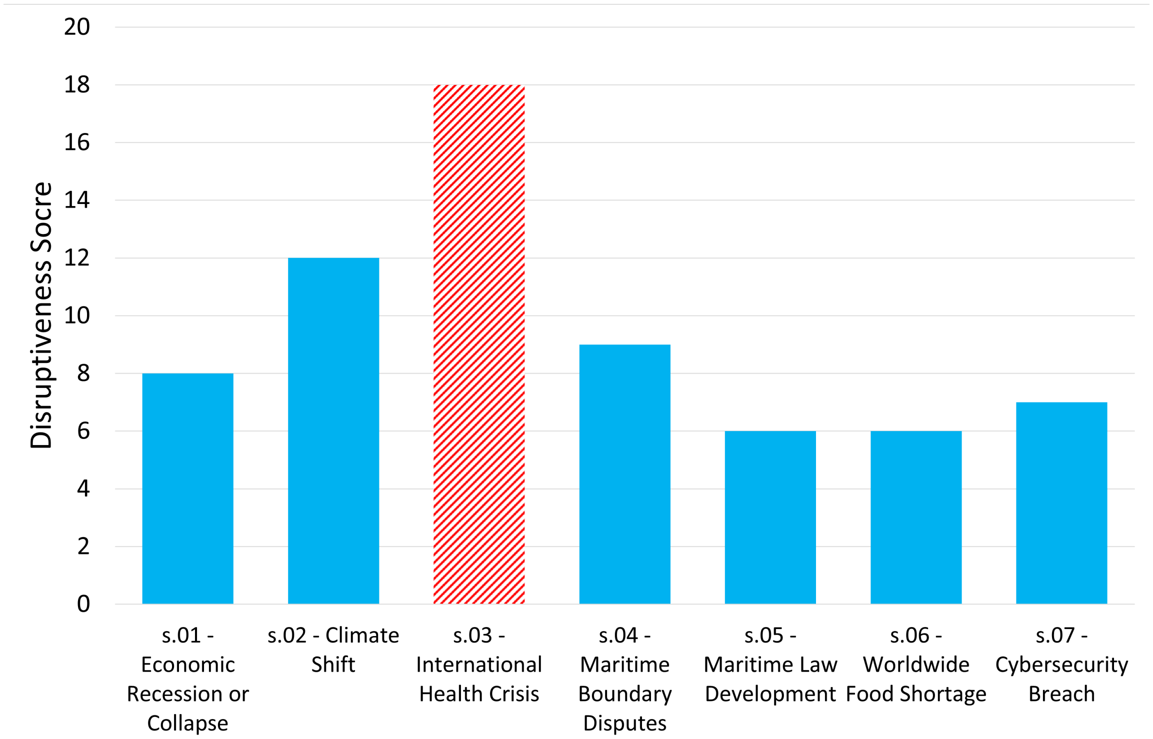


Figure 4.9: Disruptive scenarios ranking for enterprise analysis of IUU fishing from the perspective of economic growth.

From the new perspective of focusing on economic growth when making policies to deter IUU fishing, new priority initiatives emerge. In this scenario, the initiative *x.01* Enforce Strict Regional Governance is the highest priority initiative in all scenarios with the top baseline weight that is unaltered by disruptive scenarios. Initiative *x.15* Remove/Destroy Illegal Gear is still the least strategic initiative because its impact does not have a significant effect in the status, nor does it increase as a strong objective due to disruptive scenarios. Initiative *x.12* Improve Catch Monitoring Techniques follows a similar pattern. Other initiatives that increase in priority with the disruption caused by the highlighted scenarios are *x.23* Increased Maritime Law Enforcement Presence, *x.07* Increase Closed/Preservation Areas, *x.22* Increase International Trade Responsibilities, and *x.05* Reduce Demand for Stock. It is key to note that, again, these initiatives identified impacts different societal sectors, showing that the prioritization of initiatives isn't limited within one impact area across society.

4.4 Summary

Comparing the results of the enterprise risk analysis provides critical details as to the necessity of incorporating stakeholder perspectives in decision-making processes. Table 4.7 and Table 4.8 shows the criteria importance from each perspective.

Table 4.7: Baseline Scenario relative importance of Criteria for an Enforcement Agency regarding the deterrence of IUU fishing.

p.01 Enforcement Agency		
the criterion *c.xx* has	-	relevance among the criteria
c.01 - Stock Sustainability has	high	relevance
c.02 - Ecosystem Sustainability has	medium	relevance
c.03 - Decrease Threats to National Security has	high	relevance
c.04 - Reduce Levels of IUU Fishing has	high	relevance
c.05 - Reduce Prevalance of Other Maritime Crime has	medium	relevance
c.06 - Enhanced International Maritime Cooperation has	low	relevance
c.07 - Other has	medium	relevance

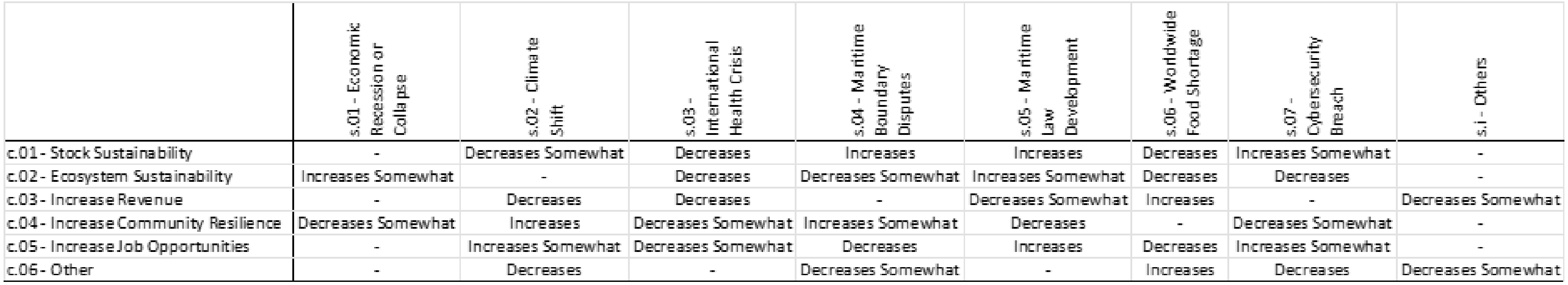
Table 4.8: Baseline Scenario relative importance of Criteria for Economic Growth regarding the deterrence of IUU fishing.

p.02 Economic Growth		
the criterion *c.xx* has	-	relevance among the criteria
c.01 - Stock Sustainability has	high	relevance
c.02 - Ecosystem Sustainability has	medium	relevance
c.03 - Increase Revenue has	medium	relevance
c.04 - Increase Community Resilience has	low	relevance
c.05 - Increase Job Opportunities has	medium	relevance
c.06 - Other has	high	relevance

An interesting note from the comparison between Table 4.7 and Table 4.8 is that despite having different objectives, some of the goals within the perspectives align. Additionally, the Scenario importance with regard to the Criteria also adjusts based on the disruptiveness of each scenario. These comparisons can be seen in Figure 4.10 and Figure 4.11.

p.01 Enforcement Agency	s.01 - Economic Recession or Collapse	s.02 - Climate Shift	s.03 - International Health Crisis	s.04 - Maritime Boundary Disputes	s.05 - Maritime Law Development	s.06 - Worldwide Food Shortage	s.07 - Cybersecurity Breach
c.01 - Stock Sustainability	-	-	Increases	-	-	-	-
c.02 - Ecosystem Sustainability	Increases	-	-	Increases Somewhat	Increases	Increases	-
c.03 - Decrease Threats to National Security	Decreases Somewhat	Decreases Somewhat	Decreases	-	-	Increases Somewhat	-
c.04 - Reduce Levels of IUU Fishing	Increases	-	Decreases Somewhat	-	Increases Somewhat	-	Increases Somewhat
c.05 - Reduce Prevalance of Other Maritime Crime	-	Increases	Decreases	-	Increases Somewhat	Increases	Decreases
c.06 - Enhanced International Maritime Cooperation	Increases	Increases Somewhat	Increases Somewhat	-	Decreases Somewhat	Decreases Somewhat	-
c.07 - Other	-	-	Increases	-	Increases	Increases Somewhat	-

Figure 4.10: Baseline criteria relevance from the Enforcement Agency perspective shifts according to disruptive impacts of scenarios.



	s.01 - Economic Recession or Collapse	s.02 - Climate Shift	s.03 - International Health Crisis	s.04 - Maritime Boundary Disputes	s.05 - Maritime Law Development	s.06 - Worldwide Food Shortage	s.07 - Cybersecurity Breach	s.i - Others
c.01 - Stock Sustainability	-	Decreases Somewhat	Decreases	Increases	Increases	Decreases	Increases Somewhat	-
c.02 - Ecosystem Sustainability	Increases Somewhat	-	Decreases	Decreases Somewhat	Increases Somewhat	Decreases	Decreases	-
c.03 - Increase Revenue	-	Decreases	Decreases	-	Decreases Somewhat	Increases	-	Decreases Somewhat
c.04 - Increase Community Resilience	Decreases Somewhat	Increases	Decreases Somewhat	Increases Somewhat	Decreases	-	Decreases Somewhat	-
c.05 - Increase Job Opportunities	-	Increases Somewhat	Decreases Somewhat	Decreases	Increases	Decreases	Increases Somewhat	-
c.06 - Other	-	Decreases	-	Decreases Somewhat	-	Increases	Decreases	Decreases Somewhat

Figure 4.11: Baseline criteria relevance from the Economic Growth perspective shifts according to disruptive impacts of scenarios.

In these comparisons, it is easy to see how some scenarios impact the system objectives differently.

Despite the differences in the outcome objectives for the system, the feedback from the analysis can identify some initiatives that align well with the system goals for multiple parties. A summary table of the various initiatives and scenario importance for building resilience into the system enterprise is provided in Table 4.9. Initiative *x.2* is a top priority and a resilient initiative from both perspectives. Initiative *x.16* aligns as an initiative that builds system resilience in both scenarios as well. This information can be useful for finding balance in meeting stakeholder objectives.

Table 4.9: Summary of Resilience for Initiatives organized by scenario perspective. Best Initiative(s) are those that are on or near the baseline value (1) and do not decrease in priority by more than 5 during disruption. Resilient Initiatives (s) are those that rise in importance more than decrease in relevance during disruptive scenarios. The most disruptive and least disruptive are the scenarios that have the most and least effect on the overall system risk or Initiative prioritization if it occurred.

	P1: Enforcement Agency	P2: Economic Growth
Best Initiative(s)	*x.14, x.23, x.10, x.02*	*x.01, x.20, x.04*
Resilient Initiative(s)	*x.16, x.03, x.22, x.17*	*x.16, x.02, x.23, x.21*
Most Disruptive Scenario(s)	*s.02, s.04*	*s.03*
Least Disruptive Scenario(s)	*s.07*	*s.05, s.06*

While some of the initiatives do not align directly with the alternative view points, several are relative to the same impacted domain area. For example, prioritizing Initiative *x.02* Increase Legal Penalties for IUU Fishing Violations also influences *x.03* Promote Responsible Fishing Practices. It is also necessary to initiative decisions can be heavily influenced in one aspect or another. The results of this analysis have most of the highest priority initiatives directed toward policy changes in enforcement practices and legal ramifications. While several initiatives focus on environmental policy-related initiatives, they are not the priority in this scenario analysis.

Comparing the results of decision-making support tools and aligning them with the goals of the system is crucial to analyzing the enterprise from a system view. This requires incorporating multiple viewpoints, involving the community and affected public or other entities. Incorporating this methodology into standard practices ensures that resilience goals are known, measurements for success are identified, potential solutions are prioritized, and resilience is inherently being built within the system.

Chapter 5

Discussion

The Enterprise Risk Analysis tool demonstrated in Chapter 4 highlights the need to utilize a systemic perspective when making decisions that cross multiple social domains. As shown in the enterprise system of IUU fishing, each initiative that increases in importance during disruptive scenarios affects another focus area. For example, an environmentally-focused initiative such as *x.07* Increase Closed/Preservation Areas can affect an policy-focused initiative like *x.16* Increase Volume of At-Sea Inspections. Other domains highlighted by the initiatives include social perceptions, education, financial support, and economic focuses.

This risk assessment technique establishes the capability, and necessity, to evaluate the impacts of decisions across domains of a complex system. Identification, interpretation, and prioritization of trade-offs can balance impacts across the entirety of the system. Doing so helps to maintain a stable SES structure that is less vulnerable to disruption and helps a system avoid panarchy and anticommons theory concepts perturbing the balance over time.

These demonstrations were chosen to highlight a high-level systems concept for societal interactions. Though seemingly unrelated, land-use planning and fisheries management influence one another. With the propensity for climate change, specifically increased sea temperatures and salinity, to shift fishery stocks and management techniques, the need to identify and secure alternative sources of food is vital. This drives the requirement to identify agricultural needs and available land to meet food source demands. The interdependence of environmental, economic, and social dynamics reinforces the necessity of providing decision-makers with a variety of effective, transparent, action-oriented tools. Critical analysis and trade-off understanding help to build systemic resilience across domains, as demonstrated in Chapter 4.

Once decisions are made and effects on the system available, the entirety of the systemic resilience framework, described in Chapter 3 can be reapplied and reassessed. As discussed previously, risks and resilience effectiveness are affected by the environment and time frame in which evaluated. Thus, the effectiveness of system resilience practices can shift over time and must be reviewed periodically, creating a cyclical framework application, demonstrated in Figure 3.1. Resilience principles in practice and the tools necessary to understand system dynamics and interconnectedness are critical for incorporating longevity into complex systems, especially those highly vulnerable to negative climate change impacts like Small Island Developing States.

The application of this Framework extends beyond that of Caribbean SIDS. The scalability of the application can be utilized by any nation, region, or community facing similar climate change concerns. The decision-making support tools described and applied in this Framework have proven versatility and effectiveness across a variety of climate change-related initiative prioritization assessments. As such, this Framework and its principles are highly applicable and effective for broad, global applications.

Chapter 6

Conclusions and Summary

The contributions of this thesis include:

1. A Framework for integration of resilience for Small Island Developing States (SIDS) with an emphasis on climate and environmental stressors.
2. Demonstration of scenario-based priority setting regarding prioritization of deterrence methods to abate Illegal, Unreported, and Unregulated (IUU) fishing for SIDS.
3. Plan for future work to extensions of the developed approach to global SIDS and similarly affected regions.

Resilience principles are broadly applicable and can be methodically built into societal systems. Using the framework outlined in this thesis, resilience strengths and gaps can be identified, expanded, or filled depending on the needs of the system being analyzed. The cyclical nature of resilience, caused by environmental and temporal variables, requires that the framework be periodically assessed to ensure the accuracy of these measurements.

It has been demonstrated through the Enterprise Risk Analysis tool that decision-support tools are critical for policy, asset, and/or initiative prioritization. Incorporating risk analysis tools into decision-making processes ensures that cross-domain risks and impacts are identified and that stakeholder perspectives are understood. The incorporation of these factors helps to build public trust and provides transparency when developing new policies.

The Framework for Resilience Principles holistically addresses systemic risk mitigation processes. By applying the framework to a societal system a deeper understanding of interconnections and overlapping risks can be identified. Temporal measures of resilience can be made to provide a snapshot of societal preparedness for a system shock. Incorporation of both technical and non-technical resilience concepts, including nature-based solutions, social resilience, risk warning systems, and action plans for technology failures show the necessity of a diverse application of resilience principles across a socio-ecological system. Utilizing risk analysis and decision-support tools, such as early land-use planning and enterprise risk assessments, can identify areas of contention between stakeholders and help prioritize actions that align with system goals. Testing the resilience of the system regularly ensures that response actions and system constructs are sufficient to withstand disruptive event impacts or are capable of adapting to find a new balance in recovery from system shocks. The framework must be incorporated in a cycle to maximize its benefits.

Small Island Developing States (SIDS), especially those in the Caribbean, are in unique circumstances regarding societal resilience integration. The relative youth of their governments allows flexibility in policy-making and their interconnectedness in global economics due to technology integration provides many opportunities for growth. However, their geographic location makes these islands highly vulnerable to climate shift impacts. These factors relegate the need for societal resilience integration to be a focus for SIDS.

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