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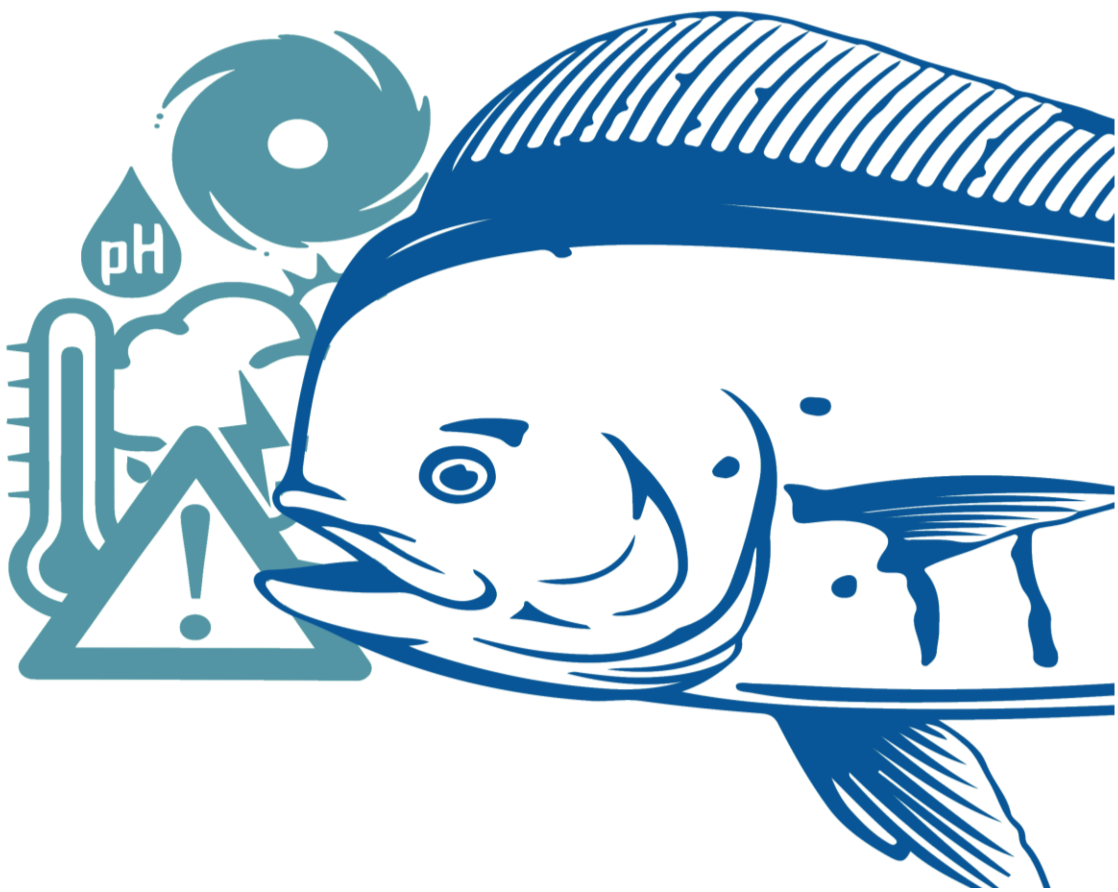
ANALYTICAL TOOLS AND MONITORING GUIDANCE FOR MEASURING CLIMATE CHANGE IMPACTS



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Analytical Tools and Monitoring Guidance for Measuring Climate Change Impacts

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Analytical Tools and Monitoring Guidance for Measuring Climate Change Impacts

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ABSTRACT

Adapting to climate-driven changes in coastal and marine ecosystems and the fisheries they support involves systematic and iterative planning. Abundant generic guidance is available to assist countries, sectors and communities alike with climate change adaptation planning. Yet, implementation of sectoral plans with measurable objectives, targeted actions and broad-based impact is still in early stages. Several reasons account for this, including the limited resources available to invest in detailed assessments to inform high-stakes decisions; the social complexity involved in transparently selecting adaptation measures to implement and weaknesses in capacity to adopt and implement adaptation measures. The *"Fishery-Related Ecological and Socio-Economic Assessments of the Impacts of Climate Change and Variability and Development of an Associated Monitoring System"* project ("the project") produced detailed quantitative ecological and economic climate change impact assessments for Caribbean fisheries as part of the Caribbean track of the Pilot Program for Climate Resilience. These assessments are published as CRFM Research Paper Collection, Volume 9. Assessment results now provide a stronger foundation for a more systematic and informed approach to climate change adaptation planning in the region's fisheries sector. This technical and advisory document represents the second major output of the project and comprises a toolkit to support climate change adaptation planning in the Caribbean fisheries sector. It starts with an overarching framework for adaptation planning, which helps to put the various steps of adaptation in context and points to the links among the tools, options and strategies offered in this document. Chapter B and Chapter C present tools for forecasting future fish-species distributions and economic impacts of climate change, respectively. Both tools featured in a training program delivered to project stakeholders in October 2019. Chapter D proposes a climate-smart monitoring framework for Caribbean fisheries, including guidance on indicators, sampling and data-collection methods pertaining to physical, biological and socio-economic dimensions of socio-ecological systems. Chapter E presents an overview of potential adaptation strategies and measures, organized around three categories of action: (1) habitat management, (2) fishery (harvest) management and (3) sustainable livelihoods and economic diversification. These strategies and measures are a compilation of the most promising adaptation measures currently in use across the globe. Chapter F gives guidance on selecting among alternate adaptation strategies and measures and Chapter G goes on to explore the use of spatial methods in ecosystem management and adaptation planning. Throughout this document, we stress the importance of linking monitoring data to decisions on adaptation and in this context, the areas in which government and non-government partnerships and cooperation could play vital supporting roles. It thus emphasizes the need to leverage existing programs and partnerships to increase capacity for climate change monitoring and impact reduction in the face of limited adaptation resources.

ACRONYMS AND ABBREVIATIONS

AF	Adaptation Fund
AGGRA	Atlantic and Gulf Rapid Reef Assessment
BQ	Big Question
CANARI	Caribbean Natural Resources Institute
CCCFP	Caribbean Community Common Fisheries Policy
CCRIF	Caribbean Catastrophe Risk Insurance Facility
CCV	Climate Change Vulnerability
CIF	Climate Investment Funds
COAST	Caribbean Oceans and Aquaculture Sustainability Facility
CPUE	Catch Per Unit Effort
CRFM	Caribbean Regional Fisheries Mechanism
DALA	Damage and Loss Assessments
DCRF	Data Collection Reference
EEZ	Exclusive Economic Zone
ENM	Environmental Niche Models
FAD	Fish Aggregating Device
FAO	Food and Agricultural Organization of the United Nations
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
FEWER	Fisheries Early Warning and Emergency Response
GBIF	Global Biodiversity Information Facility
GCF	Green Climate Fund
GDP	Gross Domestic Product
GIS	Geographic Information System
HACCP	Hazard Analysis and Critical Control Point
HSI	Habitat Suitability Index
IFAD	International Fund for Agricultural Development
ILO	International Labour Organization
IMF	International Monetary Fund
InVEST	Integrated Valuation of Ecosystem Services and Trade-offs
IPCC	Intergovernmental Panel on Climate Change
IUU	Illegal, Unreported and Unregulated fishing
LDCF	Least Developed Countries Fund
MarSIS	Marine Resource Space-use Information System
MCA	Multi-Criterion Analysis
MCDA	Multi-Criteria Decision Analysis
MORI	Mona Office for Research and Innovation
MPA	Marine Protected Area
NE	North East
NEPA	National Environmental Policy Act
NGO	Non Governmental Organization
NOAA	National Oceanic and Atmospheric Agency
NPPEN	Non-Parametric Probabilistic Ecological Niche
NRM	Natural Resource Management
NW	North West
OBIS	Ocean Biogeographic Information System
PPCR	Pilot Programme for Climate Resilience
RAPFISH	Rapid Appraisal of Fish
RHI	Reef Health Index
SAU	Sea Around Us

SCCF	Special Climate Change Fund
SE	South East
SIDS	Small Islands Developing States
SMART	Specific, Measurable, Actionable and Time-bound
SST	Sea Surface Temperature
SVG	St. Vincent and the Grenadines
SW	South West
TNC	The Nature Conservancy
UN	United Nations
UNEP	United Nations Environmental Program
UNESCO	United Nations
UNFCCC	United Nations framework Convention on Climate Change
USAID	United States Agency for International Development
WCMC	World Conservation Monitoring Centre
WECAFC	Western Central Atlantic Fishery Commission

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A. Framework for Climate Change Adaptation Planning in Fisheries

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1. INTRODUCTION

This series of technical and advisory documents represents the second major output of the "*Fishery-Related Ecological and Socio-Economic Assessments of the Impacts of Climate Change and Variability and Development of an Associated Monitoring System*" project ("the project"). Funded through the Caribbean Regional Track of the Pilot Programme for Climate Resilience (PPCR), executed by the Mona Office for Research and Innovation (MORI) at the University of West Indies at Mona, Jamaica, and with the Caribbean Regional Fisheries Mechanism (CRFM) as the co-implementer, the project aims to improve availability and use of information for "climate-smart" planning and management in the fisheries and aquaculture sector in the Caribbean. A previous phase of project work focused on ecological and socio-economic assessment of climate change impacts on the fisheries resources and sector in six focal countries (Commonwealth of Dominica, Grenada, Haiti, Jamaica, Saint Lucia and Saint Vincent and the Grenadines).

Effective planning is systematic, iterative and phased: this also applies to adapting to climate-driven changes in coastal ecosystems and the fisheries they support. Abundant general guidance is available to assist countries, sectors and communities alike with adaptation planning. National and local-level measures to reduce climate-related and disaster risks to the sector and to increase the resilience of fisherfolk are already underway (Oxenford and Monnereau, 2018), with many more identified in national adaptation plans and strategies (Government of Saint Lucia, 2018). Caribbean islands are increasingly active in sharing knowledge and contributing to developing good practice on adaptation planning through fora such as the National Adaptation Planning Global Network.

Yet, implementation of sectoral plans with measurable objectives, targeted actions and broad-based impact is still in early stages. Scientific information on expected climate conditions, biophysical and social-economic consequences is sophisticated and informative, but forecasts remain uncertain. To navigate uncertainty, adoption of no or low-regrets strategies have proven useful to get started. These are adaptation policies and measures with the potential to yield benefits even if projections about future climate end up being wrong. However, implementation of strategies and measures with transformative impact, of the scope and scale needed to contend with the adverse consequences of rapid climate change, is riskier and the case for action needs to be clear. The level and kinds of assessment that would be ideal to inform decision-making can sometimes exceed the resources available to implement assessment strategies. At the same time, there are numerous options for adaptation, but the process to transparently identify the most promising options can be socially complex, even in cases where political will exists. Additionally, the relevance of addressing adaptation to climate change and disaster risk management together is increasingly in focus (Warner, 2013; UNFCCC, 2017), which brings together communities of practice, policy and research traditionally operating in siloes. Finally, capacity of small island nations to adopt and implement adaptation options is highly variable, with many developing nations expressly stating the need for external finance in their Nationally-Determined Contributions to the global effort under the Paris Climate Agreement.

This series of technical and advisory documents is a toolkit for climate adaptation planning in the Caribbean fisheries sector. But first, we frame these tools within an overarching framework. This framework helps to put the various steps of adaptation in an appropriate context, provides the essential linkage between the tools, options and strategies offered in this document and the overall purpose of management, and facilitates the prioritization of adaptation actions.

2. A FRAMEWORK FOR CLIMATE CHANGE ADAPTATION PLANNING

The overarching framework (Figure 1) we propose is a familiar one, used widely for strategic natural resource management, including climate adaptation in other regions (Stein *et al.*, 2014, Nelson *et al.*, 2016, West *et al.*, 2017), that integrates recommendations from FAO (Poulain *et al.*, 2018). The framework begins by defining the purpose and scope of the planning process. This step sets the context and clarifies what purpose is being served by the process, who will benefit or otherwise be affected, what is the spatial and temporal scope of the process and so on. Next is the key analytical step for a climate adaptation strategy: assessing current and future vulnerabilities and risks from climate change and determining whether climate change-driven effects have in fact occurred. Once an assessment of effects is complete, the framework calls for reflection on the goals and objectives of the process that were identified initially, to determine whether they need to be revised in view of this new knowledge (see Box 1). The development of a comprehensive set of options for adaptation – essentially a list of "what could be done" to adapt to the changes predicted or observed in the assessment phase – follows. The next two steps involve selecting a subset of options from the comprehensive set, based on prioritization of options, the limitations on action imposed by constraints on resources and, conversely, the opportunities that may be available to leverage resources, and then implementing the chosen subset of options. Finally, the framework includes an evaluation stage to gauge the effectiveness of adaptation actions. The process is necessarily iterative, with learning about both actual effects and the performance of adaptation actions informing the next planning cycle.

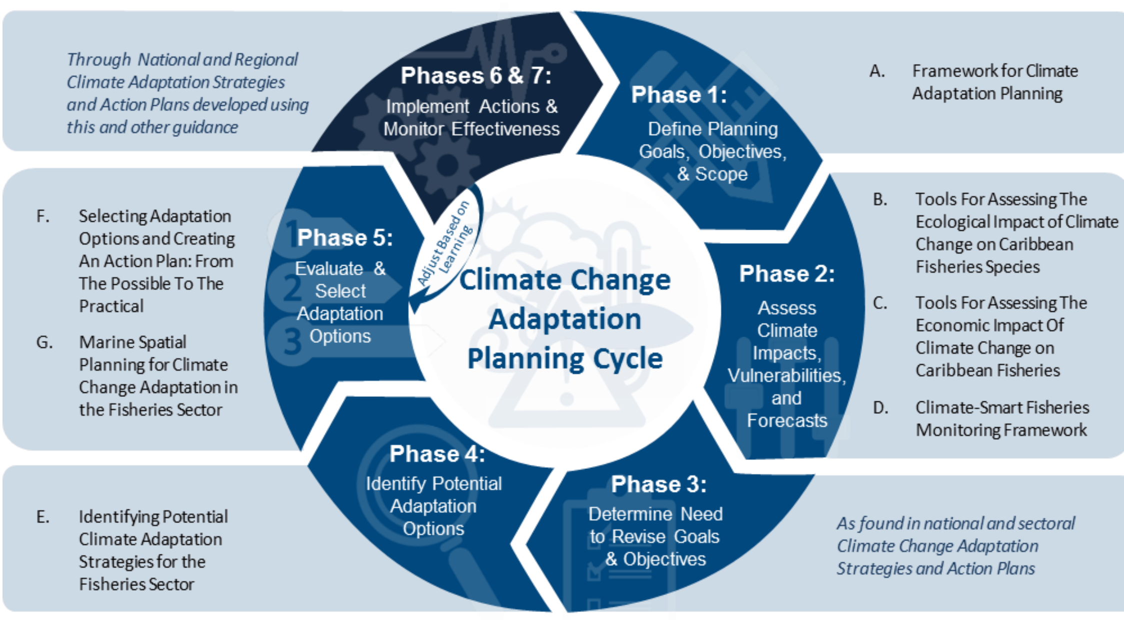

Figure 1: The climate change adaptation planning cycle annotated with the corresponding sections of this report. (Adapted from Nelson et al., 2016)

Box 1: Considerations in scoping the process and setting goals and objectives for climate-smart fisheries

The overall purpose of a climate adaptation process seems self-evident. The aim is to develop and implement a process that provides protection for nations, their citizens, and the fisheries they depend on against potential negative effects of climate change. Adaptation to climate change is a cross-cutting and multi-scale process and defining the scope of adaptation planning and intended outcomes is critical. All good decision-making processes begin by clearly defining the problem, and then agreeing upon a set of objectives that guide choices and provide a basis for assessing performance (Gregory *et al.*, 2012). Questions such as the ones below can help define the purpose and scope for a climate adaptation plan:

- Who is the plan for? Which citizens are vulnerable to either the effects of climate change? Who might benefit from, or be harmed by, actions that could be taken to adapt to climate change? Meaningful stakeholder engagement in developing a strategy / action plan is essential to achieving positive outcomes. This engagement will help to achieve consensus on goals and increase the buy-in of stakeholders, especially those who may have to make short-term sacrifices to achieve long-term benefits.

- What geographic area and time frame will the plan cover? Does it make sense to develop a national plan, or does initial implementation at a smaller scale have advantages, possibly as a "proof-of-concept"? Conversely, there might be adaptation options that would benefit from multi-national cooperation. Are there legal / institutional constraints that suggest a shorter time-frame (i.e., 5 years) would be preferable, at least for the first iteration of the plan?

Translating the overarching goal of "protection…from negative effects" into more specific, means objectives that reflect the adaptation ambitions of stakeholders and decision makers is an important scoping step. Examples of climate change adaptation goals and objectives for climate-smart fisheries are as follows (USAID, 2009):

1. Cumulative non-climate stressors on marine ecosystems are reduced to increase resilience to climate change
2. Critical marine habitats and climate refugia are protected and restored to maintain or strengthen the ecosystem services they provide to the fisheries sector
3. Fisheries harvest is sustainably managed to improve climate resilience
4. Land-based fisheries infrastructure is less exposed and vulnerable to natural hazards
5. Impacts of climate change to human health and safety are minimized
6. Livelihood opportunities are maintained or strengthened in the face of climate change
7. Governance, policy, and planning capacities for climate change adaptation in the fisheries sector are strengthened and decision making process are more inclusive

Aspirational goals and objectives such as these typically derive from a general understanding of the anticipated threats from climate change. A subsequent phase in the adaptation planning process (assessment) yields more detailed and targeted knowledge about the anticipated effects of climate change, prompting a re-evaluation of objectives and their formulation into objectives that are specific, measurable, actionable and time-bound (SMART).

This series of technical and advisory documents is organized around this overarching framework. Chapter B and Chapter C present tools for forecasting future fish-species distributions and economic impacts of climate change. Both tools featured in a training program delivered to project stakeholders in October 2019. Chapter D proposes a climate-smart monitoring framework for Caribbean fisheries, including guidance on indicators, sampling and data-collection methods. Chapter E presents an overview of potential adaptation strategies and measures, organized around three categories of action: (1) habitat management, (2) fishery (harvest) management and (3) sustainable livelihoods and economic diversification. Chapter F gives guidance on selecting among alternate adaptation strategies and measures and Chapter G explores the use of spatial methods in ecosystem management and adaptation planning.

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B. Tools For Assessing The Ecological Impact of Climate Change on Caribbean Fisheries Species

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1. INTRODUCTION

As part of Work Package 1 of this project, the current and future distributions of the selected 110 marine species were modelled using an environmental niche approach (following Hutchinson, 1957). This method quantifies the environmental preferences (e.g., temperature, salinity, dissolved oxygen) of marine species and projects their potential distribution according to present conditions determined by monitoring data and future conditions determined using earth system models projecting forward under different climate change scenarios. Understanding how to use these models would provide regional managers with the ability to update projections of species geographic ranges under future climate scenarios as more accurate input data and earth system models are released.

The purpose of this chapter is to introduce the general concepts underpinning the use of environmental niche models (ENM), also called species distribution models (SDM), and to provide a tutorial for using one of the many ENMs available as an example. The intention is for this tutorial to form the basis of more detailed practical training in this type of modelling to be delivered in-region prior to the conclusion of the project.

2. BACKGROUND CONCEPTS FOR ENVIRONMENTAL NICHE MODELLING

General concepts underpinning environmental niche modelling are expanded upon in two training presentations available for download below:

- Presentation 1: Introduction to Species Distribution Modelling
  This presentation outlines the concepts underpinning species distribution modelling, including environmental niche theory, biological and environmental data types and datasets typically used as inputs, and the open-source statistical software (R) typically used for the modelling itself. The presentation can be downloaded from the CRFM data portal (http://portal.crfm.int/).

- Presentation 2: Introduction to Spatial Data
  This presentation provides additional background information on working with spatial data, as it is the main type of data used in environmental niche modelling. Topics introduced include types of spatial data, coordinate systems, datums and projections, file types and spatial software. The presentation can be downloaded from the CRFM data portal (http://portal.crfm.int/).

3. TUTORIAL USING THE BIOMOD2 MODEL

In Work Package 1, changes in species distributions under future climates were evaluated using a combination of four environmental niche models (ENM): the (1) Bioclim and (2) Boosted Regression

Trees models from the Biomod2 R package (Thuillier *et al*., 2008), (3) Maxent (Phillips *et al*., 2004), and (4) NPPEN (Beaugrand *et al.*, 2011). These models were selected as they are currently the most widely used in the published literature given the type of data accessible for the region (Philips *et al.*, 2004; Thuiller *et al*., 2009).

This tutorial walks readers through an example application of the Biomod2 model using training data for King Mackerel or Kingfish (*Scomberomorus cavalla*) implemented in the open-source statistical programming suite known as R. It requires users to download the R Software (https://www.r-project.org/) and ideally its companion user-friendly user interface R Studio (https://www.rstudio.com/).

The R code that follows and the exercise files for completing the tutorial can be downloaded from the CRFM data portal (http://portal.crfm.int/).

Tutorial R Code

```
########################################################################
#########  Environmental Niche Modelling Tutorial in BIOMOD  ###########
########################################################################

# Produced for Work Package 2 under the Fishery-Related Ecological and
# Socio-Economic Assessments of the Impacts of Climate Change and Variability
# and Development of an Associated Monitoring System commissioned by the
# Caribbean Regional Fisheries Mechanism (CRFM) in 2019

### Step 1 basic line
rm(list = ls()) # remove all past modification on R
graphics.off() # remove all graphic previously done
setwd("~/Desktop/MODELING_SDM") # setting MODELING_SDM as your working directory

### Step 2 - Load Required libraries
# If this is the first time using these libraries, use install.packages(' ')
# with the library name between quotations
library(R.matlab) # Load communication between MatLab file and R
library(robis) # load ROBIS to download the biotic data

### Step 3 - Loading basic database
# load coordinate system of GFDL GRID
COO<-readMat('COO_GRID_VECTOR.mat')
COO<-data.frame(COO)
coord<-COO[,1:2]
COO<-data.frame(coord)

# load Environmental Database
load("~/Desktop/MODELING_SDM/GFDL_ENV_REF_PERIOD_1970_2000_SURF.RDATA")
ENV <- data.frame(ENV_SURF)

### Step 4 - Search occurrence for the species King Mackerel (Scomberomorus cavalla)
ptevol <- occurrence("Scomberomorus cavalla") # downloading all the occurrence of the
species in R from OBIS
LAT<-ptevol$decimalLatitude
LON<-ptevol$decimalLongitude
OBS<-rep.int(0, 259200) # creation of a vector of 0 of the size of the COORDINATE
SYSTEM of GFDL (0.5° from -189.75 to 189.75 of longitude and -89.75 to 89.75 of
latitude) LENGTH <- dim(ptevol)
LENGTH <- dim(ptevol)
LENGTH <- LENGTH[1]

# rasterize all the record from OBIS (vector of longitude LON and latitude LAT) into
the grid from GFDLESM2M (0.5° of resolution)
for (IND in 1:LENGTH) {
```

```
  # find closest  longitude
  difflon<-COO[,1]-LON[IND]
  a<-data.frame(abs(difflon))
  x<-which(a == min(a))
  COO2<-COO[x,]

  #find closest latitude
  difflat<-COO2[,2]-LAT[IND]
  a<-data.frame(abs(difflat))
  x<-which(a == min(a))
  RES<-COO2[x,]

  x<-which(COO[,1] == RES[1,1] & COO[,2] == RES[1,2])

  # putting a confirmed occurence in the grid cell selected
  OBS[x]<-1
}

rm(a, coord, COO2, ptevol, difflat,difflon, IND,x) # cleaning console
```

Step 5 - Preparation of the database for modeling

```
#NA deleted
SUPER <- data.frame(COO,OBS,ENV)
SUPER <- na.omit(SUPER) # removing  all the lines with NA

myRespXY <- data.frame(SUPER[,1:2] )# coordinate with value
myResp <- data.frame(SUPER[,3])# occurrence data
expl.var <- data.frame(SUPER[,4:11]) # environmental variable

rm(SUPER,ENV_SURF)

detach("package:robis", unload=TRUE) #unload ROBIS to avoid conflict with BIOMOD2
library(biomod2) # load BIOMOD2

# Formatting Data for the BIOMOD Envrionmental Niche Model
myBiomodData <- BIOMOD_FormatingData(
  resp.var = myResp,
  expl.var = expl.var,
  resp.xy = myRespXY,
  resp.name = "Null"
)

# summarizing your data
myBiomodData

# preparation for MODEL selection in BIOMOD2 please check on the tutorial to select
the best species distribution model following your data

# Definition of the name of the FILE to save the model
DOC_SAVE <- sprintf('TST_MODEL_BRT_RCP')
```

Step 6 - Creating the fundamental niche

```
myBiomodModelOut<- BIOMOD_Modeling(
  myBiomodData,
  models = c('MARS'), # put the name of the model here : name can be found in BIOMOD2
tutorial of the package
  NbRunEval = 3, # number of run to evaluate the quality of the model (need to be >=
3)
  DataSplit = 95, # percentage of the data use to run the model (here 95% and 5% are
used as pseudo independent set for evaluation)
  Yweights = NULL,
  VarImport = 0  ,
```

```
  models.eval.meth = c('TSS'), # methodology to evaluate the model (here True kill
statistic analysis)
  SaveObj = TRUE,
  rescal.all.models = FALSE,
  do.full.models = FALSE,
  modeling.id = DOC_SAVE,
  silent=TRUE
)


### Step 7 - Evaluation of the model
# summary of the model
myBiomodModelOut
# get all models evaluation
myBiomodModelEval <- get_evaluations(myBiomodModelOut)
myBiomodModelEval
# a model is considered to be a good fit for returned values over 0.75 in Testing.data


### Step 8 - Projection of the niche using the environmental paramaters we used as a
climatology
myBiomodProj <-
  BIOMOD_Projection (
    modeling.output = myBiomodModelOut,
    new.env = expl.var,
    proj.name = 'model',
    selected.models = 'all',
    binary.meth = 'TSS'
)

### Step 9 - Export the data for mapping
DATA<-data.frame(myBiomodProj@proj@val)
EXP<-data.frame(c(myRespXY,DATA))

write.csv2(EXP, file = 'TEST_MODELING.csv', quote = FALSE, na = "NaN")
```

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C. Tools For Assessing The Economic Impact Of Climate Change on Caribbean Fisheries

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1. INTRODUCTION

To estimate the economic impacts of climate-induced changes in fishery production (landings) under Work Package 1 of the project, we used a market supply and demand (S-D) fish model built in Microsoft Excel. The model provides a *partial equilibrium* analysis of economic impacts, which means it only considers the *direct* effect of climate change in a single affected market (e.g., the market for demersal fish). That is, the model does not account for the interactions between the various markets in a given country's economy. This contrasts with a *general equilibrium* analysis, where all markets are simultaneously modelled and allowed to interact with each other.

The market S-D fish model is used to perform comparative statics. In economics, *comparative statics* is used to predict the effects of an externally-driven (exogenous) shock on market outcomes. The exogenous variable shifts either the market demand curve (e.g., due to an increase in income) or the market supply curve (e.g., due to a decrease in fishery productivity). Market outcomes refer to the equilibrium price and the equilibrium quantity in the directly-affected market. Comparative statics involves—as the term suggest—a comparison of the market equilibrium before and after the change in the exogenous variable (i.e., with and without climate change). As such, comparative statics provides a comparison of two combinations of market equilibrium price and quantity.

1.1 Conceptual Framework for S-D Model

The model is based on a standard supply and demand framework, such as that shown in Figure 1. As a starting point, supply and demand curves are estimated for major fish species groupings of interest for a *Base Case* period—denoted by the subscript "0" in panel (a). These data essentially define *Base Case* consumption (Q_0) and price (P_0).

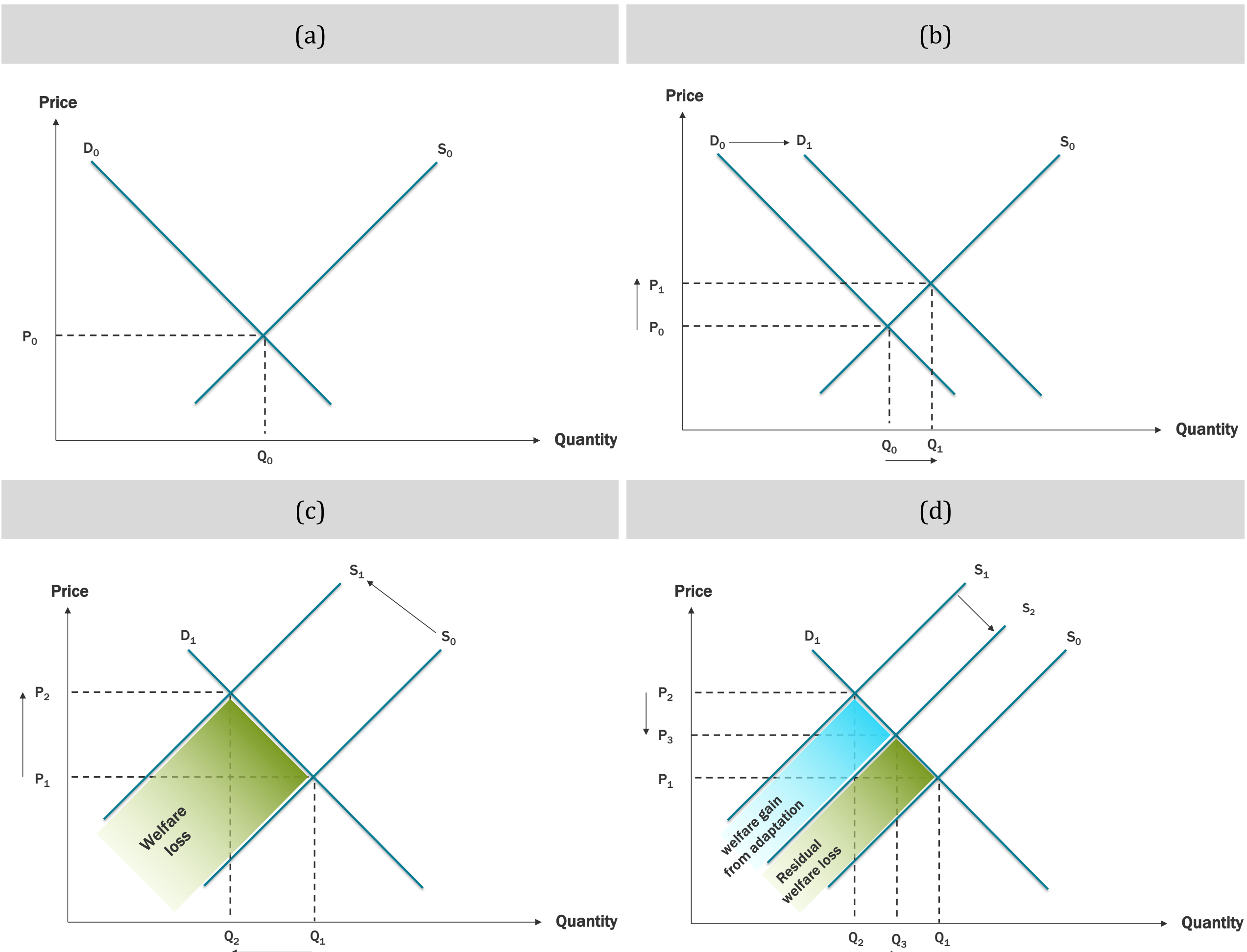
The analysis, in this case, considers two future periods: the medium-term (2035) and the long-term (2055). These future periods are selected to match output of ecological assessments also under Work Package 1 of this project. In the future, the base year period demand curve (D_0) will shift outward due to growth in population and incomes, as indicated by D_1 in panel (b). All else being equal, this shift will result in higher fish consumption ($Q_0 \rightarrow Q_1$) and price ($P_0 \rightarrow P_1$). Future demand curves are estimated for both 2035 and 2055 using the population and income projections.

The new equilibrium (P_1, Q_1) depicted in panel (b), where D_1 intersects S_0, defines the *Reference Case* against which the economic impacts of climate change on fishery production are isolated and measured. The economic impacts of climate change on fishery production are <u>not</u> measured relative to the situation shown in panel (a), namely (P_0, Q_0), since to do so would mix projected consequences of climate change with those due to socio-economic change.

Climate change is introduced into the model through exogenous shocks to the supply curve. Specifically, estimated percentage reductions in base period landings (by main fish species groupings, by climate scenario, and by future time period) obtained from the ecological assessment in Cheung *et al.* (2019), are used to make proportional shifts in the *Base Case* supply curves (S_0). This is shown by the inward shift of the supply curve in panel (c), from S_0 to S_1. Given the new future demand curve (D_1), and all else being equal, the inward shift in the supply curve will result in an increase in fish price ($P_1 \rightarrow P_2$) and a reduction in fish consumption ($Q_1 \rightarrow Q_2$).

Traditional economic welfare analysis can then be applied to measure the resultant welfare losses on the consumer side (as lost *consumer surplus*) and the producer side (as lost *producer surplus*). The aggregate reduction in consumer and producer surplus, indicated by the green shaded area in panel (c), provides a measure of the dollar value of the welfare loss due to climate-induced impacts on fishery production. This in turn provides a benchmark against which to appraise the benefits of adaptation strategies in the sector.

Figure 1: Conceptual framework for market supply-demand model



In addition to estimating the welfare loss attributable to the direct effect of climate change on the market for a fish species grouping, the model can also be used to estimate the welfare gain due to adaptation actions. Panel (d) illustrates how the model can be used to measure the benefits of planned adaptations that target the supply-side of the market, which can then be input to cost-benefit analysis for comparison with the action's costs. Effective fish aggregating devices, for example, could increase fish supply, thereby shifting the supply curve back to the right (from S_1 to S_2), lowering price ($P_2 \rightarrow P_3$) and increasing consumption ($Q_2 \rightarrow Q_3$). The depicted changes will result in a welfare gain, given by the dollar value of the aggregate increase in consumer and producer surplus. Note that when appraising adaptation strategies, the appropriate comparison is between panel (d) and panel (c).

1.2 Key Data Inputs

The market S-D fish model requires the following data inputs for each country of interest:

- For each aggregate fish species group of interest, estimates of total production (tonnes), total exports (tonnes), total imports (tonnes), total non-food consumption (tonnes), and the total value of production (constant US dollars). These data are used to construct a "balance sheet" for each aggregate fish species group, which equates total supply to total demand for a defined *Base Case* period (an average for 2009-2013 is used in the study). Note that all price data in the workbooks are in constant 2010 US dollars[1]. See Appendix A for further details.
- Estimates of the (own price) elasticity of supply, by fish species group of interest (see Box 1 for an explanation of own price elasticities).
- Estimates of the (own price) elasticity of demand, by fish species group of interest.
- Estimates of the income elasticity of demand, by fish species group of interest (see Box 1 for an explanation of income elasticities).
- Population projections covering the future periods of interest (in this study, 2035 and 2055).
- GDP per capita (constant US dollar) projections covering the future periods of interest.[2]
- Projections of the percentage change in *Base Case* production for two climate scenarios (in this study, RCP 2.6 and RCP 8.5) and two future periods of interest, by aggregate fish species group. These data were sourced from the ecological impact assessment (Cheung *et al.*, 2019).

1.3 Main Model Outputs

The following outputs are generated by the market S-D fish model:

- Estimated market supply and demand curves, with estimated equilibrium prices and quantities, for each aggregate fish species group of interest, for the *Base Case*, *Reference Case* and two climate scenarios for two future epochs (seven sets of curves in total).
- For each aggregate fish species group of interest and for all species groups, estimated percentage changes in the **quantity of fish consumed** between the *Reference Case* and two climate scenarios for two future time periods of interest. [Tabular format]
- For each aggregate fish species group of interest and for all species groups, estimated percentage changes in the **price of fish** between the *Reference Case* and two climate scenarios for two future time periods of interest. [Tabular format]
- For each aggregate fish species group of interest and for all species groups, estimated percentage changes and dollar value changes (US$ 000) in **consumer surplus** between the *Reference Case* and two climate scenarios for two future time periods of interest. [Tabular and graphical format]
- For each aggregate fish species group of interest and for all species groups, estimated percentage changes and dollar value changes (US$ 000) in **producer surplus** between the *Reference Case* and two climate scenarios for two future time periods of interest. [Tabular and graphical format]

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[1] A constant dollar value is a value expressed in dollars adjusted for purchasing power (i.e., adjusted for general price inflation).

[2] Projections for per capita GDP are generated from projections of PPP GDP and population. The latter are extrapolated from the United Nations World Urbanization Prospects: The 2018 Revision, which contains observed values over the period 1950-2017 and projected values through 2050. To derive population figures for 2055, the projected population in each country at 2050 is extrapolated to 2050 at the annual average growth rate between 2040 and 2050. The United Nations projected population values are used for 2035. GDP projections are extrapolated from the International Monetary Fund (IMF) Work Economic Outlook 2018 database, which contains observed values over the period 1980-2016 and projected values through 2023. To derive GDP figures for 2035 and 2055 the projected GDP in each country at 2023 is extrapolated to 2055 at the annual average growth rate between 2000 and 2016.

- For each aggregate fish species group of interest and for all species groups, the percentage change in **daily fish consumption** between the *Reference Case* and two climate scenarios for two future time periods of interest. [Graphical format]

Box 1: Demand, income and supply elasticities

Changes in the price (P) of a good (like fish) will lead to changes in the quantity (Q) of it purchased; the price elasticity of demand measures this relationship. Specifically, the own-price elasticity of demand ($\varepsilon_{Q,P}^{D}$) is defined as the percentage change in the quantity demanded in response to a one per cent change in price. In mathematical terms:

$$\varepsilon_{Q,P}^{D}=\frac{\%\Delta Q}{\%\Delta P}=\frac{\frac{\Delta Q}{Q}}{\frac{\Delta P}{P}}=\frac{\Delta Q}{\Delta P}\times\frac{P}{Q}$$

Because P and Q move in opposite directions along a demand curve, $\varepsilon_{Q,P}^{D}$will be negative. For example, a value of $\varepsilon_{Q,P}^{D}$ of -1 means that a 1% rise in price leads to a 1% decline in the quantity demanded. Similarly, a value of $\varepsilon_{Q,P}^{D}$ of -2 means that a 1% decrease in price leads to a 2% rise in the quantity demanded. A distinction is often made among absolute values of $\varepsilon_{Q,P}^{D}$ that are less than 1 (demand is price *inelastic*), equal to 1 (demand is *unit* elastic), or greater than 1 (demand is price *elastic*). In general, if demand is elastic, changes in price affect the quantity demand significantly; if demand is inelastic, changes in price have a negligible effect on the quantity demand.

Another type of elasticity in demand analysis is the income elasticity of demand $\varepsilon_{Q,Y}^{D}$ which measures the relationship between changes in consumer incomes and changes in the quantity demanded. In mathematical terms:

$$\varepsilon_{Q,Y}^{D}=\frac{\%\Delta Q}{\%\Delta Y}=\frac{\frac{\Delta Q}{Q}}{\frac{\Delta Y}{Y}}=\frac{\Delta Q}{\Delta Y}\times\frac{Y}{Q}$$

In the more common case of a *normal good*, $\varepsilon_{Q,Y}^{D}$ is positive, since increases in consumer income lead to increases in the quantity purchased. In the rate case of an *inferior good*, $\varepsilon_{Q,Y}^{D}$ is negative, implying a rise in consumer income leads to a decline in the quantity purchased. Among normal goods, whether $\varepsilon_{Q,Y}^{D}$ is less than or greater than one is important. If $\varepsilon_{Q,Y}^{D}$ is less than 1 for a normal good, then purchases of that good rise more rapidly than consumer income; these are called *luxury goods*. For example, if $\varepsilon_{Q,Y}^{D}$ of a good is 1.5, then a 10% increase in income will result in a 15% rise in purchases of that good. In contrast, if $\varepsilon_{Q,Y}^{D}$ of a good is 0.5, then a 10% increase in income will result in a 5% rise in purchases of that good. According to Engel's law[3] (see, for example, Timmer et al, 1983), most food products, including fish, probably have an income elasticity (much) less than 1. In general, the larger the absolute value of$\varepsilon_{Q,Y}^{D}$, the more responsive purchases are to changes in consumer income.

Changes in the quantity supplied in response to changes in price—at least in the short-term—can be described all along the same lines. The own-price elasticity of supply ($\varepsilon_{Q,P}^{S}$) is defined as the percentage change in the quantity supplied in response to a one per cent change in price. Because P and Q move in the same direction along a supply curve, $\varepsilon_{Q,Y}^{S}$ will be positive. For example, if $\varepsilon_{Q,Y}^{S}$ is 1.5, each 1% rise in price results in a 1.5% increase in the quantity supplied. In this case, the short-run supply of the good is characterized as *elastic*. If, in contrast, a 1% rise in price leads only to 0.5% increase in the quantity supplied, the short-run supply of the good is characterized as *inelastic*.

[3] Specially, Engel's law implies that the proportion of a household's total expenditures on food decreases as their income level rises. This means that the poorer the household, the higher their share of total expenditure spent on food.

1.4 Potential Future Applications

Future applications of the model could consider:

- Sensitivity analysis: testing the sensitivity of the results generated in the current study to changes in key input data. This has not yet been done. The model includes input cells that allow the user to change the following inputs by a fixed percentage (plus or minus): the supply elasticities, the demand elasticities, the income elasticities, the percentage shift in fish supply (production) due to climate change, and projected real income (GDP per capita). The model could be readily modified to allow for a more detailed sensitivity analysis –e.g., differentiating between fish species groups, climate scenarios and time periods.
- Adaptation analysis: estimating the benefits (net welfare gains) of adaptation actions that (partially or wholly) offset the projected percentage shift in fish supply (production) due to climate change. Currently, the model would need to be run with and without adaptation, saved separately, and the outputs assessed 'off-model'. The Microsoft Excel workbook could nonetheless be modified to explicitly integrate the analysis of adaptation actions.
- Extensions of the analysis: this could involve (a) applying the analysis to other countries, (b) applying the analysis to more disaggregated fish species groups, or (c) assessing impacts over long time horizons when there is greater divergence between climate scenarios (e.g., 2080s).

1.5 Caveats

Partial equilibrium analysis—as performed by the market S-D fish model—has several disadvantages that should be borne in mind when interpreting estimated outcomes. Primarily, since the model is only a partial representation of the economy, the analysis only considers a limited number of economic variables. This makes the results sensitive to a few estimated elasticities. In addition, partial equilibrium models will miss important interactions and feedbacks between various economic sectors and factors of production (like labour and capital) that are the basis of general equilibrium analyses. Nonetheless, partial equilibrium models are a valid and accepted tool for economic analysis. By virtue of their simplicity, they are transparent, easy to implement, and the results can be straightforwardly explained. They also have relatively minimal data requirements. This also means that analysis can be performed at a disaggregated (or detailed) level that is neither practical nor possible using general equilibrium modelling framework.

2. USER GUIDE

Separate market S-D fish models (Microsoft Excel workbooks) are available for each case-study country: Dominica, Grenada, Haiti, Jamaica, St. Lucia and Saint Vincent and the Grenadines (SVG). These model workbooks can be downloaded from the CRFM Portal (http://portal.crfm.int/).

2.1 Structure of workbooks

The workbook comprises eight tabs in total:

Tab 1 ("Fishery Market Data Inputs")
Tab 2 ("Economic & Pop. Data Inputs") — Data input tabs
Tab 3 ("Climate Impact Inputs")
Tab 4 ("Base & Ref. Case Calcs.") — Calculation tabs
Tab 5 ("Climate Case Calcs.")
Tab 6 ("Supply & Demand Curves")
Tab 7 ("% Change in Consumption Graphs") — Output tabs
Tab 8 ("Welfare Change Outputs")

To use the workbook, start by entering the required data in Tabs 1-3 (explained below). Tabs 4-5 will perform the necessary calculations for the *Base Case*, *Reference Case* and two climate change scenarios—in effect, implementing the conceptual framework illustrated in Figure 1. Tabular and graphical outputs from the calculations performed by Tabs 4-5 are provided in Tabs 6-8.

2.2 Tab 1: Fishery Market Data Inputs

In this tab you will enter country-specific data relating to the fishery markets of interest. The workbooks are currently set up for five aggregate fish species groups—namely: demersals; tuna & billfishes; other pelagic; other marine; and crustaceans.

In the aggregate fish balance sheet found in cells B4:I9 (an example is shown in Table 1) enter estimates total production (tonnes), total exports (tonnes), total imports (tonnes), total non-food consumption (tonnes), and the total value of production (constant US dollars), for each aggregate fish species group. Data entry cells are highlighted in grey; white cells are calculated. How these data were generated (and thus can be updated) is explained in Appendix I.

Table 1: Aggregate fish balance sheet information: example of Jamaica

		Demersals	Tuna & billfishes	Other palegic	Other marine	Crustaceans	Total
Initial average price	US $ per tonne	2,687	2,832	915	1,119	9,315	16,868
Base year value of landings	US $	30,296,694	77,970	27,137,846	40,712,976	14,245,440	112,470,926
Base year quantity consumed	tonnes	11,276	28	29,658	36,380	1,529	78,871
Base year total produced	tonnes	11,087	59	7,340	12,630	339	31,455
Net trade (-ve = imports)	tonnes	-189	31	-22,319	-23,749	-1,190	-47,415

In the table found in cells B38:E43 (an example is shown in Table 2) enter estimates of the (own price) elasticity of supply, the (own price) elasticity of demand, and the income elasticity of demand, for each aggregate fish species group. Data entry cells are highlighted in grey. How these elasticity estimates were generated (and can be updated) is explained in the accompanying report [Research Paper C: Economic Consequences of Climate Change for the Fisheries Sector in Six Caribbean Countries; Boyd and Ryan, 2019].

Table 2: Elasticity estimates: example of Jamaica

	Supply	Demand	Income
Demersals	0.398	-0.710	0.950
Tuna & billfishes	0.235	-0.540	1.423
Other palegic	0.315	-0.726	0.807
Other marine	0.357	-0.718	0.879
Crustaceans	0.353	-0.820	1.368

You can test the sensitivity of the results to changes in the estimated supply, demand and income elasticity values, by entering % changes in cell C32, C33 and C34, respectively (highlighted in grey). The updated elasticities used in the calculations are generated in the table found in cells B25:E30; the values in the table found in cells B25:E30 are picked up in Tabs 4-5 of the workbook. An example sensitivity test is shown in Table 3, considering a scenario in which all elasticities could be 10% higher or 10% lower than the central estimates.

Table 3: Testing the sensitivity of the elasticity estimates: example of Jamaica

	Supply	Demand	Income
Demersals	0.438	-0.781	1.045
Tuna & billfishes	0.259	-0.594	1.565
Other palegic	0.347	-0.799	0.888
Other marine	0.393	-0.790	0.967
Crustaceans	0.388	-0.902	1.505

Sensitivity analysis:	10.0%	= % change in elasticity supply
Sensitivity analysis:	10.0%	= % change in elasticity demand
Sensitivity analysis:	10.0%	= % change in elasticity income

	Supply	Demand	Income
Demersals	0.358	-0.639	0.855
Tuna & billfishes	0.212	-0.486	1.281
Other palegic	0.284	-0.653	0.726
Other marine	0.321	-0.646	0.791
Crustaceans	0.318	-0.738	1.231

Sensitivity analysis:	-10.0%	= % change in elasticity supply
Sensitivity analysis:	-10.0%	= % change in elasticity demand
Sensitivity analysis:	-10.0%	= % change in elasticity income

2.3 Tab 2: Economic & Pop. Data Inputs

In this tab you will enter country-specific population and gross domestic product (GDP) per capita projections. The workbook is currently set up to accept recorded population and GDP numbers for a *Base Case* (currently set at 2011, which is the mid-point of 2009-2013, used for the fish balance sheets) and projected GDP per capita and population for two future periods (currently set at 2035 and 2055, which corresponds to the climate impact projections). The GDP per capita data is used in conjunction with the estimated income elasticities of demand to estimate future market prices and quantities of fish demanded for the *Reference Case* in 2035 and 2055 (corresponding to the new demand curve, D_1, in Figure 1). Projected population data is used to calculate daily fish consumption per capita.

Data entry cells are highlighted in grey. In cells D18, D19 and D20, enter GDP per capita (in constant US dollars) data for 2011, and 2035 and 2055, respectively (as shown in Table 4). In cells E18, E19 and E20, enter population data (in constant US dollars) for 2011, and 2035 and 2055, respectively. How these values were generated (and can be updated) is explained in the accompanying research paper (Boyd and Ryan, 2019).

Table 4: Socioeconomic data for projecting future fish demand: example of Jamaica

		Income per capita	Population
2011	US $ / capita	8,069	2,828,700
2035	US $ / capita	9,823	2,908,100
2055	US $ / capita	12,421	2,626,600
2011-2035	US $ / capita	1,754	79,400
2011-2055	US $ / capita	4,352	-202,100
2011-2035	% pa	0.8%	0.1%
2011-2055	% pa	1.0%	-0.2%

You can test the sensitivity of the results to changes in projected GDP per capita only, by entering % changes in cell C13 (highlighted in grey). The updated values used in the calculations are generated in the table found in cells B4:E11; the values in this table are picked up in Tabs 4-5 of the workbook. An example sensitivity test is shown in Table 5, considering a scenario in which projected GDP per capita could be 10% higher than the central estimates.

Table 5: Testing the sensitivity of projected GDP per capita: example of Jamaica

		Income per capita	Population
2011	US $ / capita	8,069	2,828,700
2035	US $ / capita	10,805	2,908,100
2055	US $ / capita	13,663	2,626,600
2011-2035	US $ / capita	2,736	79,400
2011-2055	US $ / capita	5,594	-202,100
2011-2035	% pa	1.2%	0.1%
2011-2055	% pa	1.2%	-0.2%
Sensitivity analysis:	10.0%	= % change in assumptions	

2.4 Tab 3: Climate Impact Inputs

In this tab you enter projections of the percentage change in production (landings) for two climate scenarios and two future epochs, by aggregate fish species group. These data are used to generate the new market supply curves, as shown in panel (c) of Figure 1.

In the table found in cells B22:F34 (an example is shown in Table 6) enter estimates of the percentage change in production (landings) for each aggregate fish species group. The workbook is currently set up to accept projected impacts for two climate scenarios (RCP 2.6 and RCP 8.5), and two future epochs for each climate scenario (2035 and 2055). Data entry cells are highlighted in grey. These data are sourced from the ecological impact assessment (Cheung *et al.*, 2019).

Table 6: % change in supply due to climate change: example of Jamaica

	RCP 2.6		RCP 8.5	
	2035	2055	2035	2055
Demersals	-8.7%	-11.2%	-12.0%	-12.3%
Tuna & billfishes	-9.1%	-10.9%	-12.5%	-14.5%
Other palegic	-9.4%	-11.3%	-12.7%	-15.0%
Other marine **	-8.9%	-11.2%	-12.3%	-13.4%
Crustaceans	-10.3%	-12.9%	-13.2%	-12.9%

You can test the sensitivity of the results to projected changes in climate-related impacts on fishery production, by entering % changes in cell C18 (highlighted in grey). Currently, a single sensitivity test (% change) is applied to central projections for all aggregate fish groups, climate scenarios and future epochs. The tab could be modified in the future to enable a more disaggregated sensitivity analysis.

The updated values used in the calculations are generated in the table found in cells B4:F16; the values in this table are picked up in Tab 5 of the workbook. An example sensitivity test is shown in Table 7, considering a scenario in which projected climate change induced reductions in fishery production could be 10% higher than the central estimates.

Table 7: Testing the sensitivity of projected % shifts in fish supply due to climate change: example of Jamaica

	RCP 2.6		**RCP 8.5**	
	2035	2055	2035	2055
Demersals	-9.5%	-12.3%	-13.2%	-13.5%
Tuna & billfishes	-10.0%	-12.0%	-13.8%	-16.0%
Other palegic	-10.3%	-12.4%	-14.0%	-16.5%
Other marine **	-9.8%	-12.4%	-13.5%	-14.7%
Crustaceans	-11.3%	-14.2%	-14.5%	-14.2%
Sensitivity analysis:	10.0%	= % change in shift parameter		

In general, changing any of the input data in Tabs 1-3 will, of course, result in a different set of estimated economic impacts.

2.5 Tab 4: Base & Ref. Case Calcs.

This tab performs all calculations for the Base Case (panel (a) in Figure 1) and the Reference Case (panel (b) in Figure 1), for each aggregate fish species group. For the Reference Case, two separate projections are made; one for 2035 and one for 2055. You do not have to do anything on this tab.

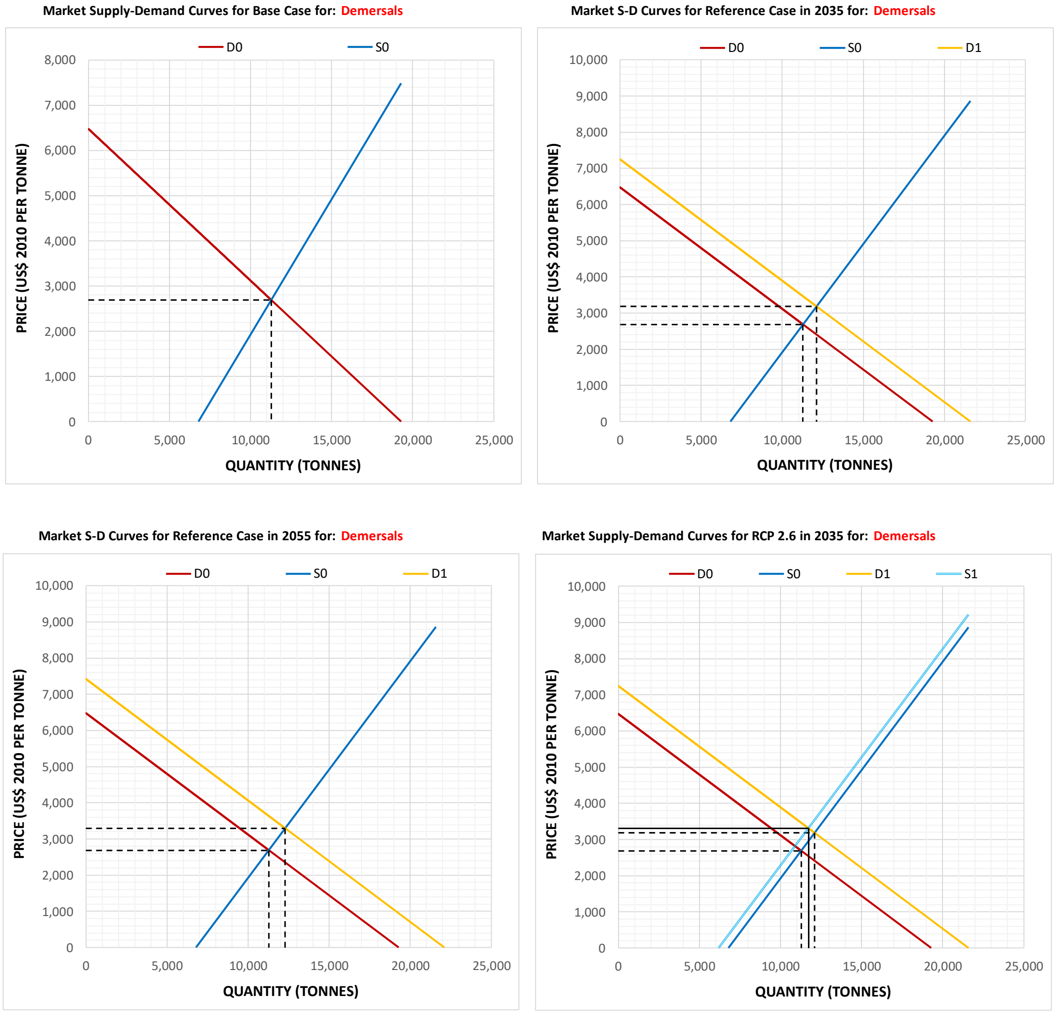
2.6 Tab 5: Climate Case Calcs.

This tab performs all calculations for two climate change scenarios (panel (c) in Figure 1), for each aggregate fish species group. For each climate change scenario, two separate projections are made; one for 2035 and one for 2055. You do not have to do anything on this tab.

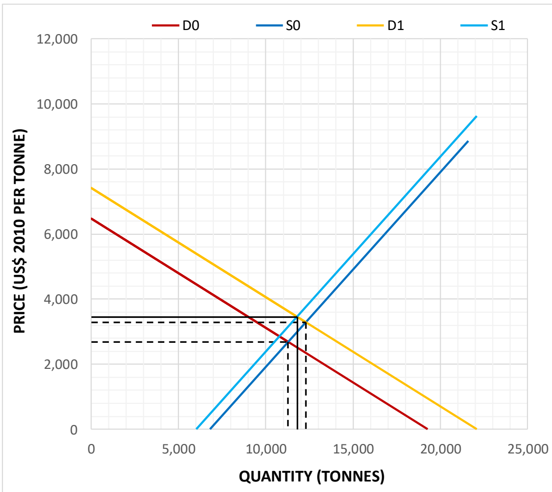
2.7 Tab 6: Supply & Demand Curves

This tab provides the estimated market supply and demand curves, for each aggregate fish species group, for each scenario and future epoch. They are provided primarily to allow the user to illustrate graphically the application of the conceptual modelling framework shown in **Error! Reference source not found.**. The estimated market supply and demand curves available in Tab 6 are shown in Figure 2 for "demersals" for Jamaica. Note that the labels for each estimate supply and demand curve match the notation used in Figure 1.

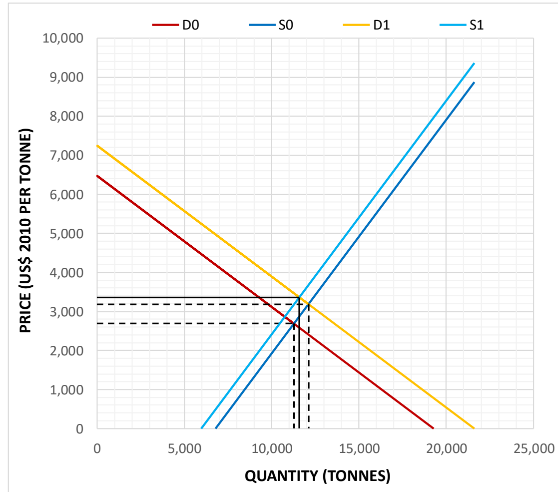
Figure 2: Market supply-demand curves: example of demersals for Jamaica



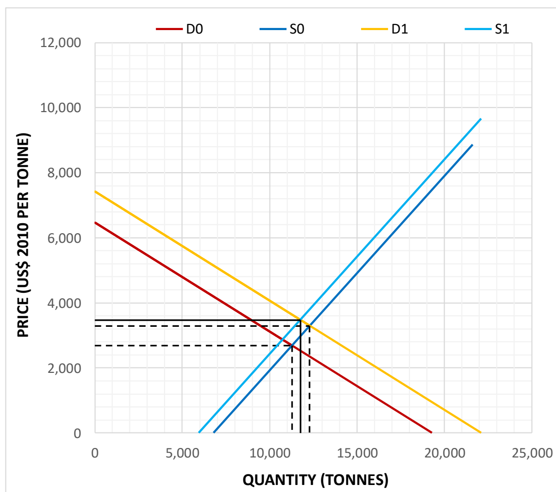
Market Supply-Demand Curves for RCP 2.6 in 2055 for: Demersals



Market Supply-Demand Curves for RCP 8.5 in 2035 for: Demersals



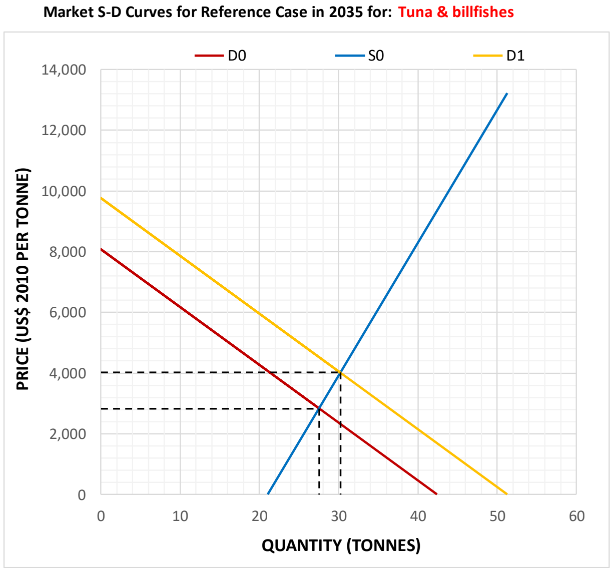
Market Supply-Demand Curves for RCP 8.5 in 2055 for: Demersals

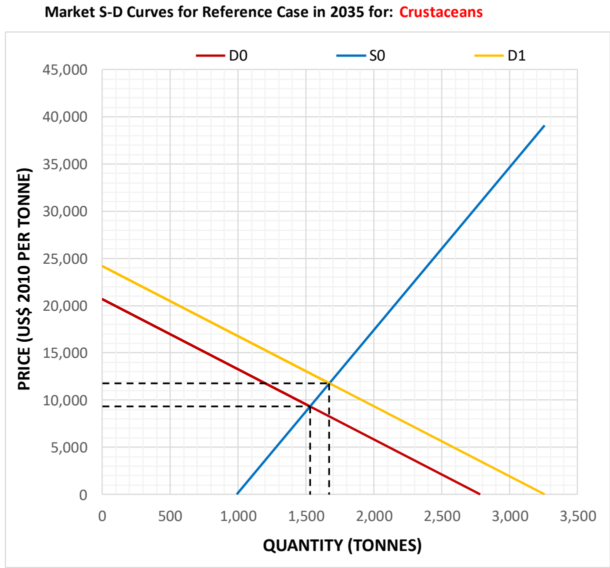


You can change the aggregate fish species group for all seven estimated market supply and demand curves by entering “1” through “5” in cell G2, as shown below:

For:	Demersals	Enter:	1	in:	**1**
	Tuna & billfishes		2		
	Other palegic		3		
	Other marine		4		
	Crustaceans		5		

The graphs will update automatically, as illustrated below when “2” (Tuna & billfishes) and “5” (Crustaceans) are entered in cell G2:

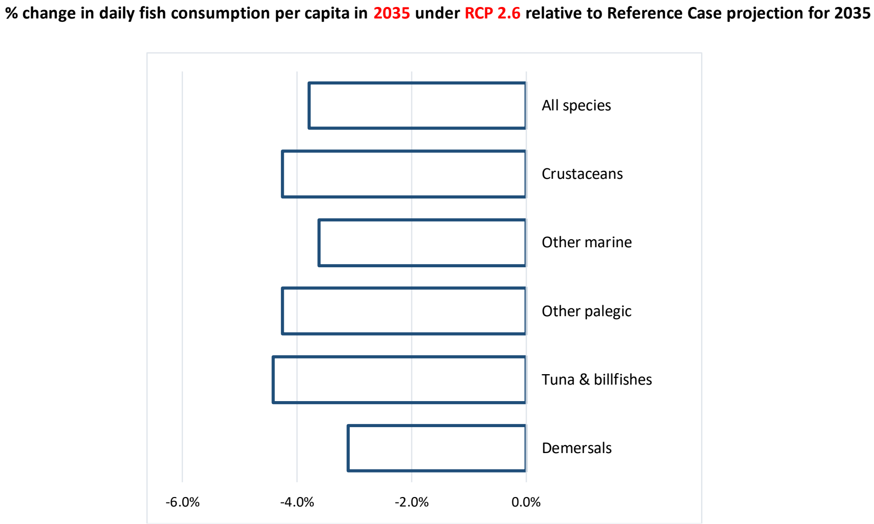




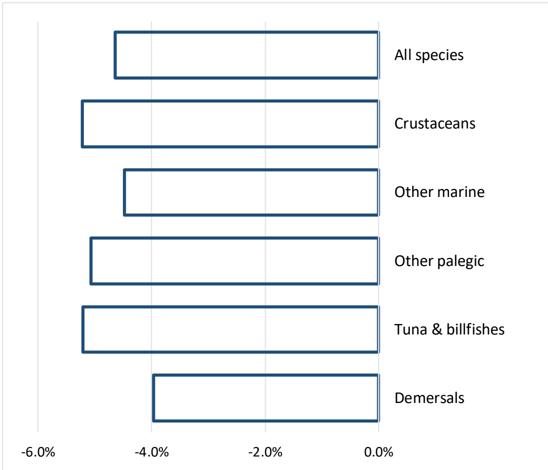
2.8 Tab 7: % Change in Consumption Graphs

This tab provides horizontal bar graphs that show the percentage change in projected daily fish consumption per capita under each of the two climate scenarios for each future epoch, with the change measured relative to the projected Reference Case. Projected daily fish consumption per capita is given by the estimated equilibrium quantity of a fish species demanded divided by projected population. Each graph presents results for each aggregate fish species group, as well as all species collectively, as illustrated in Figure 3 for Jamaica:

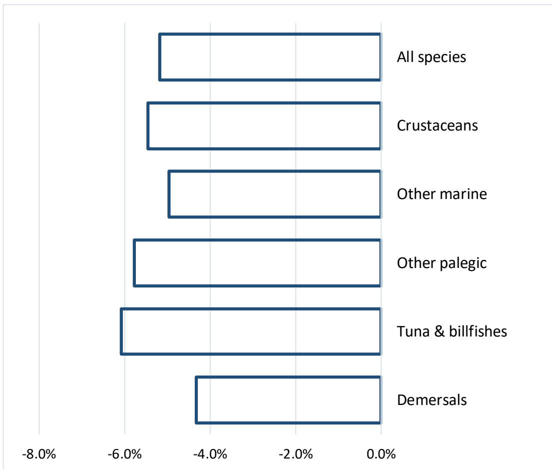
Figure 3: % change in consumption graphs by scenario and epoch: example of Jamaica



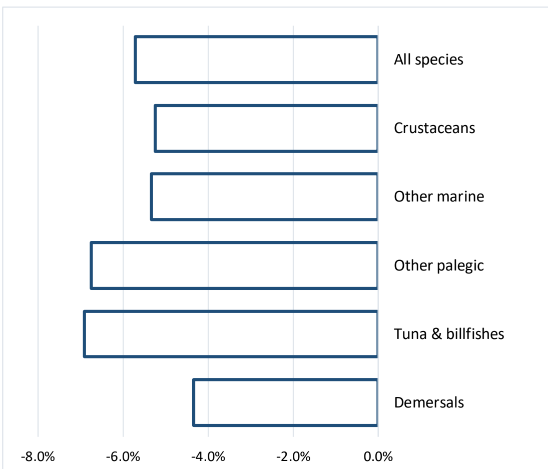
% change in daily fish consumption per capita in 2055 under RCP 2.6 relative to Reference Case projection for 2055



% change in daily fish consumption per capita in 2035 under RCP 8.5 relative to Reference Case projection for 2035

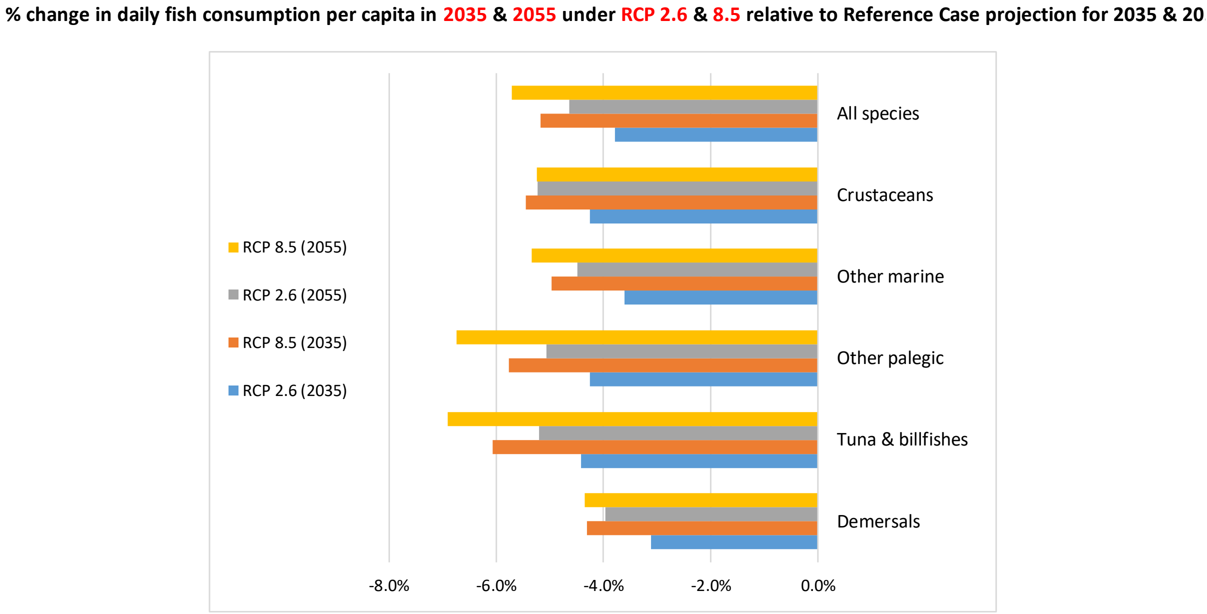


% change in daily fish consumption per capita in 2055 under RCP 8.5 relative to Reference Case projection for 2055



To facilitate comparisons across scenarios, the tab also contains a graph that shows results for both climate scenarios relative to the Reference Case for both future epochs, as illustrated in Figure 4 for Jamaica:

Figure 4: % change in consumption graph for comparison across scenarios and epochs: example of Jamaica



2.9 Tab 8: Welfare Change Outputs

This tab provides summaries of the economic (welfare) impacts estimated by the market S-D model, for each aggregate fish species group and for all species groups collectively.

One table shows the estimated percentage changes in the **quantity of fish consumed** between the Reference Case and two climate scenarios for two future time periods. The estimated Reference Case values are also shown, as illustrated below for Jamaica:

Quantity of fish consumed - % change in Reference Case under Climate Scenarios

	Projected Reference Case (tonnes)		Projected Climate Scenarios			
			RCP 2.6		RCP 8.5	
	2035	2055	2035	2055	2035	2055
Demersals	12,108	12,287	-3.1%	-4.0%	-4.3%	-4.3%
Tuna & billfishes	30	31	-4.4%	-5.2%	-6.1%	-6.9%
Other palegic	31,202	31,529	-4.3%	-5.1%	-5.8%	-6.7%
Other marine	38,660	39,147	-3.6%	-4.5%	-5.0%	-5.3%
Crustaceans	1,671	1,704	-4.3%	-5.2%	-5.4%	-5.2%
All species	**83,672**	**84,698**	**-3.8%**	**-4.6%**	**-5.2%**	**-5.7%**

One table shows the estimated percentage changes in the **price of fish** between the Reference Case and two climate scenarios for two future time periods. The estimated Reference Case values are also shown, as illustrated below for Jamaica:

Price of fish consumed - % change in Reference Case under Climate Scenarios

	Projected Reference Case (US$ per tonne)		Projected Climate Scenarios			
			RCP 2.6		RCP 8.5	
	2035	2055	2035	2055	2035	2055
Demersals	3,185	3,293	4.0%	5.0%	5.5%	5.4%
Tuna & billfishes	4,012	4,281	6.3%	7.1%	8.7%	9.5%
Other palegic	1,066	1,098	5.3%	6.2%	7.2%	8.2%
Other marine	1,316	1,358	4.5%	5.5%	6.3%	6.6%
Crustaceans	11,766	12,320	4.5%	5.4%	5.7%	5.4%
All species	**1,703**	**1,763**	**4.6%**	**5.6%**	**6.3%**	**6.9%**

One table shows the estimated percentage changes in **consumer surplus** between the Reference Case and two climate scenarios for two future time periods. The estimated Reference Case values are also shown, as illustrated below for Jamaica:

Consumer surplus - % change in Reference Case under Climate Scenarios

	Projected Reference Case (US$ million)		Projected Climate Scenarios			
			RCP 2.6		RCP 8.5	
	2035	2055	2035	2055	2035	2055
Demersals	24.6	25.3	-6.1%	-7.8%	-8.4%	-8.5%
Tuna & billfishes	0.1	0.1	-8.6%	-10.1%	-11.8%	-13.3%
Other palegic	20.7	21.1	-8.3%	-9.9%	-11.2%	-13.0%
Other marine	32.0	32.8	-7.1%	-8.8%	-9.7%	-10.4%
Crustaceans	10.4	10.8	-8.3%	-10.2%	-10.6%	-10.2%
All species	**87.8**	**90.2**	**-7.3%**	**-8.9%**	**-9.8%**	**-10.5%**

One table shows the estimated dollar value changes (US$ 000) in **consumer surplus** between the Reference Case and two climate scenarios for two future time periods. The estimated Reference Case values are also shown, as illustrated below for Jamaica:

Consumer surplus - $000 change in Reference Case under Climate Scenarios (2010 prices)

	Projected Reference Case (US$ 000)		Projected Climate Scenarios			
			RCP 2.6		RCP 8.5	
	2035	2055	2035	2055	2035	2055
Demersals	24,600	25,340	-1,510	-1,970	-2,080	-2,150
Tuna & billfishes	90	90	-10	-10	-10	-10
Other palegic	20,690	21,120	-1,720	-2,090	-2,320	-2,750
Other marine	32,020	32,830	-2,270	-2,880	-3,100	-3,410
Crustaceans	10,380	10,780	-870	-1,100	-1,100	-1,100
All species	**87,770**	**90,160**	**-6,370**	**-8,040**	**-8,600**	**-9,430**

One table shows the estimated percentage changes in **producer surplus** between the Reference Case and two climate scenarios for two future time periods. The estimated Reference Case values are also shown, as illustrated below for Jamaica:

Producer surplus - % change in Reference Case under Climate Scenarios

	Projected Reference Case (US$ million)		Projected Climate Scenarios			
			RCP 2.6		RCP 8.5	
	2035	2055	2035	2055	2035	2055
Demersals	30.1	31.4	-1.3%	-1.9%	-2.0%	-2.1%
Tuna & billfishes	0.1	0.1	-0.4%	-0.9%	-0.8%	-1.5%
Other palegic	27.5	28.5	-1.3%	-1.8%	-1.9%	-2.6%
Other marine	40.8	42.5	-1.3%	-1.9%	-2.0%	-2.3%
Crustaceans	15.7	16.6	-2.3%	-3.1%	-3.0%	-3.1%
All species	**114.1**	**119.0**	**-1.5%**	**-2.0%**	**-2.1%**	**-2.4%**

One table shows the estimated dollar value changes (US$ 000) in **producer surplus** between the Reference Case and two climate scenarios for two future time periods. The estimated Reference Case values are also shown, as illustrated below for Jamaica:

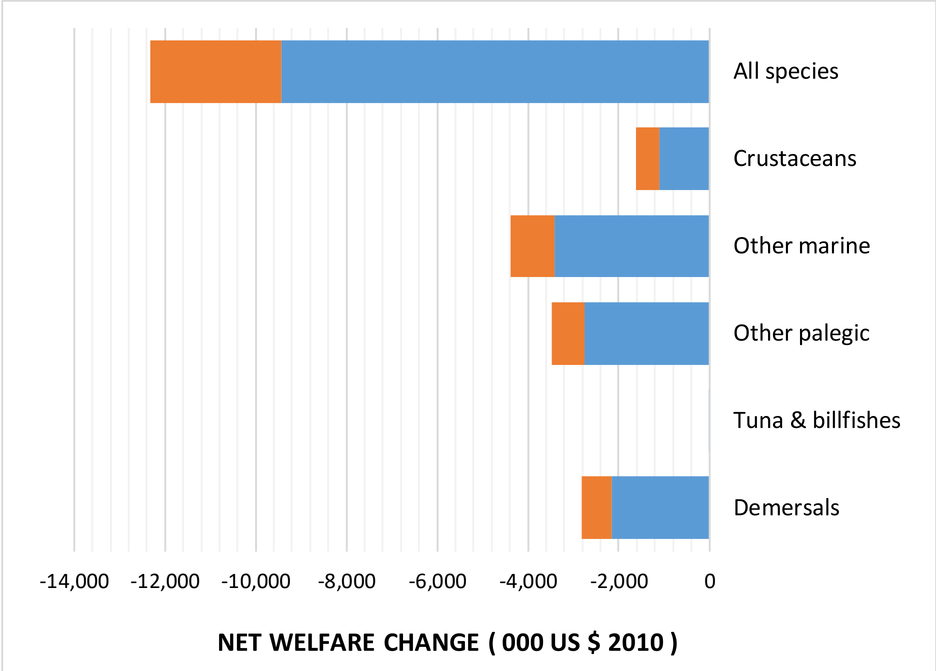
Producer surplus - $000 change in Reference Case under Climate Scenarios (2010 prices)

	Projected Reference Case (US$ 000)		Projected Climate Scenarios RCP 2.6		RCP 8.5	
	2035	2055	2035	2055	2035	2055
Demersals	30,090	31,400	-400	-600	-590	-660
Tuna & billfishes	100	110	0	0	0	0
Other palegic	27,460	28,470	-360	-510	-530	-730
Other marine	40,820	42,450	-540	-790	-800	-970
Crustaceans	15,660	16,590	-360	-510	-480	-520
All species	**114,130**	**119,030**	**-1,670**	**-2,410**	**-2,400**	**-2,890**

This tab also provides four horizontal compound bar graphs that show the estimated net welfare change (in constant US$ 000) for each of the two climate scenarios relative to the projected Reference Case, for both future time periods. Recall, the net welfare effect in a future time period is given by the sum of consumer and producer surplus under a climate scenario less the sum of consumer and producer surplus under the corresponding Reference Case.

By way of illustration, the graph depicting the net welfare effect for Jamaica in 2055 under RCP 8.5 relative to the projected Reference Case in 2055 is shown in Figure 5 (as impacts occur in a single year, they are interpreted as annual average effects); the blue bars indicate the change in consumer surplus and the orange bars indicate the change in producer surplus.

Figure 5: Net welfare impacts estimate by market S-D model: example of Jamaica in 2055 under RCP 8.5



2.10 Incorporating Adaptation Actions

As noted above and illustrated in panel (d) of Figure 1, the market S-D model can be used to assess the benefits (welfare gains) of adaptation actions that (partially or wholly) offset the projected percentage shift in fish supply (production) due to climate change.

In the current version of the Microsoft Excel workbook, the only way to analyze adaptation actions is to:

1. Run the model with projected climate change impacts on fishery production, assuming no additional planned adaptations, and save that version.
2. Estimate—using relevant literature or expert judgement—the percentage reduction or absolute reduction in the parameters used to shift the supply curves (i.e., the % change in production due to climate change) that would be anticipated with a specific adaptation action(s). Also estimate the lifecycle (investment expenditures + annual recurring costs + capital renewal costs + decommissioning costs, where relevant) of the action(s).
3. Re-run the model with the revised % change in fishery production due to climate change (revised downward through the implementation of the adaptation action(s)), all else being equal. Save the revised version.
4. Contrast the results from (3) with those from (1), to estimate the benefits (welfare gains) of the adaptation action(s). That is, the benefits of an adaptation action are given by the sum of producer and consumer surplus in (3) less the sum of producer and consumer surplus in (1).
5. Compare the estimated benefits of the adaptation action(s) with the estimated lifecycle costs of the action to determine its economic merit. Remember, the benefit estimate is an annual average value. Hence, it can only be compared with annualized lifecycle costs.

The Microsoft Excel workbook could, in principle, be modified to explicitly integrate the analysis of adaptation actions, with economic impacts being calculated endogenously.

3. OPERATIONAL CONSIDERATIONS

The market S-D model is a relatively small file (less than 140 KB) and does not run macros. It should therefore run on any basic computer with Microsoft Excel and does not require any specialist computing skills to use. A basic understanding of the economic concepts of market supply and demand curves, equilibrium prices and quantities, supply, demand and income elasticities, and consumer and producer surplus are necessary to interpret the results generated by the model, as well as to explain its underlying analytical framework.

Generating the data inputs is a different matter, however, requiring econometric expertise and specialist knowledge of country-specific fishery datasets (covering production, imports, exports, non-food consumption, and market prices).

Priority improvements to input data and the workbook would include:

- Further validation of the aggregate fish balance sheets;
- Further validation of the elasticity estimates, particularly the own price elasticities of supply;
- Generating and inputting country-specific (EEZ-specific) shift parameters for the market supply curves (data inputs to the “Climate Change Impacts” tab).
- Explicitly incorporating the analysis of adaptation actions, including cost-benefit analysis; and

- Linking the individual markets for each fish species group and adding the capability to perform optimization calculations—specifically, to maximize welfare in a country through production and consumption choices across all fish markets considered.

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APPENDIX I: Data for Aggregate Fish Balance Sheets

The market supply-demand fish model used in the economic analysis requires data for aggregate fish species groups to be structured in a balance sheet, which equates total supply to total demand for a base year period. Each fish balance sheet contains estimates of both the weight and value of fish produced for seven different aggregate fish species groupings. To smooth out the effect of relatively low and high annual values, the fish balance sheets provide multi-year averages for the period 2009-2013. The chosen species groupings are described in Table 8. The choice of grouping is largely practical; the market supply-demand fish model requires trade flow data from the Food and Agriculture Organization (FAO), which is only available for specific aggregate fish groupings. In addition, the model also requires estimates of country-specific supply, demand and income elasticities. Within the scope of this study, elasticities could only be generated for aggregate fish groupings, and not at the level of individual species.

The chosen aggregate fish species groupings are based on the categories used in the FAO statistics, with two exceptions. First, “tuna and billfishes” are split out from other pelagic species, due to the uniqueness of the tuna market (Cai and Leung, 2017). Conversely, data for molluscs (such as oysters) and for cephalopods (such as octopuses) have been combined, due to the relatively low production quantities of these organisms in the case study countries. Furthermore, freshwater and diadromous fish were present at *very* low quantities in the FAO data sets and are thus not included in the fish balance sheets.

Aquaculture data was obtained from the FAO (FAO, 2018). Production data for all other aggregate species groupings was obtained from both the Food and Agriculture Organization (FAO, 2017) and the Sea Around Us (SAU) website data portal (SAU, 2016). The FAO production data is based on officially reported statistics. The reconstructed data available from the SAU website also includes unreported catch (for further details see Zeller *et al*, 2016 and 2018). For this reason, production data provided in the aggregate fish balance sheets is based on SAU data (inclusive of both reported and reconstructed unreported data). Use of SAU data also maintains consistency with the ecological impact assessment (see Cheung, *et al*., 2019), upon which the economic analysis builds.

The production data provided in the aggregate fish balance sheets comprises the sum of artisanal, subsistence and recreational tonnages recorded in the SAU data portal. Catch by national fleets within their corresponding EEZ are included, but not catch by foreign vessels within each EEZ. Estimated discard tonnages are not included. Reported tonnages are “live weight equivalents”.

Table 8: Description of species groups in fish balance sheets

Fish species group	Description	ISSCAPP fish groups
Aquaculture	‘Farmed' marine species raised in contained environments	Various
Demersal fish	Fish that live and feed on or near the bottom of seas, including flatfish, cod, sharks	31, 32, 33, 34, 38
Pelagic - tuna & billfishes	Tuna and billfishes only	36 (excluding perch-likes)
Pelagic – other than tuna & billfishes	Fish that live within the water column, close to neither the top or the bottom, including anchovies, herrings, sardines, but also including “perch-likes” from ISSCAPP 36 (e.g., mackerel, wahoo, cero)	35, 37, 36 (perch-likes only)
Marine fish - other	Unidentified marine fish – includes both demersal and pelagic species	39
Crustaceans	Crabs, lobsters, shrimp	41, 42, 43, 44, 45, 46, 47
Cephalopods & molluscs	Oysters, mussels, octopuses, squids, cuttlefishes	51, 52, 53, 54, 55, 56, 57, 58
Freshwater and diadromous fish	Carp, tilapia, salmon	11, 12, 13, 21, 22, 23, 23, 25

In addition to production data, the balance sheets also contain estimates of the export, import, non-food consumption and total food supply of fish (i.e., consumption) for each aggregate species grouping. Trade flow data for “tuna and billfishes” is not available from the FAO. For the purpose of the fish balance sheets, it is assumed that 100% of artisanal “tuna & billfishes” catch in the SAU data set is exported and 100% of recreational “tuna & billfishes” catch is destined for domestic food supply. It is further assumed that there are no imports of “tuna & billfishes”. These are both assumptions open to question. Total food supply of fish is a calculated variable, equal to production *plus* imports *less* exports *less* non-food consumption. Data for the latter three variables is obtained from the FAO.

The aggregate fish balance sheets also provide information on daily food supply from each fish species grouping (in terms of the daily per capita fish food supply and the edible weight of fish, both on a live weight basis). Total food supply from fish is normalized to average annual population estimates over the period 2009-2013 for each case study country; population information was obtained from the FAO balance sheets (FAO 2017; FAO, 2018). The edible fraction of fish food supply is estimated from daily per capita values using "indicative factors for converting product weight to live weight for a selection of major fishery commodities" from the FAO Handbook of Fishery Statistics (FAO, 1992).

The total value of production is reported in 2010 US dollars. Where necessary, production values were converted to 2010 US dollars using the relevant annual local currency exchange rate per US dollar, as reported in the World Bank World Development Indicators (World Bank, 2018), and local Consumer Price Indices, available from the IMF World Economic Outlook Database (IMF, 2018). Unless otherwise stated, the prices provided in the aggregate fish balance sheets are ‘ex-vessel’ (see Tai *et al.,* 2017), except for aquaculture production, which is based on market prices. Only a single average price can be estimated for aquaculture production, covering all cultured species. No information was reported by the FAO for the import or export of aquaculture production; hence, values are assumed to be zero.

Climate-Smart Fisheries Monitoring Framework

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1. INTRODUCTION

1.1 The Importance of Monitoring for Climate-Smart Fisheries

Adapting fisheries to climate variability and change is an iterative process that requires monitoring (Karp *et al.*, 2018; UNFCCC, 2018; Poulain *et al.*, 2018; FAO, 2013). Monitoring data can help detect changes in real-time (e.g., nutrient levels in water bodies after a record-breaking downpour), understand the contribution of different drivers of socio-ecological change, understand patterns of climate vulnerability or resilience, parameterize and validate predictive models and inform management decisions from local to global scales (see Box 1). Governments in the region are actively engaged in developing and implementing national and sectoral adaptation plans. Discussions on what constitutes effective monitoring and evaluation and what are appropriate indicators to support adaptation progress and performance in nationally-important sectors are integral to these.

Box 1: Types of monitoring

Monitoring informs several phases in climate adaptation planning (Figure 1). In Phase 2, **status and trend monitoring** of physical, habitat, fisheries, and socio-economic indicators provides a broad assessment of climate impacts, vulnerabilities and autonomous responses. In Phase 7, **effectiveness monitoring** supports the evaluation of specific management actions. The broad scale of status and trends monitoring provides insight into spatial and temporal variability enabling the assessment of long-term trends and providing important context to interpret effectiveness monitoring data, which are typically collected on a smaller temporal and spatial scale. For example:

(1) status and trends estimates may be used as a reference for comparison (e.g. pre vs. post condition or control vs. treatment sites);
(2) estimates of natural variability from status and trends monitoring may help to inform the sample effort required for effectiveness monitoring;
(3) status and trends estimates help prevent confounding factors (e.g., gear type) from being mistaken for management action effects.

For the purpose of this report we further divide effectiveness monitoring into two sub-types: (1) **Implementation Monitoring** (which may also include compliance or enforcement) and (2) **Ecological/Socio-economic Effectiveness** (which includes observed environmental and socio-economic outcomes).

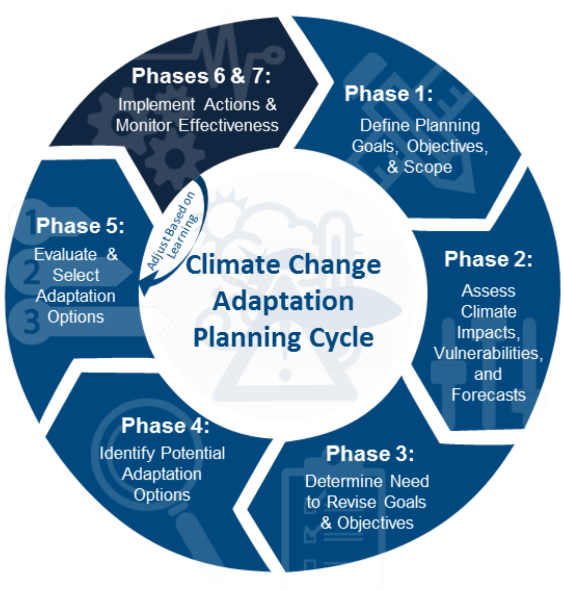

Figure 1: A framework for climate adaptation planning. (Adapted from Nelson et al., 2016)

1.2 Monitoring Change across Socio-Ecological Systems

Mapping and understanding the impact pathways linking climate, ecological and social systems is complex. One way to collate and communicate this understanding is to use conceptual models, which are abstract depictions of a real system that integrate our current understanding of its inter-related components and interactions across components. Management decisions often are taken in a complex multi-actor context and under uncertain circumstances. Thus, to be effective and useful, conceptual models need to rationalize and simplify reality. Figure 2, for example, reflects a subset of impact pathways linking changes in ocean conditions to ecological and socio-economic changes of relevance to Caribbean fisheries. Appendix I contains conceptual models of pelagic and seagrass-mangrove-coral reef ecosystems and fisheries, developed with project stakeholders at the start of the project. These conceptual models shaped assessment priorities (e.g., the climate change impacts analyzed in the economic assessment) and helped identify candidate indicators for monitoring.

Systematic monitoring of key indicators to attain even a basic understanding of risks and opportunities can be beneficial for future planning and management of marine resources and coastal areas. Early identification of climate-induced changes to fish stocks or key habitats can help build a case for enhanced habitat protection and more aggressive harvest limits for vulnerable species. Understanding the relationship between distribution, abundance, and productivity of fish stocks and climate-driven changes to the environment is necessary to predict and effectively manage those changes. Predicting the possible risk exposure of small-scale fishers and fishing communities to the impacts of climate change on target fish species can pave the way for social transitions that may be necessary to build climate resilience.

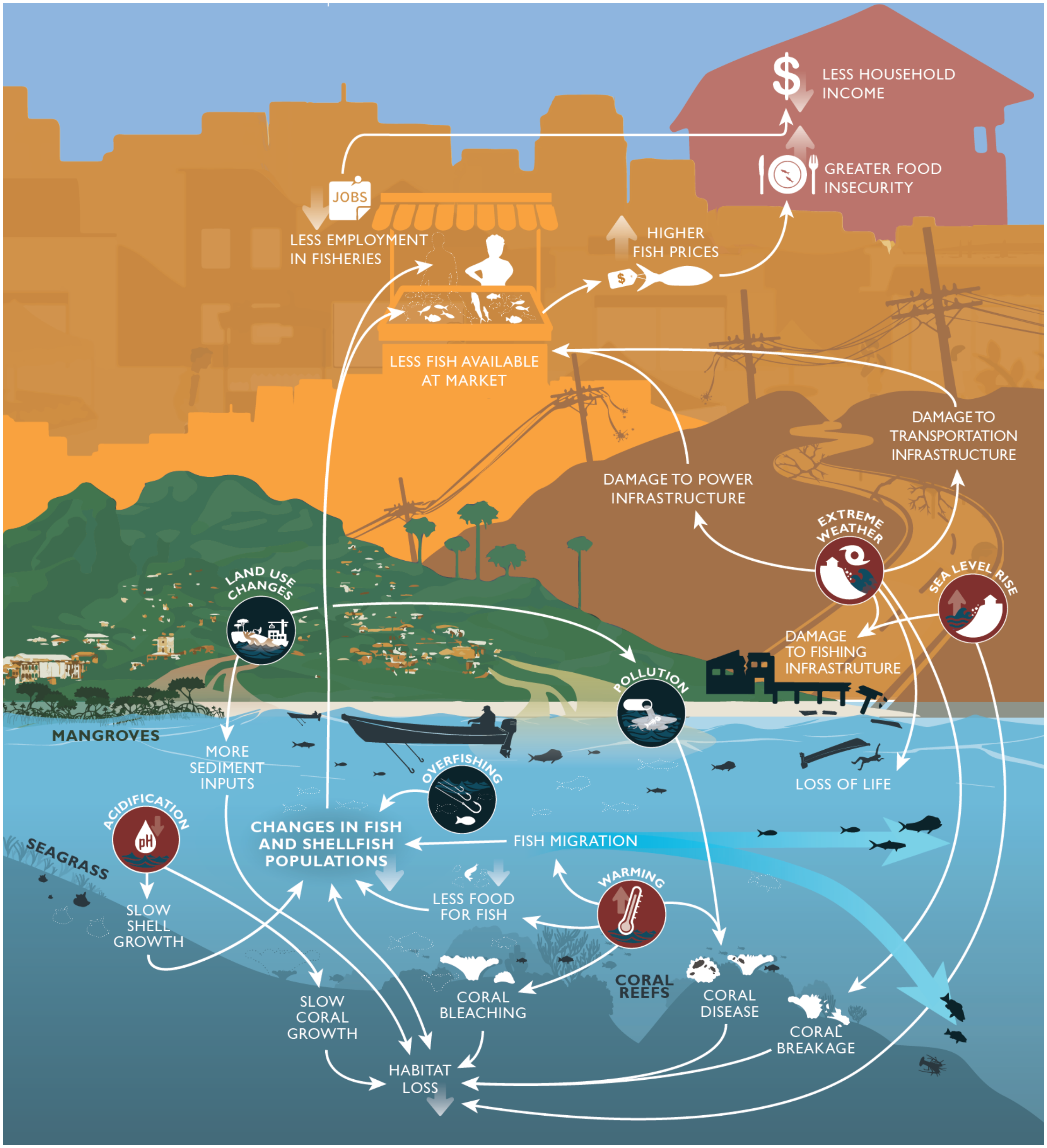

Figure 2: This figure provides a conceptual illustration of a subset of impact pathways linking climate-induced changes in ocean conditions (maroon icons) to ecological and socio-economic changes of relevance to Caribbean fisheries. Climate change and human pressures (navy blue icons) interact to adversely affect the resilience of socio-ecological systems. Note that this illustration does not capture or reflect <u>all</u> the climate change issues of concern to Caribbean fisheries.

1.3 Challenges and Best Practices in Climate-Smart Fisheries Monitoring

Extensive literature exists on fisheries monitoring, climate-induced changes on the marine environment and subsequently fish stocks and generic guidance on selecting indicators to enable climate change adaptation. However, far fewer examples specifically address the challenges of monitoring small-scale fisheries in small-island developing states (SIDS), where the fisheries tend to be multi-gear, multi-species fisheries with limited capacity and where climate adaptation closely linked to sustainable development and poverty alleviation (White *et al*., 2014; Allison *et al*., 2009). MRAG (2010) provides a useful introduction to climate change monitoring for fisheries with application to coastal fisheries in the Pacific. Wongbusarakum and Loper (2011) offer indicators to assess community-level social vulnerability to climate change, as an addendum to regional monitoring guidelines under the Global Socio-economic Monitoring Initiative for Coastal Management. Flower *et al.* (2017) provide a detailed guide for interpreting reef data to inform management decisions. A number of case studies address various components of climate-focused assessment, monitoring or management. Nevertheless, overarching frameworks linking monitoring of fisheries for climate change impacts to management strategies are lacking.

Common challenges in monitoring climate change impacts on fisheries are as follows (MRAG 2010, Doney *et al.*, 2012; Plisnier *et al.*, 2018, Hobday and Evans, 2013; Bates *et al.*, 2014; Carvalho *et al.*, 2016; Gurney and Darling, 2017; White *et al.*, 2014; Jeffers *et al.*, 2019; Monnereau *et al.*, 2017):

- **Spatial and temporal scale.** There is a need to understand large-scale climate processes and how these influence socio-ecological processes at multiple spatial and temporal scales;
- **Confounding effect of harvest.** Fisheries are the nexus of ecological systems and social systems and climate change impacts are confounded by fishing and other anthropogenic pressures such as pollution;
- **Lack of long-term data.** This was one of the most commonly cited shortcomings to understanding and managing effects of climate change;
- **Lack of information at sufficient spatial scales.** There is often insufficient spatial coverage for key biological indicators (e.g., occupancy) and measures of social vulnerability have limited spatial disaggregation;
- **Lack of consistent funding**. Consistent funding is a limitation for any monitoring program but it is particularly challenging when reliant on short-term projects led by non-governmental organization or universities as opposed to long-term national or regional initiatives;
- **Inconsistent methods.** Lack of consistent indicators and data-collection methods limits the utility of the data and limits inferential analysis. In social vulnerability research, improper scaling of socio-economic indicators to account for differences in human population concentration / settlement size can be problematic;
- **Traditional methods not suited to artisanal and small-scale fisheries.** Typical stock assessment methods were developed for large-scale commercial fisheries and may not be applicable to small-scale and multi-species fisheries such as those found in the Caribbean. Another common feature of small-scale fisheries is the fact that the activities are not centralized making it difficult to sample catch.

A number of strategies to address these challenges have emerged, such as those below (Hobday and Evans, 2013; Stein *et al.*, 2014; Karp *et al.*, 2018; Plisnier *et al.*, 2018; Carvalho *et al.*, 2016; White 2014; Jeffers *et al.*, 2019; MRAG 2010; Bates *et al*,. 2014; Larsen *et al.*, 2008; Gurney *et al.*, 2017):

- Link monitoring to management in an adaptive management feedback loop;
- Prioritize affordability. Develop efficient and cost-effective monitoring programs;
- Implement a long-term coarse assessment of a few key parameters;

- Shift from the status quo where a series of short-term uncoordinated projects are implemented with inconsistent methods and gaps in space/time to a low-effort consistent long-term program supplemented by occasional short-term projects (Figure 3);
- Leverage past work. Focus effort where successful monitoring has occurred previously. This is an indication of capacity in addition to providing a useful historical reference point;
- Maximize spatial coverage. Ensuring coverage across various gradients will enable more informative analysis (e.g., highly impacted versus pristine or leading/lagging edges of distributions);
- Seek spatial integration across scales (local, national, regional), which can be facilitated through using a nested sample design within a common sample frame;
- Develop regionally-standardized protocols. This requires regional training, agreement on key questions of interest, integration of data collection and storage, among other success factors.

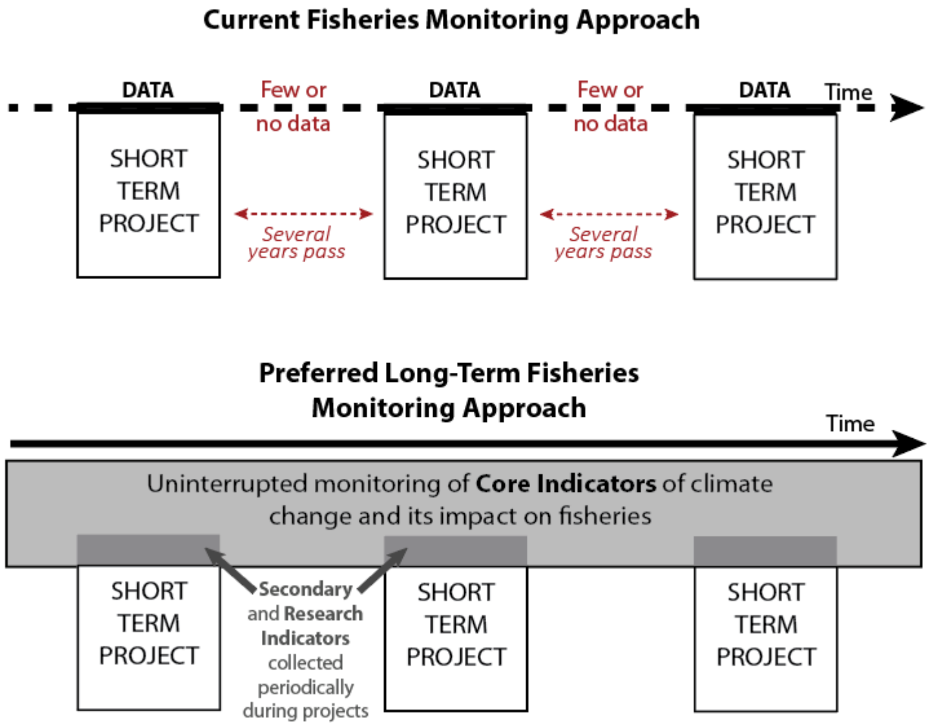

Figure 3: Recommended shift in focus from interrupted short-term monitoring projects to long-term monitoring of a few key parameters supplemented as necessary by short-term projects. (Adapted from Plisnier et al., 2018).

1.4 Objectives and Approach

As part of the "*Fishery-Related Ecological and Socio-Economic Assessments of the Impacts of Climate Change and Variability and Development of an Associated Monitoring System*" project ("the project"), this chapter provides a transparent, flexible and feasible framework to track priority climate, ecological and socio-economic indicators to support climate-smart fisheries management and planning in the Caribbean. We propose a regional framework and toolkit for fisheries managers in case-study countries to adapt and use these resources to suit their needs. Modelling studies on the ecological and economic impacts of climate change on fisheries in six Caribbean islands as well as value chain analysis carried out under this project generated a baseline assessment of projected ripple-effects of climate change and variability to the sector by mid-century. Among other uses, assessments carried out with newly-collected data may strengthen the evidence in the baseline assessment generated through this project.

Our approach to monitoring is consistent with the six steps proposed by MRAG (2010) in their report "Monitoring the Vulnerability and Adaptation of Pacific Coastal Fisheries to Climate Change".

- *Establish a baseline from previous / existing work (Situational Review – Section 2)*
- *Identify monitoring priorities regionally ("Big Questions" – Section 3)*
- Develop qualitative conceptual model to explain linkages among key parameters in climate change, marine ecosystems, fisheries production and consumption (Appendix I provides examples of conceptual models)[4]
- *Identify key indicators (Monitoring Cards – Section 4)*
- *Design survey/sampling approach (Monitoring Cards – Section 4)*
- Establish potential responses to observed changes (Identifying Potential Climate Adaptation Strategies for the Fisheries Sector – Chapter E)

This chapter contains the results of monitoring-related research and consultation with project stakeholders since October 2018, comprising four of the six steps emphasized above (shown in italics font). As with all project activities, our efforts have focused on the following six climate-sensitive: The Commonwealth of Dominica, Grenada, Haiti, Jamaica, Saint Lucia, and Saint Vincent and the Grenadines (SVG).

2. CURRENT STATUS OF FISHERIES MONITORING IN SIX CARIBBEAN NATIONS

This section provides summary profiles of current fisheries monitoring and management in Dominica, Grenada, Haiti, Jamaica, Saint Lucia and SVG. These profiles are a result of three activities undertaken between October 2018 and March 2019. First, we developed questions and parameters to guide the desk-based research. The template we used to capture information on monitoring is in Appendix II. Next, we undertook an intensive literature review for country-specific documentation of monitoring for each of the six case-study countries. Finally, we validated and supplemented individual country profiles using information from interviews with representatives from the fisheries departments of four of the six case-study countries (Dominica, Haiti, Jamaica and Saint Lucia).[5]

Establishing a baseline and identifying strengths and weaknesses of current activities is an important step in monitoring design. Budget is always a limiting factor for monitoring and, therefore, building on historical data, existing protocols, infrastructure and capacities is critical. Table 1 presents summary profiles for each of the six case-study countries. The scope of this review focused on fisheries within the Economic Exclusion Zones and does not address high-seas fleets.

A number of themes emerged from the review of current situations and from feedback received from fisheries officers during a regional training workshop held in St. Lucia in October 2019:

Fisheries Context:

- 4 of the 6 countries are strictly small-scale artisanal fisheries. [6] Jamaica and SVG has both artisanal and semi-industrial fisheries. Grenada is an unusual case where the fishery is largely semi-industrial.

[4] The conceptual models that appear in Appendix 1 are a result of participatory exercises with project stakeholders at the Regional Planning Workshop of the Caribbean PPCR Fishery-Related Ecological and Socio-Economic Impact Assessments and Monitoring System project, Kingstown, St. Vincent and the Grenadines, 25-26 April 2018.

[5] We reached out to representatives from all six case-study countries and succeeded in interviewing representatives from four countries. Each Skype interview lasted 60 minutes, on average. We circulated the draft country profile we had assembled prior to interviews, asked specific clarification questions and provided the opportunity to correct and elaborate on anything in the draft profile. We interviewed Allena Joseph and Patricia Medar (Saint Lucia), Roger Charles (Haiti) and Anginette Murray (Jamaica) on February 7, 2019. We interviewed Derrick Theophille (Dominica) on February 8, 2019. All countries were provided opportunities to comment on this report, including this chapter, both in writing and during a five-day regional training workshop in St. Lucia in October 2019.

[6] Fisheries includes industrial (large-scale, commercial), artisanal (small-scale, commercial), recreational and subsistence (both small-scale, non-commercial) sectors.

- Eastern Caribbean countries report pelagics as the primary fishery (based on % of annual landings).

Enabling Structures:

- International requirements for reporting total landings at the national level drive monitoring decisions. All 6 countries report landings to FAO at the national scale in some form. 4 of the 6 countries have relatively comprehensive catch and effort monitoring programs including a sample of landing sites at least once per month. Grenada uses a sample of the 6 largest markets, but does not have reliable information on effort. Haiti is the most capacity-limited and only provides a coarse estimate based on total weight.
- All 6 countries have laws or policies in place to enable implementation of management actions including: Marine Protected Areas (MPAs) and regulations (e.g., size, gear, closings). However in all cases there is little (4 countries) to no (2 countries) enforcement.
- Some countries have Fisheries Management Plans.

Decision Making and Learning Culture:

- Most countries report basic summary statistics. Several estimate catch per unit effort (CPUE) or total landings. Only Jamaica and SVG complete any stock assessment.[7]
- In general, monitoring data do not appear to be directly linked to management decisions. There are a few rare exceptions: landings data used to inform development decisions in Saint Lucia and mesh size adjustments in Jamaica. However, evidence of a systematic or formal linkage between monitoring data and management decisions is lacking. In addition, there does not appear to be many cases of effectiveness monitoring used to inform an adaptive learning approach to management. Several FAD studies in Grenada are an exception.

Responsibilities:

- With the exception of Haiti, where NGOs have taken a large role, Fisheries Departments have prime responsibility for fisheries management and monitoring. In a few cases, the Marine Police or Coast Guard are responsible for enforcement.

Assets:

- The total number of staff listed for fisheries management in each country ranges from 12 in Haiti and SVG to 44 in Grenada, although only 16 of these are technical staff. Typical staff include: managers and policy staff, administrators, fisheries biologists, field staff (e.g., extension officers), data technicians, and in a few cases a statistician or communication specialist.

Common Data Gaps:

Details for each country appear in individual situational awareness reviews, which are available upon request.[8] The following gaps were broadly noted:

- Biological data collection is sporadic and insufficient in all but Jamaica. Some countries do sporadic measurements or measure specific species (e.g., Queen conch or Spiny lobster).
- Water quality is collected by some countries, but documentation is sparse.
- Habitat assessments of coral reefs are generally sporadic and funded or organized through NGOs. Other habitats are not currently assessed in any systematic way.
- Frame surveys are generally unavailable or out of date. These refer to a count of the total number of fishers or vessels, which may be used to expand estimates more accurately to the total population.

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[7] The literature review focused on national efforts and does not include assessments of large pelagic stocks for management of shared resources.

[8] Draft situational awareness reviews are internal working documents but are available upon request by getting in touch with jeyzaguirre@essa.com.

- Stock assessment is a gap with the exception of a few invertebrate species of high commercial value (i.e., lobster and conch).
- Collection of socio-economic data beyond that required for catch and effort estimation is limited. The most comprehensive collection of socio-economic data occurs through Fisheries Industry Census, although these are not undertaken at predictable intervals.
- Grenada and Haiti do not appear to collect any socio-economic data. Grenada, however, has an IT-enabled vessel tracking system, for social welfare ends (safety at sea).

Other Capacity and Institutional Challenges:

- Staff shortage in critical areas such as fisheries biology and data management.
- Statistical expertise.
- Few training opportunities.
- Insufficient time to complete analyses.
- Inconsistent funding, series of short-term projects.
- Lack of field offices, vehicles and basic equipment (e.g., scales).
- Enforcement is weak and underfunded to non-existent (in the case of Haiti); a serious shortcoming.
- Weaknesses in policy and legislative frameworks (e.g., policy instruments for food safety and fisheries management underdeveloped).
- Lower importance of fisheries sector relative to others (e.g., education, health, agriculture).

*Table 1: Findings for the situational review are organized into 3 categories: Descriptors, Monitoring, and Management).*Capacity: full time (FT); part time (PT) ** Regulations: licensing (L), protection (P), closures (C), size (S), and gear (G) restrictions*

Descriptors			Monitoring							Management		
Location	**Fishery Type**	**Fish Type** (primary type in bold, based on % landings)	**Site Selection**	**Catch/Effort**	**Biological**	**Habitat**	**Socio-Economic**	**Assessment**	**Human Resources**	**Protection**	****Regulations**	**Enforcement**
Dominica 	Small artisanal	**Pelagic** (78.5-93%) Demersal (8-17.7%)	Landing sites (13 of 39) grouped into 5 zones	Yes. 3 days/week. ~1/3 of boats daily	Recent effort 1/month at same sites as catch/effort	Sporadic	Sporadic census (2005 & 2011), cost & earnings through catch monitoring, hurricane damage	Limited. CPUE	FT=2; PT=11	1 Marine Protected Area (MPA)	Shellfish S, C, G	Gap
Grenada 	Artisanal and semi-industrial	**Pelagic** (50% offshore & 25% inshore) Demersal (15-20%) Shellfish (<5%)	6 largest markets	Partial. Catch, but often incomplete effort information.	Gap	Sporadic	Gap	Limited. Summary statistics	44 staff	4 MPAs; 11 proposed	L Shellfish C, G	Some for IUU
Haiti 	Small artisanal, subsistence – but >50,000 fishers	**Demersal** (30%) Shellfish (conch/lobster)	Gap	Limited. Total Weight	Gap	Gap	Gap Census underway. Fishers involved in monitoring	Gap	Gap 12 staff Active NGO & fisher organization network	12 MPAs; 8 proposed	Gap	Gap
Jamaica 	Artisanal and semi-industrial (20,000 fishers, 9,000 vessels)	**90% inshore** 10% offshore **Lobster/conch** are prominent, Sea cucumber is an emerging fishery	Numerous landing sites (>150) divided into 3 zones	Landing sites sampled monthly at different intensities for different fisheries. Logbooks & direct observers for sampling for shellfish.	Regular biological sampling occurs for all key fisheries.	301 water quality sites; reef surveys	Limited data through licensing,	Local stock assessment; Summary statistics; depletion models (Sea cucumber; Glass eels)	27 staff across 3 zones including a statistician	24 MPAs; 1 proposed	L, G Shellfish S, C	Marine Police. Some, but not enough. Illegal foreign fishing is a problem
Saint Lucia 	Artisanal 2,458 fishers, 618 vessels	**Migratory pelagics** (60-70%); Nearshore reef (30-40%)	Stratified list of landing sites (1°, 2°, 3°)	Catch, effort, weight. On sample of boats at sample of sites.	Gap Except for conch / lobster; sea urchin pre-season dives	Some reef, water quality & beach; reef check surveys at 20 sites	Some. Earnings, costs, hurricane damage, vessels	Limited; Total landings; no stock assessment	Delay in data processing; 9 field staff; 30 in dept; 3 data staff; no statistician	9 MPAs; 9 proposed	L, S, C, G	2 fisheries wardens on land and at sea as well as The Marine Police Unit of the Royal St. Lucia Police Force

Descriptors			Monitoring							Management		
Location	**Fishery Type**	**Fish Type** (primary type in bold, based on % landings)	**Site Selection**	**Catch/Effort**	**Biological**	**Habitat**	**Socio-Economic**	**Assessment**	**Human Resources**	**Protection**	****Regulations**	**Enforcement**
SVG 	Artisanal, semi-industrial 778 vessels	**Pelagics** (20% offshore, 45% inshore); Demersal (18%); Shellfish (3.5%); Whales, sharks, turtles (small, 1%, 1%)	36 landing sites, grouped into 6 zones	Good catch/effort data since 1994. Interviews at landing zones. Simple random sampling of days, focus on pelagics	Sporadic	Limited. ReefCheck at 13 sites; maps of fishing areas by species.	Some via licensing	CPUE; stock assessment (lobster; conch); surplus production models; MSY for some species	6 field staff; 2 data; 2 comms; 2 analysis	8 MPAs; 1 proposed	S, C, G Varies by fishery	Some, Coast Guard

3. MONITORING PRIORITIES

One way to arrive at strategic clarity on why and what to monitor is to develop a short list of "Big Questions" (Alexander and Pickard, 2009). The questions are a reminder of the big picture, (i.e., what is the point of monitoring), which can often be forgotten when dealing with technical details and day-to-day demands on fisheries offers. This approach forces managers to think about how data will be used before they are collected, rather than asking what questions can be answered after collection. They provide a useful framework for reporting, improving the ability to communicate complex issues. Guiding principles in defining Big Questions are as follows. Questions should:

- Relate directly back to management decisions so as to catalyze learning and feedback loops.
- Be seen as an integrated set of questions and not taken independently.
- Be flexible enough to allow for the evolution of greater specificity of purpose and objectives.
- Be broad enough to characterize and unify all aspects of the endeavor (e.g., efforts to work toward climate-smart fisheries management).
- Be straightforward, use plain language to communicate the central questions of the endeavor.

To arrive at a final list of **Big Questions (BQ)** we circulated a draft set of questions for consideration by the project Working Group, drawn from stakeholder feedback during a Regional Planning Workshop in April 2018, selected site visits (i.e., discussions on monitoring and indicators in Dominica and SVG), literature reviews and expert judgement. The following BQ reflect the feedback received from project stakeholders and form the basis for the proposed monitoring framework and toolkit.

BQ1	How is the physical environment changing in response to climate change?
BQ2	How are habitats that support harvested species being impacted by climate change?
BQ3	How are species distributions changing in response to climate change?
BQ4	How is the growth and productivity of fished species changing in response to climate change?
BQ5	How is the distribution of fishing effort responding to climate change?
BQ6	How is dependence on fisheries changing?
BQ7	Is fishery production changing in response to climate change?
BQ8	How is post-harvest productivity changing in response to supply constraints from climate change?
BQ9	How is uptake of climate-risk management measures in fisheries changing?

4. MONITORING CARDS

4.1 Overview

Monitoring of climate change impacts, vulnerability and responses for small-scale fisheries has several challenges. Taking into account the recommended strategies for improving the effectiveness of climate change related monitoring we designed a series of comprehensive but practical "monitoring cards" that summarize the proposed monitoring approach for each Big Question. Specific considerations in developing these monitoring cards are as follows:

- **Link monitoring to management in an adaptive management feedback loop.** The overarching framework adopted for this project is embedded within an adaptive management feedback loop (see Figure 1).
- **Development of regionally standardized protocols; small but consistent set of key indicators; spatial coverage**: The monitoring cards provide a standardized set of indicators and protocols which if adopted would improve spatial coverage, facilitate regional assessments, and would provide

additional context for individual islands. Supplemental monitoring may be employed as desired depending on local priorities.

- **Spatial integration; spatial coverage:** The cards employ a nested sampling frame approach to provide consistency across the region, improve efficiency of data collection for different indicators, and facilitate both local and regional level analyses.
- **Affordable:** Taken together, the cards discuss three different ways to adjust the overall costs. (1) I**ndicator priority**, there may be a variety of indicators which help to answer a particular big question (e.g., sea surface temperature and temperature at depth). The cards rank these in terms of priority. **Core indicators** should always be collected. Secondary indicators should be collected where capacity allows or based on local priorities. (2) **Response design tiers**, refer to alternative strategies for collecting data to inform the same indicator (e.g., fisher dependent vs. fisher independent surveys of catch). Tiers differ in terms of their capacity requirements with lower tiers being simpler / cheaper strategies and higher tiers being more intensive and often more costly. (3) **Sample effort**, refers to the frequency of sampling in space and time. The monitoring cards propose a default level of effort for each indicator but these may also be adjusted according to capacity.
- **Leverage past work:** Where ever possible the cards adopt methods already employed in the region. In addition, where appropriate historical data availability may be used to select long-term monitoring sites.

The monitoring cards are intended to be a short, practical guide to assist managers in designing their monitoring and evaluation programs with more detailed references provided as necessary. Each monitoring card will include the following sections, each of which is described in more detail below:

- Rationale (i.e., the **why**);
- Indicators (i.e. the **what**);
- Sampling design, which describes **where** and **when** measurements are to be made, as well as the process by which those locations and times are selected;
- Response design, which describes **how** data will be collected (i.e., the field protocol);
- Capacity requirements, which describes the requirements associated with each response design
- Data analysis considerations, which describe **how** the data could subsequently analyzed and reported.

4.2 Types of Monitoring

Monitoring cards focus primarily on basic status and trends monitoring. However, the cards are still relevant for effectiveness monitoring. The key difference is in the sample design, where it may be necessary to add additional samples in targeted areas (e.g., where restoration has occurred, or where a marine protected area is established) in order to assess the effectiveness of the actions.

4.3 Rationale

This section describes the rationale for each Big Question. Data are often collected without sufficient thought about what data to collect and for what purpose. *"Programs risk failure if they lack a clear motivating problem or question"* (Reynolds *et al.*, 2016). Therefore, this is an important step in designing an efficient and effective monitoring program.

4.4 Indicators

Indicators are "characteristics" of the ecological or socio-economic environment that, when measured, describes the magnitude or degree of exposure to a stressor or the condition of the environment (adapted from Porter *et al.,* 2013). A metric is a quantifiable measurement unit that informs the condition or magnitude of an indicator (Porter *et al.*, 2013). It is important to select a small number of key indicators to focus efforts and ensure a cost-effective and financial sustainable monitoring program. The following criteria were considered in selecting indicators:

- **Relevance** to management objectives and actions
- **Grounded in scientific theory** so that they are scientifically-based
- **Easy to measure** with reasonable requirements for resources
- **Interpretable** so that they can be easily understood
- **Responsive** to changes in the aspects being monitored

4.5 Indicator Species

One strategy for improving the efficiency of monitoring small-scale multi-species fisheries is to identify a relatively small set of indicator species to focus efforts. Species identification may be difficult especially for smaller reef fishes or juvenile fish of any species. This is particularly true in visual surveys where the fish may only be observed temporarily. ReefCheck strongly recommends identifying indicator species of local importance and developing identification guides for these. Guide books focused on indicator species would help to ensure that the quality of information for indicator species improved. Some of the metrics (e.g., biological data) are time consuming to collect and therefore priority should be given to indicator species. Use of a consistent set of indicator species at the regional scale is important to ensure data can be widely used and regional-level assessments are possible. This list in Table 2 represents the **minimum** set of species that should be evaluated. Additional data on additional species may be collected as necessary to address local priorities.

MRAG (2010) suggests four categories of criteria to select indicator species:
(1) Baseline information – or knowledge about the species;
(2) Location information – movement patterns;
(3) Life history characteristics – specialist, ability to respond to disturbances; and
(4) Societal importance.

For the purpose of this project, societal importance[9], climate change vulnerability and projected habitat loss (as projected through assessment work under this project and related to MRAG criteria 2 and 3) were the primary considerations in selecting indicator species (Table 2). Species were selected to represent a range of vulnerabilities and habitats. The three most and least vulnerable species / species groups for each of the six countries were considered. In addition, the three species with the greatest projected habitat decline were considered. From those, species which were identified most frequently across the six countries were evaluated for societal importance. All selected species were considered of high societal importance except two: (1) parrotfish spp., selected for their role in maintaining coral reef health and (2) sea cucumber spp., selected due to consistent habitat decline projections and the fact that they are an emerging fishery. Three species: Caribbean spiny lobster, Queen conch, and Common dolphinfish, were selected for their societal importance.

[9] Societal importance was determined from Table 1 (Cheung *et al*., 2019), which provides the top 29 species or species groups identified by each of the six case-study country representatives as most important.

Table 2: Proposed indicator species and evaluation criteria. WP1 = Work Package 1 under this project; CCV = climate change vulnerability; S-M-CR = seagrass-mangrove-coral reef.

Scientific name	Common name	Projections from ecological modelling (WP1)	Frequency	Ecosystem	Important?
Acanthuridae	Surgeons, tangs, unicorn fishes	Low CCV	2	S-M-CR	Yes
Coryphaena hippurus	Common dolphinfish	High CCV	0	Pelagic	Yes
Decapterus macarellus	Mackerel scad	Low CCV	6	Pelagic	Yes
Holothuria spp.	Sea cucumber spp.	Habitat Decline	0	S-M-CR	No
Istiophorus albicans	Atlantic sailfish	Habitat Decline	2	Pelagic	Yes
Lobatus gigas	Queen conch	Medium CCV	0	S-M-CR	Yes
Lutjanidae spp.	Snapper spp.	High CCV	3	S-M-CR	Yes
Panulirus argus	Caribbean spiny lobster	Low CCV	0	S-M-CR	Yes
Scaridae spp.	Parrotfish spp.	High CCV	5	S-M-CR	No
Thunnus spp.	Tuna spp.	Habitat Decline	2	Pelagic	Yes

4.6 Response Design

The response design describes **how** the data are to be collected (Table 3). Within each monitoring card a brief description of the approach is provided for each indicator or metric. In many cases, 2-3 Tiers of response design are proposed and tradeoffs discussed. Detailed protocols are referenced as appropriate. There are a few common categories of response design included in the monitoring cards:

Remote sensed information can readily be applied at broad spatial scales and does not require local capacity to collect. External expertise (e.g., NOAA) can be leveraged. Field methods are applied at smaller scales to validate remote-sensed information and provide additional information where necessary. A combination of remote sensed approaches and field methods should be employed (MRAG 2010).
Field-based surveys include the following:

Habitat surveys are on-the-ground assessment of habitat condition using transect-based approaches. These methods tend to involve a long list of indicators measured either at points, quadrats, or continuously along transects. These methods tend to require relatively tedious set up and a team of at least two people, more for scuba surveys. In general, even rapid assessment approaches like ReefCheck likely take at least half a day, particularly when set up and travel time are incorporated. However, it is generally easier to observe trends in habitats of sessile organisms and, therefore, these are particularly important methods for informing climate-smart management.

Landing site or market surveys (fisher dependent). There are a number of indicators that can be addressed through vessel surveys, including those requiring information on: catch, species, location, or fishing effort. When landing sites are known and are not too dispersed, these methods are relatively efficient. When landing sites are unknown or too broadly dispersed an alternative approach is to interview vendors at markets. One potential advantage of market surveys is that they may be better suited to capturing information about Illegal Unregulated and Unreported (IUU) catch (Lloret *et al.*, 2015). Although useful and efficient, vessel surveys and vendor surveys are fisher dependent and inherently biased. Bias may occur as a result of size-selective fisheries, fishing effort avoiding the edges of distribution ranges, and landing costs or other socio-economic drivers. A weakness of vendor surveys at markets is that the fisher cannot be interviewed and therefore little to no information on location is possible and effort cannot be directly assessed.

To supplement the responses from the landing site or market survey, a “snowball” method may also be used, specifically for data collection on socio-economic indicators. This involves asking respondents for names of additional people that could be interviewed, as part of the survey effort. Employing this approach will help identify value-chain actors associated with the catch of fishing vessels (e.g., boat owners, processors, major vendors).

Fish surveys (fisher independent). Surveys that involve directly collecting or observing fish and can be used to evaluate many of the same indicators as with the fisher-dependent methods described above. Although there are methods for evaluating effort using fisher independent approaches, these are not recommended for this program. Rather fisher independent methods are proposed as an option for collecting distribution and fish growth and productivity data. Adding a fisheries-independent method can be costly and time consuming but may address biases associated with fisher dependent surveys. In particular, location is much easier to identify through direct surveys than fisher or vendor surveys. Visual surveys are limited in their ability to collect biological data, with the exception of length. When fish are handled, species identification, counts and biological data collection are easier however there are handling costs in terms of time and impact to the fish.

***Other infrastructure / secondary sources*.** In selected cases, the possibility exists to use information pertaining to socio-economic indicators already recorded and reported by Fisheries Departments (e.g., statistics from post-disaster Damage and Loss Assessments; reports from food safety inspections) and from national or global datasets (e.g., annual national gross domestic product).

Table 3: This table identifies the indicators and Big Questions that can be informed by each response design. More detail is provided in the Monitoring Cards

BQ#	Dimension	Census Remote sensed	Landing site surveys (Fisher dependent)	Reef surveys (Fisher independent)	Pelagic surveys (Fisher independent)	Other infrastructure / secondary sources
		Core	Core	Core	Secondary	
BQ1	**Physical**	SST	X	Temperature at depth	Temperature at depth	X
BQ2	**Habitat**	Extent of key habitats (mangrove, coral reef, seagrass); primary productivity	X	Habitat condition; water quality	X	X
BQ3	**Fish (distribution)**	X	Species ID, Location; Abundance	Species ID, Location, Abundance	Species ID; Location; Abundance	X
BQ4	**Fish (growth & productivity)**	X	Biological data	Length	Biological data	X
BQ5	**Fisher effort (distribution)**	Total # of boats by port	Location, Effort	X	X	
BQ6	**Socio-economic (dependence & diversification)**	X	Livelihood dependence; Seafood for food security; Flexibility within the sector; Occupational mobility	X	X	Economic dependence
BQ7	**Socio-economic (supply pressures)**	X	Disruptions to fishing operations	X	X	Fishery production; Non-compliance with food safety standards; Damage and loss to fisheries-sector assets
BQ8	**Socio-economic (post-harvest productivity)**	X	Waste; Product Improvement	X	X	X
BQ9	**Socio-economic (climate risk management)**	X	Use of climate-responsive tool, instrument, strategy, or activity	X	X	X

4.7 Sample Design

The sample design section of the monitoring card describes ***where*** and ***when*** measurements are to be made, and the process by which those locations and times are selected. The sample design is directly related to the response design and these are described together in a single table. Preliminary sample effort recommendations are based on the expected relative variability in space and time of each indicator, past experience designing monitoring programs, and logistical constraints (Box 2). The designs can continue to be refined as data are collected. The monitoring cards use a common overarching sample frame from which more detailed designs for each Big Question may be nested. This approach helps to ensure data may be aggregated and reported in a consistent manner. Wherever possible, monitoring cards propose integrating monitoring across cards so that sites are co-located for different questions. This minimizes travel time, which can be substantial, and facilitates analysis across indicators (e.g., reef health, fish distribution, and water quality may all be measured at the same location). The master sample frame and three commonly-employed designs are described in detail here and referenced as appropriate in the monitoring cards.

Box 2: Sample effort

Decisions about how to allocate monitoring effort over space and time are very important to a cost-effective and efficient design. Considerations include:

- Desired precision (how good does the information need to be to inform my management decision?)
- Variance in space and time (which depends on: sampling error, measurement error, and process error. The first two sources of error depend on the response design and sampling design.)
- Feasibility (including cost and logistical constraints)

In general, more effort should be allocated when the desired precision is high (e.g., if one strata is particularly important for your management decisions) or the variability is high (e.g., high variability over space or time, sample more frequently in space or time respectively). The overall efficiency depends on the precision for cost, which depends on the feasibility of alternative approaches (e.g., remote sense surveys versus snorkel surveys for reef extent).

Sample design optimization: There are numerous texts on sampling design (Cochran, 1977) and free sample size calculators to help determine how many samples to allocate to strata over space and time. All of these use preliminary estimates of variability to evaluate trade-offs of alternative designs.

A common mistake is to think about sampling effort in terms of proportions or rates. While this seems intuitive, using a fixed sample rate does not leverage the true power of a good sample. The number of samples is more important than the proportion sampled. As suggested with the soup metaphor, you don't need to eat 20% of a pot of soup to know how it tastes before you serve it (assuming it is well mixed).

4.7.1 Master Sample Frame

The master sample frame for each country should include (see Figure 4):

- **Country**
- **Economic Exclusion Zones (EEZs)**
- **Fishing grid:** Grid (5 mile x 5 mile), this grid can be used as a standardized method to identify location for both fisher dependent and independent surveys. This approach is currently used in Dominica.

- **Quadrants:** Divide grid into 4 quadrants (NE, NW, SE and SW).
- **Pelagic zones:** Create contours in the pelagic habitat based on distance from shore, 5 mile spacing up to 25 miles.
- **Habitat extent:** Best available information on spatial extent of key habitats: coral reef, mangrove, and seagrass habitats.
- **Fish Aggregating Devices:** Best available information on the location of FADs.
- **Landing sites or markets:** Specify whether landing sites or markets will be used for surveys and digitize the location of known landing sites or markets.

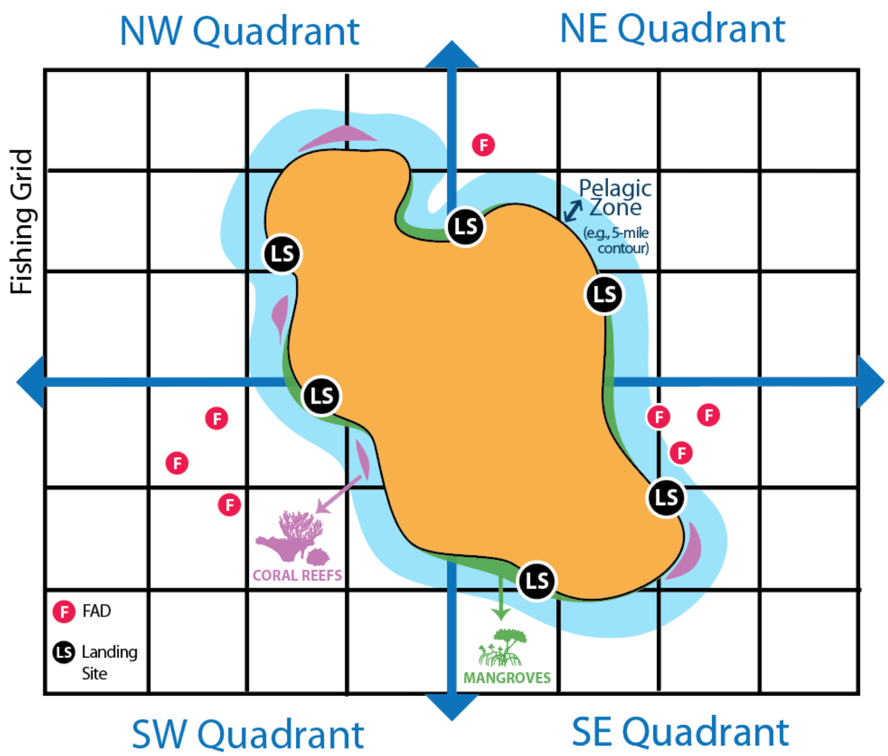

Figure 4: Use of a common master sample frame within which all sampling efforts can be nested enables data aggregation and reporting efforts both within countries and across the region. The master sample frame explicitly identifies each of the nested design elements (i.e., pelagic zone, reef habitat, mangrove habitat, FADs, Landing Sites, 5x5 mile grid) within each country.

- **Other infrastructure.** Digitize other land-based fisheries sector assets (e.g., seafood processing plants, critical control points for food safety inspection, government offices, fisheries cooperatives, export facilities, etc.). The Caribbean Catastrophe Risk Insurance Facility (CCRIF) has an extensive spatial database with count, replacement cost and vulnerability ratings of different building classes and infrastructure at a 1km^2 resolution, for member countries.[10]

4.7.2 Standard Sample Design #1: Landing Site or Market Survey

This design is the core recommended sampling approach for many of the Big Questions. Most countries are already employing some variation on this sampling approach, however the focus is on catch and many of the indicators recommended in the monitoring cards are not adequately addressed (e.g., biological information and effort).

[10] https://www.ccrif.org/sites/default/files/publications/CCRIF_Support_for_DRM_in_the_Caribbean_May_2019.pdf

Strata:
- Spatial: 4 quadrants (NE, NW, SE and SW) to ensure spatial coverage and in particular to ensure the North/South gradient is captured. This was the simplest approach to capture leading/lagging edges within and across countries as well as for a variety of species.
- Size: divide landing sites or markets into 3 size categories: primary, secondary and tertiary. This classification is based on the one used by St. Lucia to stratify landings by: the fishery type, the volume of fish being landed and the number of vessels operating at the site (Department of Fisheries, 2010). A similar approach could be used for markets.

Selection of sites:
- Within each quadrant, select a stratified random sample of sites.[11] Depending on capacity and priorities it may not be appropriate to assess all size strata, as a default the largest strata should be prioritized. Recommendations on spatial and temporal frequency for specific indicators are provided in Table 4.

Repeat visits:
- Once selected, the same sites should be visited throughout the year to minimize the variability associated with site to site differences within a year and to minimize the effort involved in learning about new sites and building relationships in new communities.
- At the end of each year a new set of sites should be selected. This will ensure that all sites continue to have some probability of being selected, thus limiting the potential for fisher behaviour to shift to avoid monitors and maximizing the total spatial coverage.

Effort:
The total number of surveys and sites in a day can vary considerably, depending on the number of personnel available, the complexity of the survey instrument, familiarity with the survey instrument, relationships with local fisherfolk and travel distances.

For each site selected in a given year, the following represent the **minimum frequencies** for indicators by question (Table 4). Many countries are already exceeding these frequencies in order to meet their FAO reporting requirements for landed catch. However, even in countries with extensive catch monitoring programs it may not be possible to collect all of the additional indicators during every survey.

Table 4: Minimum frequencies suggested for the range of indicators proposed in this framework

Big Question	Metrics	Frequency
Fish distribution (BQ3)	• Species ID, location[12]	A minimum of monthly to provide a summary of the distribution of different species throughout the year.
Growth & productivity (BQ4)	• Length • Weight, sex, and maturity	Biological metrics require additional handling and are more time-consuming thus sub-sampling is required. Sample a minimum of quarterly to ensure ability to identify shifts in spawn timing and age at maturity. Measure length on every second survey, for

[11] We considered whether to oversample in areas where habitat suitability was projected to decline/increase for different species, leveraging information on leading and lagging edges within EEZs. However, we opted for a simple design and focus effort to ensure coverage of north-south gradients from a regional perspective to capture shifts at this scale.

[12] Fishers may be hesitant to inform where fish are caught or may be unable to provide precise location information.

Big Question	Metrics	Frequency
		indicator species only. Measure the remaining metrics (weight, sex, and maturity) on every fourth survey, for a subset of fish that are measured for length. For efficiency employ a second survey crew to assess biological metrics on a subset of the surveys completed by the regular crew
Fisher distribution (BQ5)	• Location, fishing effort	A minimum of monthly to provide a summary of fisher distribution throughout the year as fisher vulnerability may vary by season.
Fisheries dependence and diversification (BQ6)	• # of persons that fish / sell fish / own fishing vessels • Income from fishing relative to other sources • use of catch for own consumption • % able to access new fishing grounds / switch target species / sell different species • Success rate in accessing capital / credit • Perceived urgency in accessing livelihoods outside the sector • Perceived availability of livelihood options	Monthly for direct surveys with fishers to be able to detect trends over the year (to inform targeted diversification initiatives). Less frequent sampling would need to rely on recall, reducing the accuracy of data collected. Yearly for snowball sampling[13] of other value-chain actors.
Supply pressures (BQ7)	• Foregone fishing days / month due to weather, *Sargassum* incursions	Monthly. Less frequent sampling would need to rely on recall, reducing the accuracy of data collected.
Post-harvest productivity (BQ8)	• Average discards per week by weight • Reported use of spoilage-prevention methods at sea • Reported use of spoilage-prevention methods during transportation • Proportion of harvest meat weight going into certified, branded, fresh premium, portioned, preserved or other value-added products	Monthly for direct surveys with fishers, yearly for snowball sampling of other value-chain actors
Climate risk management (BQ9)	• Extent to which fisherfolk use tools, instruments, strategies and activities to manage risks from climate variability or climate change (type, # and frequency of use)	Monthly for direct surveys with fishers, yearly for snowball sampling of other value-chain actors

[13] Snowball sampling is an approach often used in social surveys of rare or hard to identify populations. It is based on the premise that members of the population know one another and so when one member is interviewed, they are asked to identify others (Lohr 1999). This can lead to a relatively large sample of a rare population. It does not represent a probabilistic sample and so caution should be used in making inference beyond the sampled individuals.

4.7.3 Standard Sample Design #2: Coral Reef Sample Design

Strata:

- North (combine the NE and NW quadrants) and South (combine the SE and SW quadrants). This was the simplest approach to capture leading/lagging edges within and across countries as well as for a variety of species. The number of strata was reduced from four to two to minimize the number of samples required for this more expensive sampling approach.
- Depth (limit sampling to reefs which are <12m, as recommended by ReefCheck for safety reasons)

Selection of sites:

Within each stratum (North/South) select a random sample of sites which meet the depth criteria.

Repeat visits:

The revisit frequency across years is particularly important for reef surveys, where fish have relatively high site fidelity. Revisiting the same sites over time provides the best information on long-term site level trends. However, this comes at a cost as it limits the number of sites which may be visited (McDonald, 2003). We recommend implementing a simple rotating panel design which splits effort among repeat and new sites. This design results in a consistent annual level of effort, which is best from a practical implementation and planning point of view but also provides annual estimates. This design would be replicated in both the North and South strata.

Effort:

Panel 1 (sample size, n=2 sites) is visited each year[14], and 5 additional panels (sample size, n=3 sites each) are visited once every 5th year.[15] This will result in a total of 5 sites per year and 17 sites after 5 years, in each of the North and South strata (Figure 5). The total effort would then be 10 sites per year and 34 sites after 5 years. After 15 years, there would be 4 sites that have 15 years of data and 30 sites that have been revisited 3 times. Each site represents a randomly selected reef from the sample frame, within each site multiple transects are surveyed as described in the Monitoring Card for BQ2.

	sample size						# of surveys per year	Total # of sites
	n=2	n=3	n=3	n=3	n=3	n=3		
Year	Panel 1	Panel 2	Panel 3	Panel 4	Panel 5	Panel 6		
1	X	X					5	5
2	X		X				5	8
3	X			X			5	11
4	X				X		5	14
5	X					X	5	17
6	X	X					5	17
7	X		X				5	17
8	X			X			5	17
9	X				X		5	17
10	X					X	5	17
11	X	X					5	17
12	X		X				5	17
13	X			X			5	17
14	X				X		5	17
15	X					X	5	17

Figure 5: Illustration of the proposed rotating panel design for coral reef surveys.

[14] In order to leverage existing data where possible the permanent sites (Panel 1) may be selected from locations with historical data.

[15] Lovell and Sykes (2008) found evidence of recovery from a temporary bleaching event within a 5-year window.

For each site selected in a given year: Complete snorkel surveys for reef condition once per year and opportunistically collect all additional metrics (Table 5) during these annual visits to minimize travel time. Sampling once per year is usually sufficient to characterize changes in reef condition (ReefCheck) and the cost of completing snorkel surveys is likely prohibitive to revisiting sites more than once per year. If budget allows or local priorities demand it, additional sampling for other metrics (e.g. water quality) could be implemented.

Table 5: Minimum frequencies suggested for selected indicators proposed in this framework (reef)

Big Question	Metrics	Frequency
Physical (BQ1)	• Temperature at depth • Water quality	Once per year at all sites
Habitat (BQ2)	• Reef condition • Presence of mangrove or seagrass	Once per year at all sites
Habitat (BQ2)	• Mangrove / seagrass condition	Once per year at a subset of sites
Fish distribution (BQ3)	• Species identification and location	Once per year at all sites
Fish growth and productivity (BQ4)	• Length	Once per year at all sites

4.7.4 Standard Sample Design #3: Pelagic Sample Design

The main purpose of this survey design is to provide fisher-independent information to supplement the fisher-dependent landing site surveys. This is most relevant to BQ 3 (distribution) and BQ4 (growth and productivity). Fisher-dependent information about distribution is less precise and may not capture the edges of the range. Growth and productivity estimates based on catch alone may be biased as a result of size-selective fisheries.

Strata:

- Spatial: 4 quadrants (NE, NW, SE and SW) to ensure spatial coverage and in particular to ensure the North/South gradient is captured which is particularly important for questions of fish distribution. This was the simplest approach to capture leading/lagging edges within and across countries as well as for a variety of species.
- Distance from shore: priority is the first 5 miles (8.04km), but other distance strata could be incorporated if warranted and capacity allows.
- FADs: If the position of FADs is known, this information may be used to improve the efficiency of sampling.

Selection of sites:

Randomly sample FADs or grid cells within each quadrant. If FADs are present and their position is known, then these could be used as sampling locations to increase the likelihood of capturing fish.[16]. Given that the data are not being used to estimate absolute abundance but rather distribution and growth, this should not result in undue bias.

Revisit design: It is not necessary to revisit exact locations given the mobility of pelagic fish and lack of fidelity to sites and therefore site to site / year to year variability.

Effort: Each sampling event within this design is expected to be costly in terms of time, training, and equipment required. Therefore we propose using as few samples as possible initially to provide preliminary estimates of variability. A minimum of 3 surveys per quadrant per year would provide

[16] Note that there is a concern that FADs may affect distribution, movement, and growth in which case sampling FADs could create a bias. However, if FADs are treated as a stratum this concern could be alleviated as results would only be extrapolated to other FADs and additional sampling effort could be applied to 'non-FAD' strata.

estimates of variability within and between quadrants to inform future refinement of the design. This would consist of a total of 12 surveys per year. If additional distance strata are of interest, additional samples could be collected.

For each site selected in a given year the following represent the minimum frequencies for indicators by question (Table 6).

Table 6: Minimum frequencies suggested for selected indicators proposed in this framework (pelagic)

Big Question	Metrics	Frequency
Physical (BQ1)	Temperature at depth	Sample each site once per year. Target the peak fishing season for most pelagic species. Given the cost involved in traveling to a survey site and collecting fish, we recommend collecting all of these metrics during each fisher independent survey.
Fish distribution (BQ3)	Count by species for all fish	
Fish growth and productivity (BQ4)	• Length for all indicator species • Weight, sex, maturity for subset of individuals by indicator species	

4.8 Capacity Requirements

The capacity requirements are directly related to the response design and the sampling design and are described together in a single table in each of the monitoring cards. A brief overview of key personnel or equipment requirements is provided for each of the tiers of monitoring.

4.9 Data Analysis Considerations

When and how the monitoring data are analyzed and reported is critical to informing the decision-making and planning needs. Analytical methods depend on the specific question of interest (e.g., local versus regional trend, single versus multi-species etc.). Each monitoring card provides a brief description of suggested approaches to analyzing and reporting on the data collected, focusing on how to generate the indicators of interest at the local or national scale. More complex analyses comparing across Big Questions or evaluating regional trends are discussed in Section 5 (Aggregation of Information).

4.10 Monitoring Card 1: Changes in the Physical Environment

BQ1: How is the physical environment changing in response to climate change?

Rationale:

Climate change is expected to drive a range of changes in the physical ocean environment including: pH, O_2, sea level, currents, and temperature (Cheung *et al.*, 2019; MRAG 2010). However, it is the effects on water temperatures that are expected to drive the most significant impacts to biogenic habitats and associated fisheries species distribution (Hobday and Evans, 2013) and condition by causing direct physiological stress resulting in abnormal development, disease, and mortality (Brill, 1994; Brill and Lutcavage, 2001; Doney *et al.*, 2012). Remote sensing can provide information on changes to sea surface temperatures; however, in-situ monitoring is important to track temperature trends at depths where fished species and supporting habitats are found. In-situ monitoring can also help to identify local variation in physical parameters that could indicate climate refugia which may warrant protection (Bongaerts *et al.*, 2010) or make good candidate sites for future habitat restoration activities.

Indicators:

The core indicator for this monitoring card is sea surface temperature. Temperature at depth is also desired but likely only worth the effort if collected simultaneously with field-sampling efforts from other questions (i.e., reef surveys for BQ2 and pelagic surveys for either BQ3 or BQ4). The benefits of direct sea level monitoring may not be worth the cost to do at a broad spatial and temporal scale. Broad scale model predictions are likely more useful to management as they could be used to prioritize areas for mitigation.

Indicator	Priority	Relevance
P1. Sea surface temperature	Core	Sea surface temperature is a relatively easy to measure indicator of the ocean temperature, a useful indicator of climate changes as well as biological responses such as habitat (BQ2) and distribution of fishes (BQ3).
P2. Temperature at depth	Secondary	Measurements at a variety of depths are required to fully evaluate the condition of habitats for fishes and to confirm predictions from SST. Most pelagic fisheries occur within the top 200 feet (Oxenford and Monnereau, 2017).
P3. Sea level	Secondary	In addition to direct impacts on people, sea level rise may affect key habitats by reducing light availability for seagrass and coral reef habitat (Short and Neckles, 1999). Mitigation measures will depend on the ability for habitats to migrate (e.g., space for mangroves to move inland).
P4. pH	Tertiary (low priority at this time)	At this time, pH is not recommended for the CRFM monitoring program. pH data are highly variable, difficult to measure, and require long time-series to extract a meaningful signal (World Meteorological Organization). There is emerging research on potential methods for assessing pH indirectly via isotope analysis (Fietzke *et al*., 2014) or via a combination of satellite derived indicators (Land *et al.*, 2015). Improved pH sensors coupled with autonomous diving instruments (e.g., Argo floats) which last up to 5 years are being deployed by the Southern Ocean Carbon and Climate Observations Modeling project (https://soccom.princeton.edu/) may be useful in the future.

Data collection:

Data-collection methods including response design, sample design and capacity requirements are shown for sea surface temperature, temperature at depth, and sea level.

P1. Sea Surface Temperature (SST)	
Response design	Remote sensed
Sample design	SST estimates may be extracted from existing models at the scale of the individual country or the region as a whole. The resolution of the data in the Caribbean is 10km x10km. Estimates are available on a variety of time scales (e.g., diurnal, daily, seasonally) depending on the question of interest.
Capacity requirements	Personnel: Data extraction, manipulation, and analysis require moderate technical skills. Equipment: Minimal. These data are readily available at no cost.

<table>
<tr><th colspan="3">P2. Temperature at depth</th></tr>
<tr><th></th><th>Tier 1 - Temporary deployment</th><th>Tier 2 - Permanent deployment</th></tr>
<tr><td>Response design</td><td colspan="2">Data can be collected using long-term multiuse data loggers also capable of tracking tides through pressure sensors. There are numerous brands of data logger available which are suitable for marine use. These range in quality, durability, and cost. There are many relatively cheap options for temporary deployment. Permanent deployment in reef habitats is possible although there is no guarantee against vandalism and more loggers are required for permanent deployment. More expensive versions are required for permanent deployment in the pelagic environment (e.g., http://www.argo.ucsd.edu/) and these are likely beyond the capacity of the CRFM. Temporary deployment will provide better spatial coverage (lat, long, and depth) but only provides a snapshot in time. Whereas permanent deployment provides continuous measurements with limited spatial coverage. For the purpose of the CRFM broad spatial coverage (obtained via temporary deployment) is a priority to detect temperature shifts nationally and regionally and inform management decisions. However, in some cases (e.g., to evaluate the effectiveness of management measures such as MPAs) it may be of interest to assess temperature over time (via permanent deployment).</td></tr>
<tr><td>Sample design</td><td>Sample unit: Point locations with multiple depth measurements.
Strata: pelagic and reef habitat
Selection of sites: Reef sites [Sample Design 2]; Pelagic sites [Sample Design 3]
Timing: instantaneous sample collected opportunistically when sites are visited for other purposes (e.g., reef surveys or pelagic surveys)</td><td>Point locations, at fixed depth
Strata: reef habitat
Selection of sites: subset of Reef sites selected for BQ2 [Sample Design 2].
Timing: continuous measurements</td></tr>
</table>

Capacity requirements	Personnel: Minimal training Equipment: Hobo water temperature pro v2 data logger (max depth 120m) ~$15USD	Personnel: Data management and analysis of continuous data are more complex. Equipment: Permanent deployment requires multiple loggers and materials/effort to anchor the logger.

P3. Sea level		
	Tier 1 – Fixed reference	**Tier 2 – Automated tide gauge**
Response design	Local sea level rise may be measured using a tide gauge which measures changes in sea level relative to a height reference. (See manual: IOC, 2006)	
	A measuring stick is permanently attached to a pier and the water level is manually transcribed.	Automated tide gauges are fitted with sensors which continuously record the water level and transmit the data.
Sample Design	Sample unit: point location (ports) Strata: 4 quadrants (NE, NW, SE, SW) Selection of sites: same as for landing surveys [Sample Design 1], countries which use market surveys instead should capture at nearby ports within each quadrant.	
	Timing: 1/month when completing landing surveys	Timing: Continuous
Capacity requirements	Personnel: Support may be needed for initial installation, but ongoing costs and training requirements are minimal.	Personnel: Support may be needed for initial installation, but ongoing costs and training requirements are minimal. Equipment: costs start from: $1500 USD (Giardina *et al.*, 1998).

Potential Data Analyses:

- Assess shifts in temperature indicators (SST and temperature at depth) across North / South gradient. This can be done by looking at individual sites over time and by relating latitude to temperature across many sites. Statistics of interest (e.g., mean during daylight versus night) may vary depending on the question (e.g., by species), however using metrics consistent with modelling efforts from WP1 would be a useful default to ensure easy comparison.
- Long-term trend data for SST and temperature at depth could be used to confirm physical conditions within MPAs (i.e., evaluate the effectiveness of MPAs selected as climate refugia) and inform the selection of new MPAs.
- Compare observed sea-level rise with predictions.
- Physical variables such as temperature may be explanatory variables driving changes in biological or socio-economic indicators, for example:
    - Use regression analysis to assess temperature-driven effects on growth and productivity [BQ 4] of indicator species.
    - Confirm species-specific Habitat Suitability Index (HSI) modelled estimates by comparing temperature and distribution/abundance data [BQ 3].

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4.11 Monitoring Card 2: Changes in Critical Habitats for Fished Species

BQ2: How are habitats that support harvested species being impacted by climate change?

Rationale:

Direct effects on the physiology and distributions of harvested species can be exacerbated by the loss of supporting habitats (e.g., coral reefs, seagrass, coastal mangrove forests and pelagic habitats). Coral reefs are particularly vulnerable to increasing sea surface temperature, acidification, and extreme weather events resulting in coral bleaching, increased susceptibility to disease and breakage. Deeper reefs (30-150m) known as mesophotic or 'middle light' zones will likely be more resilient to climate impacts and may be able to serve as a source population to degraded shallow reef ecosystems (Hoegh-Guldberg *et al.*, 2017). Sea grass is sensitive to a number of climate-induced changes including sea-level rise and turbidity, which may affect light penetration (Short and Neckles, 1999; Dennison *et al*., 1993). Coastal vegetation (i.e., mangrove forests) provides protection against extreme weather events, which damage coastal infrastructure and can distribute debris into nearshore coastal areas that also damage habitat. As sea level rises these forests may be inundated and degraded. Migration inland may be limited by human activities. Primary productivity is affected by climate directly (e.g., sea surface temperature) and indirectly (e.g., currents, upwellings, nutrient or light availability) (Krumhardt *et al.,* 2017). Primary productivity is directly related to productivity of fisheries, particularly in the shelf areas encompassed by most EEZs (Blanchard *et al*., 2012). Monitoring changes in essential fish habitats may provide an early warning of impending changes to fish distribution, enabling implementation of proactive management strategies (Karp *et al.*, 2019; Anderson *et al.*, 2015).

Indicators:

Habitat extent is a core indicator for all key habitats. Habitat quality as measured by field surveys is a core indicator for shallow reef habitat. Quality of seagrass and mangrove habitats is also of interest but not considered part of the core field monitoring.[17] Water quality as it relates to climate change is focused on impacts to key habitats (i.e., reefs) and should be collected opportunistically as part of all reef surveys.

Category	Indicator	Priority	Metric / relevance
Habitat Extent	E1 Extent of key habitats	Core	Area of key habitats (mangrove forest, shallow reef, and seagrass beds) (m^2 and % of EEZ)
	E2 Extent where key habitats coincide	Core	Total area where all 3 key components of coastal habitat (mangrove forest, shallow reef, and seagrass beds) are present in combination. Numerous papers describe the important linkages between these habitats (MRAG, 2010) and the benefit of an integrated management strategy (Guannel *et al.*, 2016).
Habitat Quality	E.3 Primary productivity	Core	Ocean productivity, as measured by chlorophyll a.
	E.4 Coral reef (<30m)	Core	Habitat area by EEZ (m^2 and %) that is degraded or dysfunctional.
	E.5 Sea grass	Secondary	
	E.6 Mangroves	Secondary	
	E.7 Water quality	Secondary	Water quality • Temperature and pH (refer to BQ 1) • Suspended solids and turbidity
	E.8 Mesophotic reef (>30m)	Research	Difficult and costly to measure this is primarily a research venture at the present time and beyond the scope of this regional effort.

[17] Mangroves may be more important than coral reefs for some coastal areas and in those cases, the effort could focus on sampling of mangrove habitats.

Data collection:

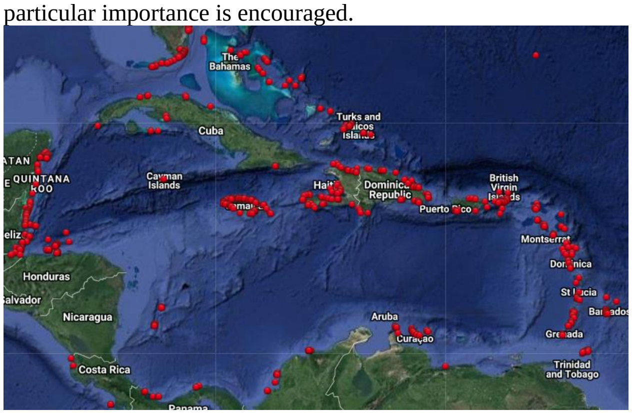
Data collection methods, including response design, sample design and capacity requirements are shown for habitat extent, habitat quality (primary productivity), habitat quality (coral reefs), habitat quality (seagrass and mangroves) and habitat quality (water quality).

Habitat Extent	
Response design	Remote sensed methods using satellite images can be used to map and classify key habitat types (coral reef, seagrass, and mangroves). Distribution maps of varying accuracy of different biogenic habitat types (Landsat imagery acquired in the late 90s early 2000s) are available as shapefiles through the UNEP & WCMC Ocean Data Viewer for seagrasses, mangroves, and coral reefs. More recent data layers exist for: Antigua and Barbuda, Dominica, Dominican Republic, Grenada, Haiti, Jamaica, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines (http://caribnode.org/maps/60).
Sample design	Collect best available data for the entire EEZ. Timing: repeat mapping exercise periodically (at least 1/5 years) to evaluate long term trends.
Capacity	Remote sensing [could be contracted out] and GIS expertise

Habitat Quality – Primary productivity	
Response design	Remote sensed methods using satellite images can be used to estimate primary productivity from measures of chlorophyll a. These datasets are readily available.
Sample design	Estimates may be extracted at whatever scale is of interest (e.g. EEZ) within the limit of the grid scale. Estimates are also available on a variety of time scales (e.g., daily, monthly, seasonally) depending on the question of interest.
Capacity	GIS expertise

Habitat Quality	**Seagrass beds**	**Mangrove forests**
Response design	Established in existing guidance documents (http://www.seagrasswatch.org/manuals.html)	Established in existing guidance documents such as the Manual for Mangrove Monitoring in the Pacific Islands Region (Ellison *et al*., 2012).
Sample design	Sample unit: transect surveys Complete seagrass surveys at a sample of sites where reefs and seagrass beds are in close proximity.	Sample unit: transect surveys Complete mangrove forest surveys at a sample of sites where reefs and mangrove forests are in close proximity.
Capacity	Personnel -Training in protocol Equipment -Minimal (GPS, compass, 50m tape)	Personnel -Training in protocol Equipment -Minimal (GPS, compass, 50m tape)

Habitat Quality – Water quality		
	Tier 1 – remote sensed	Tier 2 – in-situ monitoring
Response design	There are emerging remote sensed methods for evaluating sedimentation in marine environments. https://www.dhi-gras.com/	Established in existing guidance documents such as the NEPA water quality monitoring protocol.
Sample design	Estimates may be extracted at whatever scale is of interest (e.g. EEZ) within the limit of the grid scale.	Sample unit: point based surveys Collect water quality data at all reef sites.
Capacity	Remote sensing [could be contracted out] and GIS expertise	Personnel: Training in protocol Equipment: handheld water quality meter (range from US$100-US$1,500); minimum of turbidity, Total Dissolved Solids, and temperature

<table>
<tr><th colspan="3">Habitat Quality Shallow coral reefs</th></tr>
<tr><td rowspan="2">Response design</td><td>Tier 1 - ReefCheck surveys</td><td>Tier 2 - AGGRA reef surveys</td></tr>
<tr><td>A rapid visual assessment completed along belt transects. This protocol has been used extensively within the Caribbean, making it useful for regional and global comparisons. Methods are designed to be used by citizen scientists and are relatively simple. Identification of and focus on indicator species of particular importance is encouraged.


Surveys include 3 components which should all be completed at each sample site:

Substrate transects
Invertebrate transects
Fish transects

Reference: https://reefcheck.org/ecoaction/monitoring-instruction/</td>
<td>Visual survey completed along belt transects. This standardized assessment method was developed for the Atlantic and Gulf regions. Over 2400 surveys have been completed since 1997. AGGRAs data explorer houses the largest database on Caribbean coral reef health indicators. Surveys include 3 components which should all be completed at each sample site:

Benthos: 1m wide, 10m long belt transects, plus point and quadrat data within each transect
Coral: 1m wide, 10m long belt transects
Fish: 2m wide, 30m long belt transects

Reference: http://www.agrra.org/training-tools/agrra-method/</td></tr>
<tr><td>Sample design</td><td colspan="2">Sample frame: GIS layer of coral reef habitat derived from habitat extent maps and constrained to <12m consistent with ReefCheck protocols.
Sample unit: belt transects within a reef with spatial extent of at least ~200m x 200m
Strata: North (combine NE and NW quadrants) and South (combine SE, SWquadrants); constrain sampling to reef <12m deep.
Selection of sites: implement repeat visit design [Sample Design 2] within the North and South strata.</td></tr>
<tr><td>Capacity requirements</td><td>Personnel: Teams of two, trained in the ReefCheck protocol, specifically species identification, focus is on indicator species.
Equipment:

Scuba gear
Boat – depending on distance from shore
ReefCheck Caribbean field guide (US$16)
</td>
<td>Personnel: Teams of two for each of the components (benthos, coral, and fish), trained in the AGGRA methods, specifically species identification.
Equipment:

Scuba gear
Boat – depending on distance from shore
AGGRA survey equipment (Equipment list provided by Ocean Research & Education Foundation) http://www.agrra.org/training-tools/equipment/
</td></tr>
</table>

Potential Data Analyses:

To track changes in status and trends over time:

- % change over time in extent or quality of habitat as observed through either periodic remote sensed surveys or the rotating panel design.
- Map shifts in distribution over time (North/South or migration inland).
- Generate Reef health index (RHI) scores using the same approach as taken with TNC – Eastern Caribbean Coral Reef Report Cards http://caribnode.org/
- Early warning of impending changes to fish populations (link to BQ3 distribution)

To inform management decisions:

- Consider new MPAs where all 3 habitat types are present and healthy in combination to support holistic ecosystem function and multiple life stages of fished species.
- Inform selection of nature-based adaptation opportunities – e.g., restore mangroves where reef/seagrass are stable, or restore/protect seagrass and reef where mangroves have room to migrate inland.
- Water quality assessments may inform where to focus erosion control efforts or upland watershed management as well as evaluate the effectiveness of such actions (e.g., Jamaica's ridge to reef program https://www.nepa.gov.jm/projects/r2rw.htm)
- Confirm findings that healthy habitats (particularly in combination) are correlated with increased resilience to climate change in fish populations (Maharaj *et al.*, 2018).

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https://reefcheck.org/ecoaction/monitoring-instruction/
http://www.seagrasswatch.org/manuals.html

4.12 Monitoring Card 3: Changes in Fished Species Distributions

BQ3: How are species distributions changing in response to climate change?

Rationale:

Regional shifts in species distributions, with species moving poleward and to greater depths to stay within their preferred temperature ranges and avoid physiological stress, are anticipated to be one of the most immediate responses of fisheries resources to climate change (Bates *et al.*, 2013). Range shifts may involve expansions at the leading edge of the range or contractions at the lagging edge of the range. A particular challenge with assessing range shifts is that available data (e.g., catch estimates) tend to be particularly sparse at the range edge (Przeslawski *et al.*, 2012). There are a number of emerging methods to detect changes in the leading and lagging edges of species ranges (Bates *et al.*, 2013; Amorim *et al.*, 2014; Fogarty *et al.*, 2017; Karp *et al.*, 2018). Given the Caribbean's proximity to the equator and the habitat suitability modelling results from Work Package 1 of this project (Cheung *et al.*, 2019; Cheung *et al.*, 2019a), range contractions are the primary focus, although there may be some range expansion in the northern-most regions. Tracking potential range shifts will help to detect whether climate modelling predictions are being fulfilled and inform proactive planning and policy-making that anticipates future distributions (Fogarty *et al.*, 2017).

Indicators:

Bates *et al.* (2013) identify three stages of range expansion and range contraction (see table below). Different indicators are necessary to assess different stages. This is a useful generic approach to framing questions of distribution for individual species. Occupancy (presence/absence) is a core indicator, but it is only able to detect the 'arrival' stage of range expansion or the 'local extinction' stage of range contraction. Confirming absence is more difficult than confirming first sightings. Wherever possible indicators of abundance should be collected even if coarse in nature. Growth and productivity data from BQ4 can help to determine whether there is a performance decline which is an early warning sign of an impending range shift. Species diversity is an additional core indicator, which helps track ecosystem-level shifts in distribution.

	Stage	Definition	Indicators	Priority
Range expansion	Arrival	Presence of one or more individuals in a new geographic region	E.9 Occupancy (Presence or First sightings)	Core
	Population increase	Via migration and/or self-recruitment	E.9 Index of Abundance (e.g., catch per vessel or fish per day per vendor)	Core
	Persistence	Population stability in a given area	E.10 Index of abundance over time	Secondary
Range contraction	Performance decline	Reduced growth, condition, reproductive potential, change in spawn timing	E.11 Growth and productivity [BQ4]	Secondary
	Population decrease	Sustained decrease in abundance and/or occupancy	E.12 Index of Abundance	Secondary
	Local extinction	Protracted absence of populations from previously occupied habitats at a range boundary	E.13 Occupancy (Absence)	Core

Data collection:

Studies have shown that 'first sightings' can be reliable early warning signs of range shifts as 'first sightings' are likely related to long-term climate changes (Fogarty *et al.*, 2017). This *ad hoc* approach requires a minimum of: species ID, date, and location to be documented. Reporting can include non-commercial fisherfolk (i.e., recreational) or marine workers (i.e., tour operators). For example, Redmap (Range Extension Database and Mapping project, http://www.redmap.org.au/) in Australia allows community members to report uncommon species sightings.

Distribution can be monitored through fisheries-dependent (e.g., landing site or markets surveys) methods or fisheries independent (e.g., underwater census or direct sampling) methods. Fisheries-dependent methods are relatively efficient but are inherently biased. Adding a fisheries-independent method can be costly and time consuming but may address biases due to size selective fisheries, provide better location information, and can target areas at the edge of ranges where fishing effort may be lower. Surveys involve directly collecting or observing fish. For each survey, collect data on key metrics including: location, species identification and count.

Species Distribution			
	Tier 1) anecdotal first or rare sightings	**Tier 2) Fisher dependent surveyat landing sites or markets**	**Tier 3) Fisher independent surveys using fishing gear (Pelagic) or visual surveys (Reef)**
Response design	Species: in each case, fish are directly observed and fish are identified to the highest taxonomic level possible, species is preferable. Method: FAO, 2016		
	Location is directly observed. Count is not documented.	Data are collected via interviews. Location: where possible catch is linked to location on gridded map [Master Sample Frame], at a minimum the location of the landing site or market can be recorded. Count: where possible, count the total number of fish caught, a less desirable alternative is to use a coarse log scale Method: White *et al.*, 2014	Location and count are directly observed by monitors. Pelagic: Collect fish using standard gear at FADs if possible, otherwise along transects within the site. Reef surveys: under water visual surveys
Sample Design	NA, however tour guides and fishers may be actively engaged, particularly in the leading edge of distributions	Sample unit: A nested set of sample units including (1) the landing site or market; (2) the vessel or vendor. Site selection [Sample Design 1]	Pelagic surveys: Sample unit: FAD or transect within random grid cell Selection of sites: [Sample Design 3] Reef surveys: Sample unit: transects within reefs Selection of sites: [Sample Design 2]
Capacity requirements	Personnel/training: Ability to accurately identify species Equipment: Mechanism for reporting encounters (phone number or website to report to, etc.)	Personnel/training: The primary requirement for this BQ is the ability to accurately identify species. Equipment: Survey instrument	Personnel/training: Species identification and training in pelagic and reef surveys. Equipment: Pelagic survey: Requires access to a boat and sampling gear (e.g., hook and line), likely easiest to partner with a fisher who can follow a specific survey plan (i.e., conduct a “test fishery” at leading or lagging edges of range that fishers are usually more unlikely to visit) and then bring the fish to market to be identified and sampled. Reef survey: refer to BQ2 monitoring card for details

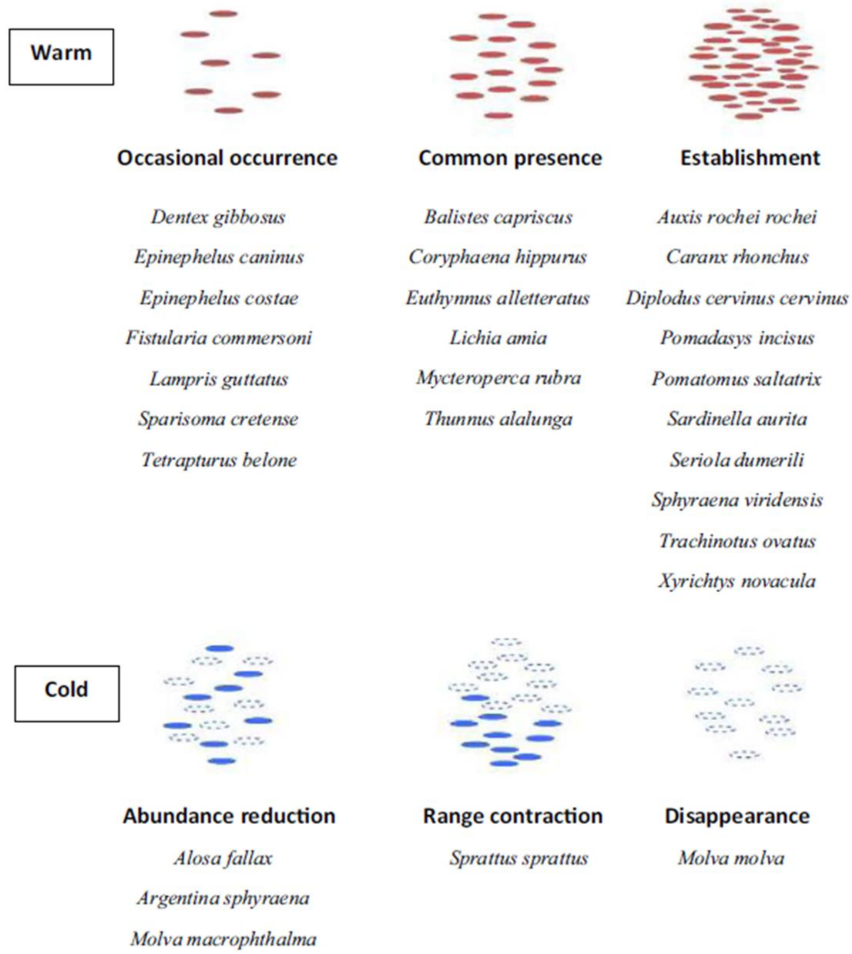
Potential Data Analyses:

Multiple species:

Calculate species diversity indices at a variety of spatial scales (e.g., site level, North vs. South, reef vs. pelagic, MPA vs unprotected). There are several commonly used indicators of species diversity (e.g., Shannon index, Simpsons Index, and the total number of species). The basic concept it to identify the 'effective number of species present', methods primarily differ in their sensitivity to rare species (Hill, 1973). Usually the unit of assessment is species, but other groupings can be used (e.g., functional groups) so long as the units are consistent throughout the dataset. In their assessment of the sensitivity of the fisheries sector to climate variability & change, Pinnegar *et al.* (2019) incorporate an indicator of catch diversity using an index of "Shannon diversity of fisheries landings". They aggregate information to the parish level and disaggregate data to species level. Methods and statistical code for these and other diversity approaches are freely available in the statistical software package R (e.g., using the R package 'vegan', https://cran.r-project.org/web/packages/vegan/vignettes/diversity-vegan.pdf).

Individual species:

Use best available data (including data from BQ4) to identify the stage of range shift (Bates *et al.*, 2013) for each species possible, focusing on indicator species or groups. At minimum, species range shifts can be quantified by tracking the position (latitude and longitude) of the leading edge, lagging edge, and mean position (centroid) of species occurrence data points over time (e.g., quarterly and annual summaries in GIS software). This type of analysis can and should be done at both national (EEZ) and regional scales. A more multifaceted approach for greater confidence in documenting range shifts is provided by Lloret *et al.*, 2015 (see figure below for a simple approach to reporting out this information). Whenever possible, new occurrences should be entered into the Ocean Biogeographic Information System (OBIS) database (https://obis.org/) to facilitate regional and global tracking and analysis of climate-induced species range shifts.



Possible reporting format to use to summarize stages of range shift for a variety of species (Source: Lloret et al., 2015)

- Implement RAPFISH, a rapid assessment tool for evaluating fisheries sustainability status, uses evidence of range reduction within a 10-year period or loss of a sub-population as indicators of future range collapse (http://www.rapfish.org). This could be monitored through presence/absence of species within their historical geographic range.
- Validate / calibrate models used in Cheung *et al.* (2019). Compare actual distributions to areas of predicted gain, loss, or maintenance based on CC predictions from Work Package 1 of this project.
- Inform implementation of spatially explicit stock assessments.
- If presence of a new species is identified – consider precautionary approach on fishery and prioritizing research accordingly.
- Adjust harvest management strategies.
- Re-evaluate stock boundaries and/or MPAs.

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4.13 Monitoring Card 4: Changes in Species Growth and Productivity

BQ4: How is the growth and productivity of fished species changing in response to climate change?

Rationale:

Both direct temperature impacts on the physiology of harvested species (through increased physiological stress impacting feeding, growth and reproduction) and increased fishing pressure (due to more fishers targeting fewer fish) are expected to result in a trend towards smaller body sizes at capture, which can have knock-on impacts for population productivity due to the lower reproductive output of smaller fish (Clarke, 1987; Berkeley *et al*., 2004; Claramunt *et al.*, 2007). A reduction in biological performance may also be an early indicator of future range shifts (Big Question 3) (Bates *et al*., 2013). Systematically monitoring the size and maturity of harvested individuals provides information on both climate impacts and the overall health of the population and is necessary to inform harvest management decisions.

Indicators:

Several important indicators of population health may be obtained through collection of a few metrics.

Dimension	Indicators	Priority	Metric
Growth	E.14 Size distribution; Growth; mortality; MSY (a number of assumptions involved in latter 3)	Core	Length
Condition	E.15 Fish condition index (Length / weight relationship)	Secondary	Length & Weight
Productivity	E.16 Spawn timing; age at maturity (e.g., L50)	Secondary	Sex
			Maturity stage

Data collection:
In general biological data requires 'hands on fish'. There are a few different response designs for actually collecting fish and these are associated with different sample designs and capacity requirements. However, once a fish is 'in hand' the method for assessing biological metrics including: length, weight, sex, and maturity stage are the same. The only exception is for visual surveys, which may provide a coarse estimate of length but are not able to assess weight, sex, or maturity stage with confidence. Length data may be collected relatively quickly, whereas sex and maturity stage typically involve opening up the fish and examining the gonads. Focus monitoring efforts on indicator species.

Fish Growth and Productivity		
	Tier 1 – Fisher dependent (Landing site surveys)	**Tier 2 – Fisher independent (pelagic or reef surveys)**
Response design	Biological data can be monitored through both fisheries-dependent (e.g., landing site or markets surveys) and fisheries-independent methods (e.g., underwater surveys). Adding a fisheries-independent method can be time consuming, but helps to provide information on reproductive output through juvenile recruitment and abundance that is not readily apparent through monitoring of catch as there is an inherent bias in catch data for size selective fisheries. Methods for biological data: FAO 2016 Estimating length from underwater visual surveys: Estimate the total length of each fish using the 10-cm increments on the T-bar for scale, and assign it to one of the following size classes: 0 - 40 cm (e.g. 3@60). http://www.agrra.org/training-tools/agrra-method/	
Sample Design	Sample unit: A nested set of sample units including (1) the landing site or market; (2) the vessel or vendor. Site selection: Collect data on a subset of sites from [Sample Design 1] • A minimum of quarterly • collect length data on every second survey • collect weight, sex, and maturity stage data on every 4th survey Only collect biological data on recommended indicator species or locally important species.	Pelagic surveys: Same design as for BQ3 [Sample Design 3]. Given the cost of traveling to these sites and collecting fish, we recommend collecting biological data at all sites. Reef surveys: Same design as for BQ3 [Sample Design 2]. Length is estimated at all sites, weight, sex, and maturity data cannot easily be captured. Only collect biological data on recommended indicator species or locally important species.
Capacity requirements	Personnel/training: Collection of biological data takes additional time and would be best if 2 monitors could work together. 1 team can complete surveys for BQ 3 & 5, while the other team follows completing the biological data measurements on a subset of surveys. All of the requirements for BQ3 in addition to training on how to collect biological data. Special Equipment: Digital camera, scale, measuring tape, ruler or gridded background.	Personnel/training: All of the requirements for BQ3, in addition to training on how to collect biological data. Special Equipment: Requires access to a boat and sampling gear (e.g., net), likely easiest to partner with a fisher who will then bring the fish to market. Digital camera, scale, measuring tape, ruler or gridded background.

Potential Data Analyses:
Estimation of changes in growth indicators:

- <u>Size distribution</u>: Plot length distributions at various scales of interest (e.g., North vs. South, changes over time) (e.g., histograms, boxplots, or cumulative distribution functions). Calculate and compare key statistics (e.g., median) and / or compare distributions (e.g., using Kolmogorov-Smirnov tests).

- <u>Growth</u>: Use von Bertalanffy growth equation[18] to estimate key parameters (growth and mortality). These approaches may be used with length data and several assumptions. Rahman *et al.* (2018) provide a practical example of this approach.
- <u>Condition</u>: The relationship between length and weight is commonly accepted as a useful indicator of general well-being or condition in fishes (Bolger and Connolly, 1989). This information can be compared with monitoring information on habitat quality to understand how resource availability for fish might be changing in response to changes in habitat.

Estimation of changes in productivity indicators:

- <u>Size at maturity</u>: Report the distribution of sizes at maturity. Report the median or L50 (the size at which 50% of the distribution is capable of spawning). This information can be used to adjust size-based harvest control rules to ensure the fishery is not targeting sizes of fish that are still expected to be immature.
- <u>Spawn timing</u>: Plot the spawning fraction monthly to identify the spawning window. This information can be used to understand how reproductive phenology might be changing over time and potentially to inform adjustments to the timing of the fishing season to avoid catching fish before they reproduce. This could also support BQ3, as shifts in spawn timing are one of the indicators of a range shift. Note that females provide a better representation of spawn timing. Schemmel *et al.* (2016) provide a practical example of how to generate and report these productivity estimates.

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[18] $L_t = L_\infty\{1 - e^{[-K(\ )t - t_0]}\}$, Length (L) is expressed as a function of age (t). L_∞ is the asymptotic length, K(year-1) is a curvature parameter that determines how fast the fish approaches L (i.e., growth), and t_0 is when the fish has ‘zero’ length.

4.14 Monitoring Card 5: Changes in the Distribution of Fishing Effort

BQ5: How is the distribution of fishing effort responding to climate change?

Rationale:

Climate change is expected to cause shifts in the distribution and abundance of fished species. The ability to change vessels, gear or fishing locations to respond to changes in species distribution and abundance is a strategy to increase adaptive capacity. However, implementation of such changes may be difficult to implement as forecasts are still uncertain and may not be trusted. For example, during an El Niño event in the 1990s, forecasts were used to influence Peruvian harvest regulations with mixed reviews (Broad 1999). Because climate change is expected to have great impact coastal species as well as the habitats they depend on, climate change may also be expected to result in fishers moving away from depleted coastal areas and needing to fish farther out at sea to target pelagic species. As a consequence, fishers may see increasing time investment, increased expenses for boat fuel, and increased expenses for transitioning to new fishing gears, making fishing more costly and reducing profit margins.

Indicators:

This question is the crux between the biological and socio-economic systems. Fishing effort at the scale of an individual vessel is the core indicator, which is best addressed via interviews at landing sites where there is direct access to fishers. These surveys can be implemented at the same time as those for other questions. These data will provide information on the spatial and temporal distribution of effort as well as vessel-level estimates of effort. In addition, the total number of vessels may be used to estimate the total level of effort.

Indicators	**Priority**	**Metric / rationale**
E.17 Fishing effort (vessel level)	Core	Fishing location, fishing activity/gear-type, FAD (Y/N), catch, length of time spent actively searching and fishing, length of trip, total number of fishers.
E.18 Fishing effort (total)	Secondary	Total number of vessels. The size of the fleet is critical because it is what fisheries officers use to expand the sampled catch to obtain estimated national catch. This information is already being captured by fisheries monitors in many of the countries.

Data collection:

Data collection methods including response design, sample design and capacity requirements are shown for fishing effort (vessel level), pelagic fishing effort, and total fishing effort.

<table>
<tr><td colspan="3">Fishing Effort (vessel level)</td></tr>
<tr><td rowspan="3">Response design</td><td>Tier 1 - Fisher dependent survey at market sites</td><td>Tier 2 - Fisher dependent survey at landing sites</td></tr>
<tr><td>Market surveys do not provide direct access to fishers or vessels. If it is not feasible to implement a landing site survey, then consider:
a) Interviewing fishers as they sell their catch
b) Asking vendors for names of fishers, for follow up interviews (i.e., snowball sampling, Lohr, 1999).
c) Using surrogate information, such as: # of fishers which sell to a vendor each day</td><td>Data are collected via interviews with a representative from each vessel.</td></tr>
<tr><td colspan="2">Regardless of the method for identifying the interviewee, the following trip specific information is collected: fishing location, fishing activity/gear-type, catch, length of trip, total number of fishers.

Location: ID fishing zone from gridded map [Master Sample Frame], at a minimum the location of the landing site or market can be recorded.

Fishing activity/gear-type: use standardized gear codes (see Table 1 in FAO, 2019)</td></tr>
</table>

	Trip length: total number of hours on the water or distance traveled Number of fishers: number of unique fishers on the vessel
Sample Design	Sample unit: A nested set of sample units including (1) the landing site or market; (2) the interviewee (vessel or fisher) Selection of sites [Sample Design 1] Effort: collect data a minimum of 1/month to provide a summary of fisher distribution throughout the year as fisher vulnerability may vary by season.
Capacity requirements	Personnel/training: Ideally the same person would do this survey as the fish distribution survey. No additional training is required. Special equipment: Survey instrument

Frame survey (Total number of vessels)		
Response design	**Tier 1 – Google earth estimate**	**Tier 2 – Direct observation**
	Estimate the total number of vessels by counting the number of boats at a sample of ports using Google earth imagery. This is a useful method for estimating the size of the fleet when capacity is too low to do regular national fisher censuses (e.g., counting boats in person). Reference: Keramidas et al. 2018; Johnson et al. 2017.	Estimate the total number of vessels by counting the number of boats via planes, drones, or on foot via port visual surveys.
Sample Design	Sample unit: landing sites Stratification: 4 quadrants (NE, NW, SE, SW); size (use the same strata as with [Sample Design 1]). Put the greatest effort into the largest sites, Kerimidas *et al.* (2018) found most boats were recorded near large cities. Selection of sites: random sample within each strata Effort: In the absence of any data to inform sample sizes, begin by taking a sample of n=30 sites per quadrant measured once.[19] The design may be refined once preliminary estimates of variability and the nature of the data are known.	
Capacity	Personnel/training: GIS skills Special Equipment: Computer & internet	Special Equipment: Plane, drone, travel

Potential Data Analyses:

Vessel-specific data collected in this card provide information about where and when fishing effort occurs, which may be used to evaluate:

- Whether or not fisher distributions are following changes observed in species distribution, which can be calculated in a similar way to change in species distribution by tracking the position of the leading edge, lagging edge, and mean position (centroid) of effort data points (e.g., in GIS software). Changes in fishing distribution can be compared to changes in fish distribution to identify areas of mismatch.
- Whether or not gear types are changing as fishers enter new fisheries.
- The relative effort associated with FADs vs reef fisheries.
- Whether the time or distance travelled (can also be measured as fuel consumed) to reach productive fishing grounds is increasing over time or differs by fishery and/or North to South.
- Whether the fishing time is increasing over time or differs by fishery and/or North to South.

Frame surveys provide an understanding of how many fishing vessels are active, which enables vessel specific estimates to be rolled up to the national or regional level, thus providing estimates of total effort or total catch.

[19] The Central Limit Theorem refers to the phenomenon that even for highly non-normal data, $\bar{X}$ (the mean) tends to be normally distributed for 'large n'. A typical rule of thumb which is often conservative is that the CLT applies when n≥30 (Devore 1995).

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4.15 Monitoring Card 6: Change in Fisheries Dependence and Diversification

BQ6: How is dependence on fisheries changing?

Rationale:

Dependence on fisheries and extraction of marine resources is highly relevant to climate change adaptation, as the more dependent households, communities and national economies are on fisheries, the harder it may be to bounce back from severe disturbances in the sector (Allison *et al.*, 2009; Cinner *et al*., 2012). Indeed, dependence on fisheries is one way to assess sensitivity to the impacts of climate change (Allison *et al*., 2009; Jepson and Colburn, 2013; Morzaria-Luna *et al.*, 2014; Wabnitz *et al.*, 2018; Pinnegar *et al.*, 2019). On the flip side, flexibility and diversification are characteristics with the potential to confer adaptive capacity to fisherfolk and fishing economies, reducing sensitivity to climate-related shocks to fisheries (e.g., Wongbusarakum and Loper, 2011; Badjeck *et al*., 2010). Diversification can refer to mobility within the sector (e.g., different fishing gears/ target species; shifts to value added post-harvest) (Cinner *et al.*, 2013). Diversification can also mean engaging in alternative or supplementary activities outside of the sector to reduce dependence on fisheries and aquaculture for income generation, nutrition and revenues.

Tracking changes in dependence on fishing activities and the extent of diversification strategies pursued alongside trends in physical changes in the marine environment and in fish catches helps understand the spatial extent and rate of responsiveness of fishers to these shifting conditions. This information is relevant to a number of policy domains, from trade policy to food security and health to education and skills development. At a management level, information on fisherfolk's abilities to cope with variations in catch due to changing climate conditions can inform analysis of the social and economic impact of reforms in fisheries management (e.g., gear restrictions, closures), as well as engagement strategies and programming within the sector (how to improve mobility across the fish value chain) and with other sectors (e.g., agriculture, tourism, finance).

Indicators:

The indicators selected to understand trends in dependence on fisheries and reported or perceived diversification pursuits stem from published climate change vulnerability studies in coastal environments and guidance on assessing social vulnerability in particular. Following the approach of Colburn and Jepson (2016) and others (e.g., Blasiak *et al*., 2017; Wabnitz *et al.*, 2018; Pinnegar *et al*., 2019), indicators of dependence on fisheries encompasses employment, income and food. Indicators of diversification aim to capture local dynamics within the sector and across sectors. Diversification from and dependence on fisheries are inversely related.

Category	Indicator	Priority	Metric	Comments
Dependence	S1. Importance of the marine fishery sector to local livelihoods	Core	**TIER 1** S1.1 # of persons that fish / sell fish / own fishing vessels per km coastline (#/km length of coastline)*	# of fishers is an employment indicator under the WECAFC Data Collection Reference (DCRF) Framework in development (FAO, 2019). Collecting or accessing current and area-based data on the area's labour force may not be possible (see Pinnegar *et al.*, 2019).
			TIER 2 S1.2 # of persons that fish / sell fish / own fishing vessels out of economically active population in the area*	
		Secondary	S1.3 Proportion of household income from fishing / selling of fish (%) relative to other sources of income*	People can derive income from non-fishing sources despite being employed in the sector full time. This metric also takes into account livelihood activities of other household members, as reported by the key informant
	S2. Importance of seafood for food security	Core	S2.1 Proportion of household use of fish catch for own consumption (%) relative to sales*	By definition subsistence fishers have access to fish for food but persistent supply shocks hamper food security in the long term, with potential impacts on nutrition in the absence of appropriate substitutions.
		Secondary	S2.2 Seafood protein as proportion (%) of all animal protein consumed in the household*	
	S3. Importance of the fisheries sector to a country's economy	Core	S3.1 Monetary value of total landed fish as a proportion (%) of total gross domestic product (GDP)	Total landed value is an economic indicator under the WECAFC DCRF in development (FAO, 2019). These are macro-economic indicators to shed light on a country's dependence on the sector for revenue and export earnings.
		Secondary	S3.2 Monetary value of fisheries exports as a proportion (%) of total exports	
Diversification	S4: Flexibility within the sector	Core	S.4.1 Proportion of fisherfolk (%) able to access new fishing grounds / switch between target species / sell different fish species*	As the climate change signal becomes stronger and enabling conditions are put in place movement or optimization across the fish value chain will likely follow.
		Secondary	S4.2 Success rate (frequency) in accessing capital/credit to purchase new gear or equipment when needed*	
	S5: Occupational mobility	Core	S.5.1 Perceived level of urgency or need to find alternative or supplementary livelihoods outside the sector*	Fishing and other activities in the sector may become unsustainable due to climate change in combination with other stressors. Exiting the sector may be necessary despite hesitation to change occupation or retrain (Khan et *al.*, 2019). The availability of alternative livelihood options can lower people's perceptions of vulnerability (Wongbusarakum and Loper, 2011).
		Secondary	S5.2 Perceived alternative livelihood options available, either seasonal, temporary, or long-term*	

*Disaggregated by sex (M/F); age (<18; 18-65; >65); category (full time / part time)

Data collection:

The series of tables below include guidance on data collection for all indicators except S3 (Importance of the fisheries sector to a country's economy). National governments already collect data for S3 and report on this indicator, feeding into global datasets (World Bank, FAOSTAT, FAO FishStat, UN Trade Statistics). The data-collection approach for the rest of the indicators relies on key informant interviews / surveys at landing sites or fish markets (Standard Sample Design #1). The desired unit of analysis is the fishing vessel, to maximize potential coverage across the value chain since fishers, vendor(s), boat owners, seafood processors and other major consumers (e.g., restaurants) can be associated with the operations and raw supply of a given vessel. Where capacity is limited, effort should focus on populating core indicators.

<table>
<tr><th colspan="4">S1. Importance of the marine fishery sector to local livelihoods</th></tr>
<tr><td rowspan="2">Response design (How)</td><td>S1.1 # of persons that fish / sell fish / own fishing vessels per km coastline (#/km coast)</td><td>S1.2 # of persons that fish / sell fish / own fishing vessels out of economically active population in the area</td><td>S1.3 Proportion of household income from fishing / selling of fish (%) relative to other sources of income</td></tr>
<tr><td colspan="3">Key informant interviews / surveys at landing sites (required)
Potential for snowball interviews with other value chain actors at less frequent intervals
Capture of respondents' socio-demographic characteristics is also recommended: sex (M/F); age (<18; 18-65; >65); category (full time / part time)</td></tr>
<tr><td>Sample design (Where and When)</td><td colspan="3">Sample unit: Fishing vessels at landing sites

Strata: 4 quadrants (NE, NW, SE, SW)

Selection of sites: same as for landing surveys, countries that use market surveys instead should capture at nearby landing sites within each quadrant. Within sites, capture information for every other returned vessel

Timing: once per month (i.e., monthly) for direct interviews (first point of contact at the vessel); snowball sampling to other value-chain actors associated with the vessel annually

S1.1 requires spatial data on coastline lengths from secondary sources. S1.2 requires disaggregated labour force statistics (total number of people employed in the fisheries sector in the area) from secondary sources (e.g., national census, Survey of Living Conditions).</td></tr>
<tr><td>Capacity requirements</td><td colspan="3">Personnel; Training in the conduct of the interview / survey, including ethical considerations and how to deal with sensitive questions (e.g., income); personnel with some experience in qualitative research methods; basic GIS skills, if using S1.1

Equipment: Rugged tablets (water-resistant, drop proof) for streamlined data capture, where possible</td></tr>
</table>

<table>
<tr><th colspan="3">S2. Importance of seafood for food security</th></tr>
<tr><td rowspan="2">Response design (How)</td><td>S2.1 Proportion of household use of fish catch for own consumption (%) relative to sales</td><td>S2.2 Seafood protein as proportion (%) of all animal protein consumed in the household</td></tr>
<tr><td colspan="2">Key informant interviews / surveys at landing sites
Capture of respondents' socio-demographic characteristics is also recommended: sex (M/F); age (<18; 18-65; >65); category (full time / part time)</td></tr>
<tr><td>Sample design (Where and When)</td><td colspan="2">Sample unit: Fishing vessels at landing sites

Strata: 4 quadrants (NE, NW, SE, SW)

Selection of sites: same as for landing surveys, countries that use market surveys instead should capture at nearby landing sites within each quadrant. Within sites, capture information for every other returned vessel

Timing: once per month

Both S2.1 and S2.2 require the respondent to speak on behalf of the household and assume the respondent is knowledgeable about food consumption at home. Formulating a question for S2.2 requires local knowledge of typical sources of protein for household consumption.</td></tr>
<tr><td>Capacity</td><td colspan="2">Personnel</td></tr>
</table>

requirements	-Training in the conduct of the interview / survey -Personnel with some experience in qualitative research methods Equipment -Rugged tablets (water-resistant, drop proof) for streamlined data capture, where possible

S4: Flexibility within the sector		
Response design (How)	**S.4.1 Proportion of fisherfolk (%) able to access new fishing grounds / switch between target species / sell different fish species**	**S4.2 Success rate (frequency) in accessing capital/credit to purchase new gear or equipment when needed**
	• Key informant interviews / surveys at landing sites (required) • Potential for snowball interviews with vendors and processors at less frequent intervals • Capture of respondents' socio-demographic characteristics is also recommended: sex (M/F); age (<18; 18-65; >65); category (full time / part time)	
Sample design (Where and When)	Sample unit: Fishing vessels at landing sites Strata: 4 quadrants (NE, NW, SE, SW) Selection of sites: same as for landing surveys, countries that use market surveys instead should capture at nearby landing sites within each quadrant. Within sites, capture information for every other returned vessel Timing: quarterly for direct interviews (first point of contact at the vessel); snowball sampling to vendors associated with the vessel annually	
Capacity requirements	Personnel: Training in the conduct of the interview / survey, including ethical considerations and how to deal with sensitive questions (e.g., access to financing); personnel with some experience in qualitative research methods Equipment: Rugged tablets (water-resistant, drop proof) for streamlined data capture, where possible	

S5: Occupational mobility		
Response design (How)	**S.5.1 Perceived level of urgency or need to find alternative or supplementary livelihoods outside the sector***	**S5.2 Perceived livelihood options available, either seasonal, temporary, or long-term***
	• Key informant interviews / surveys at landing sites (required) • Potential for snowball interviews with vendors and processors at less frequent intervals Capture of respondents' socio-demographic characteristics is also recommended: sex (M/F); age (<18; 18-65; >65); category (full time / part time)	
Sample design (Where and When)	Sample unit: Fishing vessels at landing sites Strata: 4 quadrants (NE, NW, SE, SW) Selection of sites: same as for landing surveys, countries that use market surveys instead should capture at nearby landing sites within each quadrant. Within sites, capture information for every other returned vessel Timing: quarterly for direct interviews (first point of contact at the vessel); snowball sampling to vendors associated with the vessel annually	
Capacity requirements	Personnel: Training in the conduct of the interview / survey, including ethical considerations and how to deal with sensitive questions (e.g., future outlook of livelihoods); personnel with some experience in qualitative research methods Equipment: Rugged tablets (water-resistant, drop proof) for streamlined data capture, where possible	

Potential Data Analyses:
The methods outlined above permit: (1) scaling up estimates to the broader population for indicator values generated by direct interviews / surveys at sites of different size classes (primary, secondary, tertiary landing sites); (2) reporting on the variability in these estimates among site size classes and (3) presenting unweighted and unscaled indicator values from snowball sampling per quadrant.

Countries can use indicator values for S1-3 to develop a "fisheries-sensitivity index" and track trends over time and space using one variable. This composite index could be the unweighted average of the indices of fisheries importance for livelihoods (S1), food security (S2) and the economy (S3), with resulting values normalized and scaled to range from 0 to 1. Higher values would represent greater sensitivity.

Countries can also use indicator values for S11-S13, combined with values for indicators S4 and S5 (BQ6) and S13 (BQ9) to develop a fisheries "adaptive capacity index" and track trends over time and space using one variable. This composite index could be the unweighted average of all five indices, with resulting values normalized and scaled to range from 0 to 1. Higher values would represent greater adaptive capacity.

Livelihood diversification is a complex process, shaped by external (e.g., resource availability and access, norms and market opportunities) and individual (e.g., occupational identity and attachment to place) factors (Wongbusarakum and Loper, 2011; Cinner *et al*., 2018). The socio-economic indicators suggested here help understand whether (actual and leading) shifts in diversification within the sector and across sectors are taking place (i.e., what is happening). Trends derived from analysis of data on distribution in fishing effort [BQ5] provide additional information to corroborate the extent of diversification in harvesting activities. These indicators do not measure why this is happening and whether the changes are positive or negative on welfare.

Sharing findings from analysis of indicators S1, S2, S4 and S5 with fishing families via town hall meetings or focus group discussions is one approach to enable co-production of knowledge, including interpreting trends, identifying root causes and action points.

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4.16 Monitoring Card 7: Changes in Fishery Production

BQ7: Is fishery production changing in response to climate change?

Rationale:
Climate change impacts, such as rising sea-surface temperatures, increased ocean acidification and more intense tropical cyclones, are likely to exacerbate ongoing challenges facing the fisheries sector in the near- and long-term, contributing to smaller catches, harvest losses, disruptions to harvest and post-harvest operations and reduced earnings across the fish value chain (Boyd and Ryan, 2019). Economic losses to the sector due to extreme weather are already substantial. For example, the estimated value of fishing vessels, gear and FADs damaged or destroyed in Dominica during Hurricane Maria in 2017 amounted to EC$14 million (CoD, 2017). With increasing frequency and / or intensity of extreme weather and ocean conditions resulting from climate change direct loss and damage to the fisheries sector and disruptions to fishing operations are also expected to increase. Projections of ecological impacts of climate change on fished species and related economic modelling indicate the potential for Caribbean nations to experience a loss in economic well-being due to too little production, price increases and reduced consumption of seafood (Boyd and Ryan, 2019).

Tracking instances of climate-related disruptions in the supply of fish and seafood and their economic consequences will help further cement the case for sector-specific investment in climate change adaptation and disaster risk management in the sector. Examining macro-indicators of fishery production alongside trends in the physical environment (BQ1), fish abundance (BQ3) and fisher effort (BQ5) can help isolate the role of climate change in driving adverse long-term impacts on marine resources and fisheries, relative to non-climate stressors.

Indicators:
The indicators selected to understand the climate signal in trends in fishery production capture both gradual and event-based phenomena and target different scales of response (fisher and sectoral). Consistent with available evidence, some indicators (S7, S8, S9) explicitly assume a decline in fishing days or fisheries losses.

Category	Indicator	Priority	Metric	Comments
Gradual shifts	S6. Fishery production	Core	**TIER 1** S6.1 Total annual landings (tons)	S6.1 is part of standard data collection and reporting S6.2 is a measure of risk, calculated as the ratio of the standard deviation of the weekly/monthly total landings over the last three years to the mean of total landings (for more information see: Anderson *et al.*, 2015)
			TIER 2 S6.2 Intra-annual landings volatility	
		Core	S6.3 Monetary value of total landed fish (US$)	Total landed value is an economic indicator under the WECAFC Data Collection Reference (DCRF)

				Framework in development (FAO, 2019). Also see S.3.1
	S7. Disruptions to fishing operations	Core	S7.1 Foregone fishing days / month due to weather, *Sargassum* incursions	Inclement weather and *Sargassum* incursions are reported factors that affect fishing operations (CoD, 2011) Estimates can be combined with average monthly / seasonal catch value to calculate foregone harvest value.
	S8. Non-compliance with food safety standards	Core	S8.1 Presence of unacceptable levels of biotoxins during seafood safety inspections (type & #/month)	The viability of micro-organisms is strongly influenced by temperature, pH and water activity, all of which are influenced by climate change (Ryder *et al*., 2014). Biotoxins to focus on : ciguatera and shellfish poisons (Goulding, 2016)
Extreme events	S9: Damage and loss to fisheries-sector assets	Core	S.9.1 Type of assets lost or damaged and their value (US$) due to weather and climate-related disasters	Countries undertake Damage and Loss Assessments (DALA), disaggregated information for the fisheries sector could be used to report on this indicator. Guidelines are available to undertake DALAs (e.g., PIOJ, 2012).

Data collection:

The series of tables below include guidance on data collection for all indicators except S6 (Fishery production). National governments already collect data for S6, report on this indicator and feed into global datasets (World Bank, FAOSTAT, FAO FishStat), with additional plans afoot to improve data collection (FAO, 2019). The data-collection approach for the rest of the indicators includes key informant interviews / surveys at landing sites or fish markets (Standard Sample Design #1) and compilation of reported data (food safety inspection reports, loss and damage assessments). Where capacity is limited, effort should focus on populating core indicators.

S7. Disruptions to fishing operations	
	S7.1 Foregone fishing days / month due to weather, *Sargassum* incursions
Response design (How)	• Key informant interviews / surveys at landing sites • Capture of respondents' socio-demographic characteristics is also recommended: sex (M/F); age (<18; 18-65; >65); category (full time / part time)
Sample design (Where and When)	Sample unit: Fishing vessels at landing sites Strata: 4 quadrants (NE, NW, SE, SW) Selection of sites: same as for landing surveys, countries that use market surveys instead should capture at nearby landing sites within each quadrant. Within sites, capture information for every other returned vessel Timing: monthly
Capacity requirements	Personnel: Training in the conduct of the interview / survey; personnel with some experience in qualitative research methods Equipment: Rugged tablets (water-resistant, drop proof) for streamlined data capture, where possible; monthly weather records, in case this is needed to prompt respondents.

S8. Non-compliance with food safety standards	
	S8.1 Presence of unacceptable levels of biotoxins (Ciguatera, shellfish poisons) during seafood safety inspections (type & #/month)
Response design (How)	• Compilation of secondary data: reports of food safety inspections by the Fisheries Department. Desired information: instance of biotoxin breach / biotoxin / location / type and number of seafood products / unit value of seafood product • Compilation of secondary data from hospitals on number of cases of illness from Ciguatera and shellfish poison provides an alternative approach to data collection if reliable and regular reports from food safety inspections are not feasible to acquire. In this case the metric would be "Cases of illness due to Ciguatera and shellfish poisoning (type & #/month)
Sample design (Where and When)	Sample unit: Inspection points (seafood processing plants, hotels, beaches and restaurants) or hospitals (if collecting proxy data) Strata: 4 quadrants (NE, NW, SE, SW); overlay inspection points on these 4 quadrants Selection of sites: N/A; compile information from all reporting activities. Timing: compile monthly statistics on a quarterly basis
Capacity requirements	Personnel: Collaboration with food safety inspection officers, proficiency in Excel or similar Equipment: No special equipment required

S9: Damage and loss to fisheries-sector assets	
	S.9.1 Type of assets lost or damaged and their value (US$) due to weather and climate-related disasters
Response design (How)	• Compilation of secondary data: damage and loss assessment reports in the aftermath of weather and climate-related disasters (e.g., excess rainfall, tropical cyclones). Desired information per hazard event: physical units of structures, vessels, gears (e.g., traps, lines, nets), catches lost or damaged due to the hazard event and their monetary value.
Sample design (Where and When)	Sample unit: N/A Strata: 4 quadrants (NE, NW, SE, SW); data on damage and losses is typically aggregated by parish, which can be overlaid onto these 4 quadrants Selection of sites: N/A; compile information from all reports. Timing: compile monthly statistics on a quarterly basis
Capacity requirements	Personnel: Collaboration with disaster management agencies; proficiency damage and loss assessment methods (particularly if fisheries officers are involved in assessment activities), proficiency in Excel or similar Equipment: No special equipment required

Potential Data Analyses:

The methods outlined above permit: (1) scaling up estimates for to the broader population for S7 indicator values generated by interviews / surveys at sites of different size classes (primary, secondary, tertiary landing sites), (2) reporting on the variability in these estimates among size classes and (3) presenting unweighted and unscaled indicator values per quadrant for S8 and S9. Other possible analyses are as follows:

- Validate / calibrate models used in Cheung *et al.* (2019) (Work Package 1 under this project), which projected reduction in maximum catch potential in the EEZs of countries studied by mid-century due to climate change
- Pool sector-specific data on loss and damages from tropical cyclones across the region to improve the

damage function used in Boyd and Ryan (2019) (Work Package 1 under this project)

- Inform improvements to food safety protocols and capacity development of supply chain actors
- Inform priorities for adaptation of land-based fisheries assets and emergency preparedness among fishers, including applications for insurance coverage

The Fishery Performance Indicators: A Management Tool for Triple Bottom Line Outcomes

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4.17 Monitoring Card 8: Changes in Post-Harvest Productivity

BQ8: How is post-harvest productivity changing in response to supply constraints from climate change?

Rationale:

Fish spoilage is a major issue within the industry, both at sea and during sales (Khan *et al.*, 2019). While at sea, fishers use a number of strategies to prevent fish spoilage, including use of ice, an ice box (freezer), covering fish with banana leaves and removing fish guts. However, their effective and consistent application can be hampered by lack of availability of ice and other cold-storage solutions (DoC, 2011). Fish discards (e.g., heads, skin, bones) are common during processing, creating loss but also an opportunity for value addition into commercial uses (e.g., fishmeal, bait or pet food). With potential constraints to raw material supply on the horizon, due to climate change impacts and efforts to curb overfishing, post-harvest activities should make efforts to reduce losses and waste, and embark on value-added production (FAO, 2011). Strategies such as these can also be useful during short-term supply gluts.

Tracking changes in post-harvest productivity equips managers with information on opportunities for improving sector performance. Since commercial opportunities and changes in regulations can influence trends in post-harvest productivity and product enhancements, changes in post-harvest productivity need to be tracked alongside climate change-induced constraints to supply.

Indicators:

The indicators selected to understand post-harvest productivity focus on waste and value addition. Metrics stem from questions related to the practices of fishers elicited through Industry Censuses (DoC, 2011) and literature on post-harvest performance (FAO, 2011; Stanford *et al.*, 2017; Anderson *et al.*, 2015). The assumption is that climate change-induced constraints to supply will motivate fisherfolk to maximize the use of raw material and extend the value of catches, decreasing discards and instances of fish spoilage and increasing the entry of improved products. These types of behavioural changes in response to a supply signal are also evidence of adaptive capacity.

Category	Indicator	Priority	Metric	Comments
Waste reduction	S10. Discards	Core	S.10.1 Average discards per week by weight (pounds)	Includes component of catch thrown overboard before landing and disposed of between landing and sale.
		Secondary	S.10.2 Proportion of catch discarded per week by weight (pounds)	
	S11. Fish spoilage	Core	S11.1 Reported use of spoilage-prevention methods at sea (%)	Methods include, ice box, ice, gut removal, banana leaf cover and crocus bag cover and electricity-powered freezers. Power failures can disrupt access to cold storage options.
		Core	S11.2 Reported use of spoilage-prevention methods during transportation (%)	
Value addition	S12: Improved products	Core	S12.1 Proportion of harvest meat weight going into certified, branded, fresh premium, portioned, preserved or other value-added products (%)	Processing and marketing increases catch value for fishing households (Stanford *et al*., 2017). This metric is modified after Anderson *et al*. (2015). This BQ focuses on value addition, indicator S4.1 measures the proportion of fisherfolk able to sell different fish species than they have been used to selling,

Data collection:

Data-collection methods including response design, sample design and capacity requirements are shown for discards, fish spoilage and improved products. The data-collection approach relies on key informant interviews / surveys at landing sites or fish markets (Standard Sample Design #1) and compilation of reported data (food safety inspection reports, loss and damage assessments).

	S10. Discards	**S11. Fish spoilage**		**S12: Improved products**
Response design (How)	**S.10.1 Average discards per week by weight (pounds)**	**S11.1 Reported use of spoilage-prevention methods at sea (%)**	**S11.2 Reported use of spoilage-prevention methods during transportation (%)**	**S12.1 Proportion of harvest meat weight going into certified, branded, fresh premium, portioned, preserved or other value-added products (%)**
	• Key informant interviews / surveys at landing sites (required) • Potential for snowball interviews with vendors and processors at less frequent intervals • Capture of respondents' socio-demographic characteristics is also recommended: sex (M/F); age (<18; 18-65; >65); category (full time / part time)			
Sample design (Where and When)	Sample unit: Fishing vessels at landing sites Strata: 4 quadrants (NE, NW, SE, SW) Selection of sites: same as for landing surveys, countries that use market surveys instead should capture at nearby landing sites within each quadrant. Within sites, capture information for every other returned vessel Timing: monthly for direct interviews to fishers (first point of contact at the vessel); snowball sampling to other value-chain actors associated with the vessel annually. S11.1, S11.2 and S12.1 are relevant for vendors and processors as well as fishers			

Capacity requirements	Personnel; Training in the conduct of the interview / survey; personnel with some experience in qualitative research methods Equipment: Rugged tablets (water-resistant, drop proof) for streamlined data capture, where possible

Potential Data Analyses:

The methods outlined above permit: (1) scaling up estimates to the broader population for indicator values generated by direct interviews / surveys at sites of different size classes (primary, secondary, tertiary landing sites); (2) reporting on the variability in these estimates among site size classes and (3) presenting unweighted and unscaled indicator values from snowball sampling per quadrant. Possible analyses are as follows:

- Comparing differences in waste creation and product improvements along a north-south gradient and alongside data on the physical environment (BQ1), fished species distributions (BQ3) and fish productivity (BQ4)
- Comparing differences in waste creation and product improvements as a function of socio-demographic variables (sex, age and whether full or part time occupant of the sector)

Countries can also use indicator values for S11-S13, combined with values for indicators S4 and S5 (BQ6) and S13 (BQ9) to develop a fisheries "adaptive capacity index" and track trends over time and space using one variable. This composite index could be the unweighted average of all five indices, with resulting values normalized and scaled to range from 0 to 1. Higher values would represent greater adaptive capacity.

Sharing findings from analysis of indicators S11 and S12 with fisherfolk via town hall meetings or focus group discussions is encouraged as a way to enable co-production of knowledge, including interpreting trends, identifying root causes and action points.

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4.18 Monitoring Card 9: Changes in Uptake of Climate Risk Management

BQ9: How is uptake of climate-risk management measures in fisheries changing?

Rationale:
Extreme weather events are expected to increase in frequency / intensity or duration and the economic and social impacts these events have on fisherfolk and throughout the fish value chain can be significant. Impacts include reduced personal safety at sea, loss of life, losses of assets and equipment, foregone revenue from disruptions to supply chains and critical infrastructure and services. Implementing and promoting risk management is a crucial component to increasing resilience and fostering sustainable livelihoods. Early-warning systems and safety at sea protocols (Shaffril *et al.*, 2017; Chang *et al.*, 2013; Badjeck et al., 2010; Cinner et al., 2018; FAO, 2019); use of safe harbours (Anderson *et al.*, 2015; Oxenford and Monnereau, 2018), use of insurance and safety net schemes (Stanford et al. 2017; Cinner et al., 2012; Badjeck et al., 2010; Government of St. Lucia, 2018); and efforts to increase redundancies and alternatives (e.g., back-up refrigeration) are some of the strategies being pursued in small-scale fisheries in the region and beyond.

Understanding the baseline use of a range of climate risk management measures across the value chain and tracking changes in uptake over time and space provides information to substantiate the need for government interventions and course corrections in program design and delivery if the extent of uptake of existing measures is less than societally optimal.

Indicators:
The indicator selected to monitor update of climate risk management practices and measures is based on a core indicator used and promoted by the Pilot Program for Climate Resilience (PPCR): extent to which vulnerable households, communities, businesses, and public-sector services use improved PPCR-supported tools, instruments, strategies, and activities to respond to climate variability or climate change (CIF, 2018). A *"climate-responsive tool, instrument, strategy, or activity is one that incorporates climate variability and climate change considerations or can be applied to enhance climate risk management of people, products, or services (CIF, 2018)".* For this purpose of this monitoring framework, attribution to PPCR is not necessary and the targets are fisherfolk.

Indicator	Priority	Metric	Comments
S13: Use of climate-responsive tool, instrument, strategy, or activity	Core	S13.1 Extent to which fisherfolk use tools, instruments, strategies and activities to manage risks from climate variability or climate change (type, # and frequency of use)	The intent is to understand practices by fishers, boat owners and fish vendors. Response options would to be tailored to national contexts, using the following typology. Note that the examples provided are non-exhaustive. • **Technologies or infrastructure investments:** use of safe harbours, FEWER, fuel efficient boats and low-emitting engines, use of improved marketing facilities, back-up refrigeration • **Data, analytical work, technical studies and training**: safety at sea protocols, vulnerability or climate risk assessments, safe handling techniques • **Planning:** supplier arrangements to diversify inputs (e.g., catch for processors) • **Public awareness platforms**: weather information, stakeholder networks (FEWER Whatsapp group) • **Financial instruments**: micro/insurance

			(COAST, Livelihood Protection Policy), micro/finance, small grants, loans • **Social safety nets**: loans from family / friends, lending circles	

Data collection:
Data-collection methods including response design, sample design and capacity requirements are shown below. The data-collection approach relies on key informant interviews / surveys at landing sites or fish markets (Standard Sample Design #1). In cases where government departments or non-governmental organizations already compile such information (e.g., PPCR programming units), it may be possible to leverage reported data as well.

S13: Use of climate-responsive tool, instrument, strategy, or activity	
	S13.1 Extent to which fisherfolk use tools, instruments, strategies and activities to manage risks from climate variability or climate change (type, # and frequency of use)
Response design (How)	• Key informant interviews / surveys at landing sites (required) targeting fishers • Potential for snowball interviews with other value chain actors at less frequent intervals, targeting vendors and boat owners who are not fishers • Capture of respondents' socio-demographic characteristics is also recommended: sex (M/F); age (<18; 18-65; >65); category (full time / part time)
Sample design (Where and When)	Sample unit: Fishing vessels at landing sites Strata: 4 quadrants (NE, NW, SE, SW) Selection of sites: same as for landing surveys, countries that use market surveys instead should capture at nearby landing sites within each quadrant. Within sites, capture information for every other returned vessel Timing: monthly for direct interviews with fishers (first point of contact at the vessel); snowball sampling to other value-chain actors associated with the vessel annually
Capacity requirements	Personnel; Training in the conduct of the interview / survey); personnel with some experience in qualitative research methods; knowledge of climate risk management measures of relevance to respondents / typology Equipment: Rugged tablets (water-resistant, drop proof) for streamlined data capture, where possible

Potential Data Analyses:
The methods outlined above permit: (1) scaling up estimates to the broader population for indicator values generated by direct interviews / surveys at sites of different site size classes (primary, secondary, tertiary landing sites); (2) reporting on the variability in these estimates among size classes and (3) presenting unweighted and unscaled indicator values from snowball sampling per quadrant. Possible analyses are as follows:

- Comparing differences in uptake of climate risk management along a north-south gradient and alongside data on fished species distributions (BQ3), (BQ4), diversification (BQ6), fishery production (BQ7) and post-harvest productivity (BQ8)
- Overlaying penetration rates of climate risk management over mapped information on exposure to climate-related hazards to identify potential risk management shortfalls and capacity gaps
- Along with information on new programs (objectives, intended beneficiaries, area of influence), data collected against this indicator could support effectiveness monitoring

Countries can also use indicator values for S11-S13, combined with values for indicators S4 and S5 (BQ6) and S13 (BQ9) to develop a fisheries "adaptive capacity index" and track trends over time and space using one variable. This composite index could be the unweighted average of all five indices, with resulting values normalized and scaled to range from 0 to 1. Higher values would represent greater adaptive capacity.

Sharing findings from analysis of indicators S13 with fisherfolk via town hall / community meetings or focus group discussions is encouraged as a way to enable information sharing, co-production of knowledge, including interpreting trends, identifying root causes and action points.

Key References:

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5. AGGREGATION OF INFORMATION

5.1 Synthesis across Spatial Scales

Use of consistent indicators, sampling and response designs enables indicators to be reported at multiple spatial scales. Reporting may occur regionally on the lowest common denominator, whether that is the species, species group, indicator, strata, among others. Information may not be sub-divided to smaller scales than the unit of measure. Indicators may be aggregated to national or regional scales using simple stratified random sample estimation methods to report average or total values by strata. A data collection initiative by the Western Central Atlantic Fishery Commission (WECAFC) is currently underway and encompasses the entire area of interest to the Caribbean Regional Fisheries Mechanism (CRFM) (FAO, 2019). The spatial resolution of the data collection program under development is coarser than that proposed here, so data collected and analyzed using the project's proposed framework could also be aggregated to support the WECAFC initiative.

If thresholds exist (e.g., the reef health index used in the Eastern Caribbean Coral Reef Report Cards; http://www.agrra.org/resources/) then it may be more informative to report scores rather than raw indicators. For example, maps could be presented illustrating each of the reef sites and their score to illustrate any spatial patterns requiring further investigation.

For some of the questions, analysis can be done independent of national boundaries. For example, all of the available information on distribution of species may be combined and indexed by the latitude / longitude. The combined number of observations should enable species distributions to be mapped more completely and inform the location of leading and lagging edges and potential range shifts. These updated occurrence datasets can also be used to validate and update species distribution modelling under future climate projections.

5.2 Synthesis across Big Questions

The real power of the proposed monitoring framework is in the ability to combine multiple types of information from multiple questions to inform management strategies. Weight-of-evidence approaches as well as traditional regression or modeling approaches may be appropriate for combining information. The term "Weight of Evidence" has been widely used in the literature but there is no agreed upon definition (Weed, 2005). Broadly speaking, weight-of-evidence approaches use multiple lines of evidence to make statements about the relative likelihood of different hypotheses (Pickard *et al.*, 2019). Burkhardt-Holm and Scheurer (2007) outline an approach that evaluates the plausible mechanism, exposure, correlation/consistency, thresholds, specificity, and experimental evidence through a series of questions (Figure 6). Given the complexity of monitoring and evaluating the magnitude and severity of broad climate change impacts on coastal fisheries a weight of evidence approach is recommended (MRAG 2010).

Regression analysis may also prove useful as it is a fundamental statistical tool used to estimate relationships between one or more response variables and one or more explanatory variables using observed data. There are many variations on this overarching methodology and numerous texts on the subject, depending on the details (Dobson 1990; Draper *et al.*, 1998). This method is relatively complex and requires advanced statistical expertise. Existing models may be validated and updated as new data are collected.

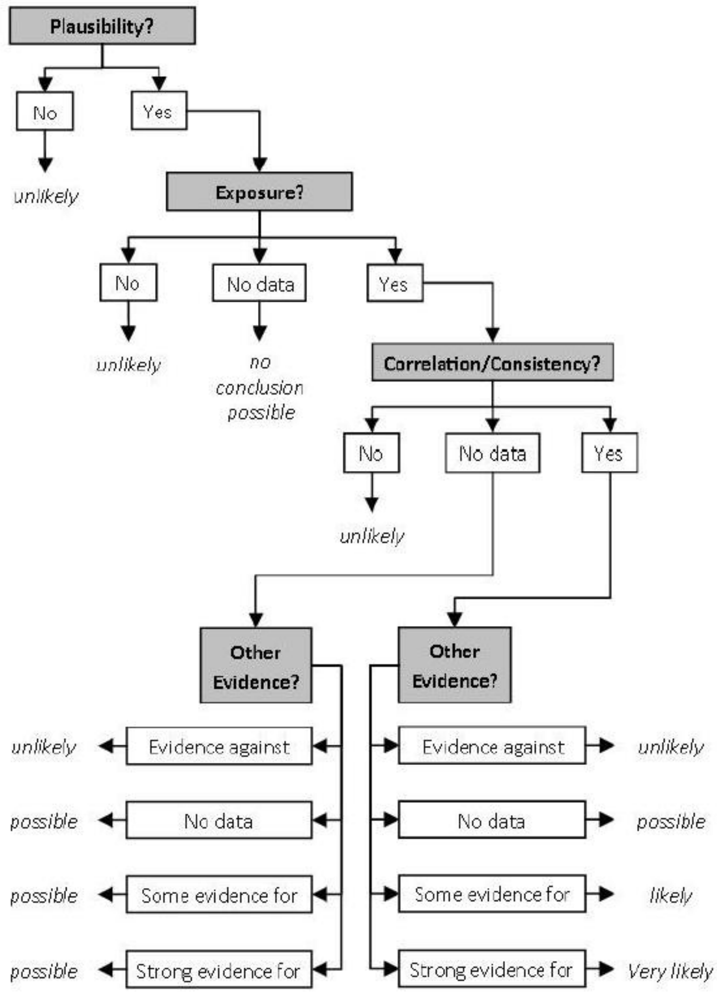

Figure 6: Guiding questions to assess the strength of and agreement among evidence (Adapted from Burkhardt-Holm and Scheurer, 2007).

5.3 Addressing Uncertainty

As described above, we are often faced with multiple sources of evidence and it can be very difficult to determine how to weight those different sources. Bates *et al.* (2013) propose an approach to evaluate the amount, quality and consensus of evidence. This information is then combined into a "confidence score". For example, in cases with low-quality information (e.g., indirect accounts or anecdotal evidence) but a large volume of evidence that all agrees, it would still be possible to have high confidence in the conclusions. Likewise, high-quality data with less volume (i.e., fewer sites) may still be considered high confidence.

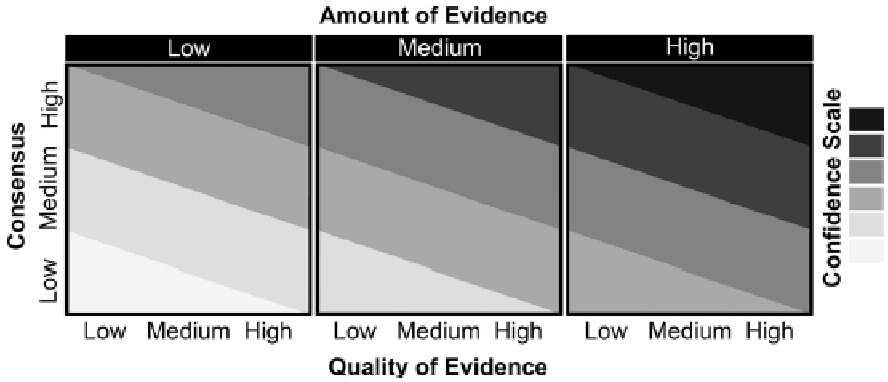

Figure 7: This figure illustrates how the amount of evidence, quality of evidence, and consistency of evidence (i.e., consensus) can be used to generate a confidence score (Source: Bates et al., 2014).

Similarly, the Intergovernmental Panel on Climate Change (IPCC) has issued guidance to evaluate the degree of confidence in findings of climate change assessments (Mastrandrea *et al.*, 2011) (Figure 8).

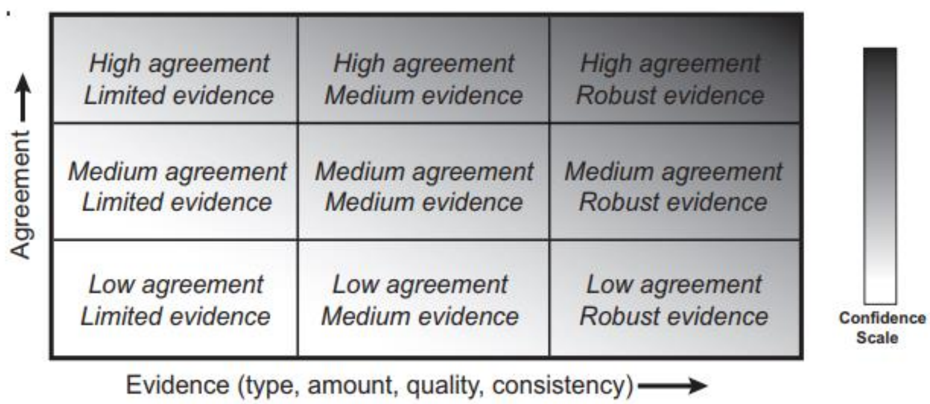

Figure 8: Guidance provided by the IPCC to authors of climate change assessments to evaluate confidence in their findings (Mastrandrea et al., 2011).

The adoption of practices such as these in reporting results from the analysis of monitoring data helps readers interpreting findings, builds credibility and confidence in decision-making and enables the identification of research priorities.

6. CONCLUSIONS

Adapting fisheries to climate change and variability is an iterative process that relies on sustained monitoring to inform many of its steps. Yet, several challenges hinder monitoring for climate change effects on fisheries and for tracking responses to these effects. These include inadequacies in the spatial and temporal scales of monitoring efforts, reliance on short-term projects and inconsistent data-collection methods, which limit the ability to undertake inferential analysis. As well, traditional monitoring methods to inform stock assessment were not devised to address particularities of artisanal, multi-gear, multi-species, small-scale fisheries.

This chapter provides a transparent, flexible and feasible framework to track priority climate, ecological and socio-economic indicators to support climate-smart fisheries management and planning in the Caribbean. The framework, which draws on approaches consistent with MRAG (2010), encourages a focus on answering nine Big Questions that are applicable region-wide. The framework includes a master sample frame with nested sampling at co-located sites. The framework includes practical "monitoring cards" that, among other aspects, summarize why, what, when, where and how to monitor for each Big Question. Use of a master sampling frame, core indicators and standardized methods facilitates data analysis across spatial scales (e.g., reporting at regional, national, site, species and strata –levels) and Big Questions. Above all else, the framework is a toolkit that countries can take up over time, based on their needs and capacities, refining design considerations using an adaptive approach.

By linking monitoring to the needs of decision makers – e.g., as inputs into designing adaptation projects or reforming existing fisheries management approaches – the value of investing in monitoring quickly becomes apparent. Nevertheless, continued funding and political support are critical to sustaining climate change monitoring efforts. Chapters D and E in this publication offer insights on enabling conditions and strategies that promote successful implementation of climate adaptation planning.

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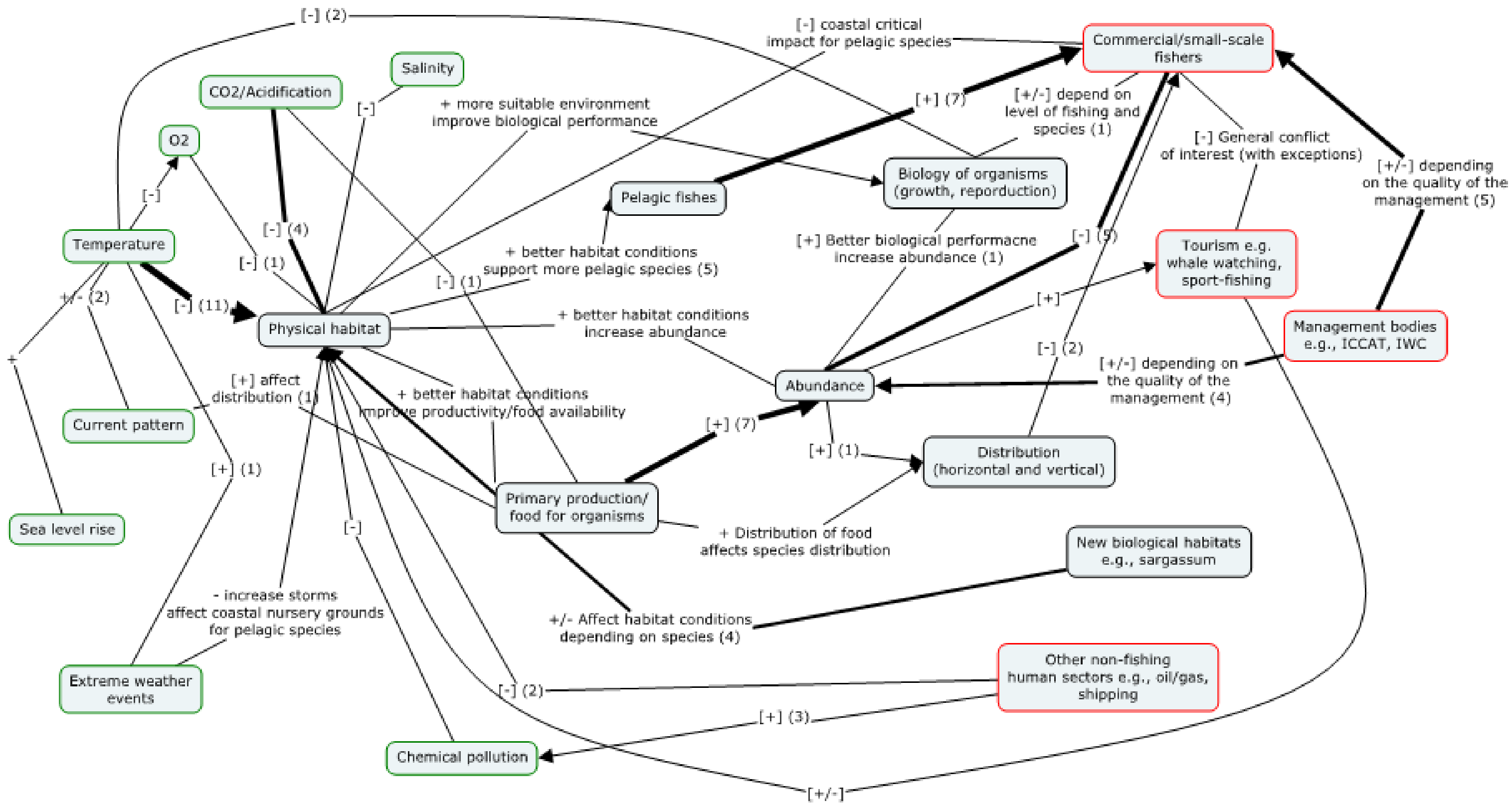
APPENDIX I: Conceptual models explaining linkages between climate change and the fisheries sector in the Caribbean

The qualitative conceptual models are provided here as background information for readers wishing to further understand the relevance of monitoring priorities (Big Questions and indicators) proposed in Chapter D.

(A)



(B)

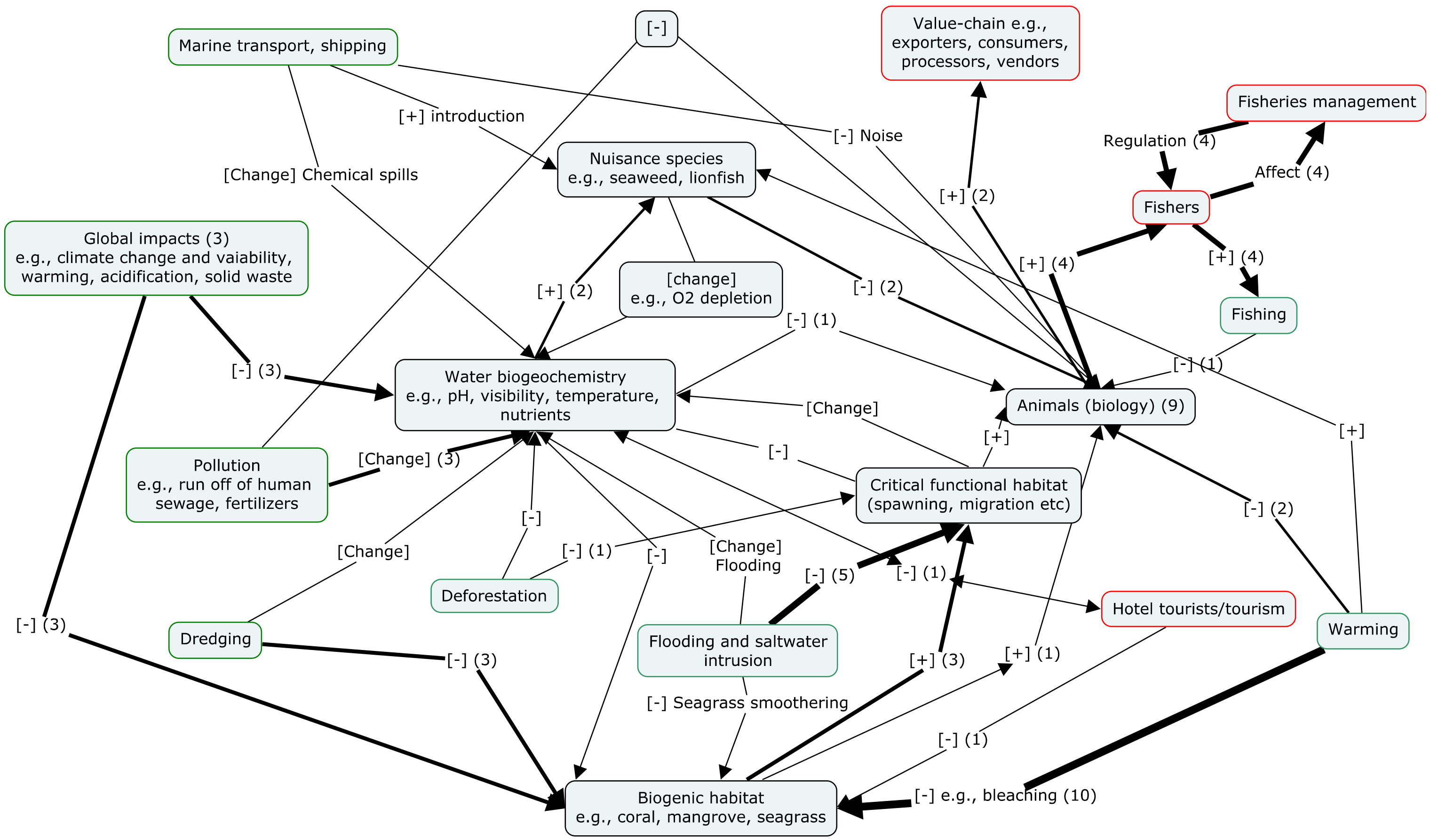
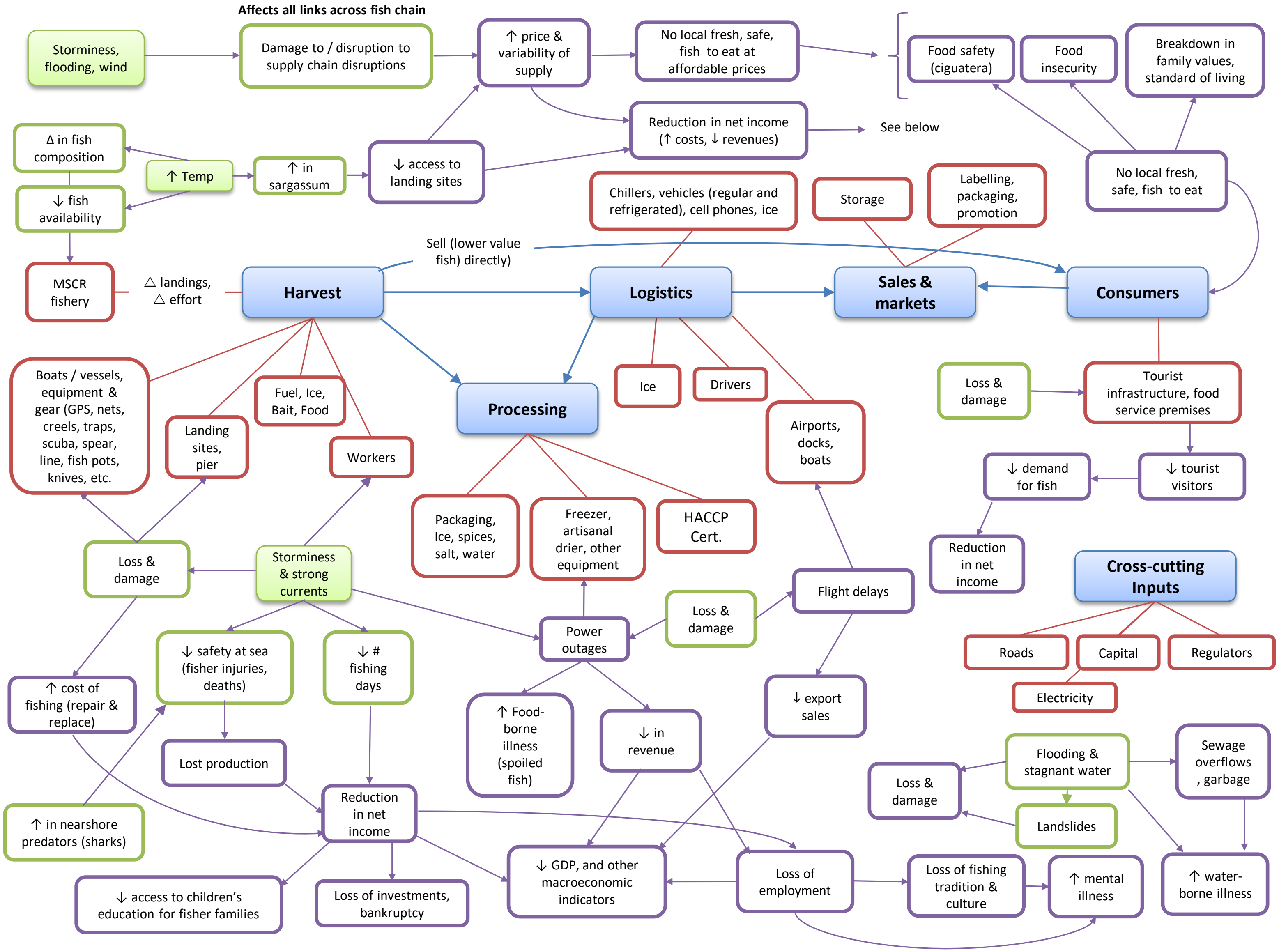


Figure 9: Conceptual models of the (A) pelagic ecosystem and (B) seagrass-mangrove-coral reef ecosystem visualized using Cmaptool. Boxes represent the biophysical components (black outline), environmental drivers (green outline) and human components (red outline) of the ecosystems. The arrows represent linkages and the nature of their impact ([+]: positive influence, [-]: negative influence). The number on each arrow represents the vote count of their importance. The thickness of the arrows is positively related to the number of votes to highlight the most important linkages.

(A) Mangrove-Seagrass-Coral Reef Fisheries



(B) Pelagic Fisheries

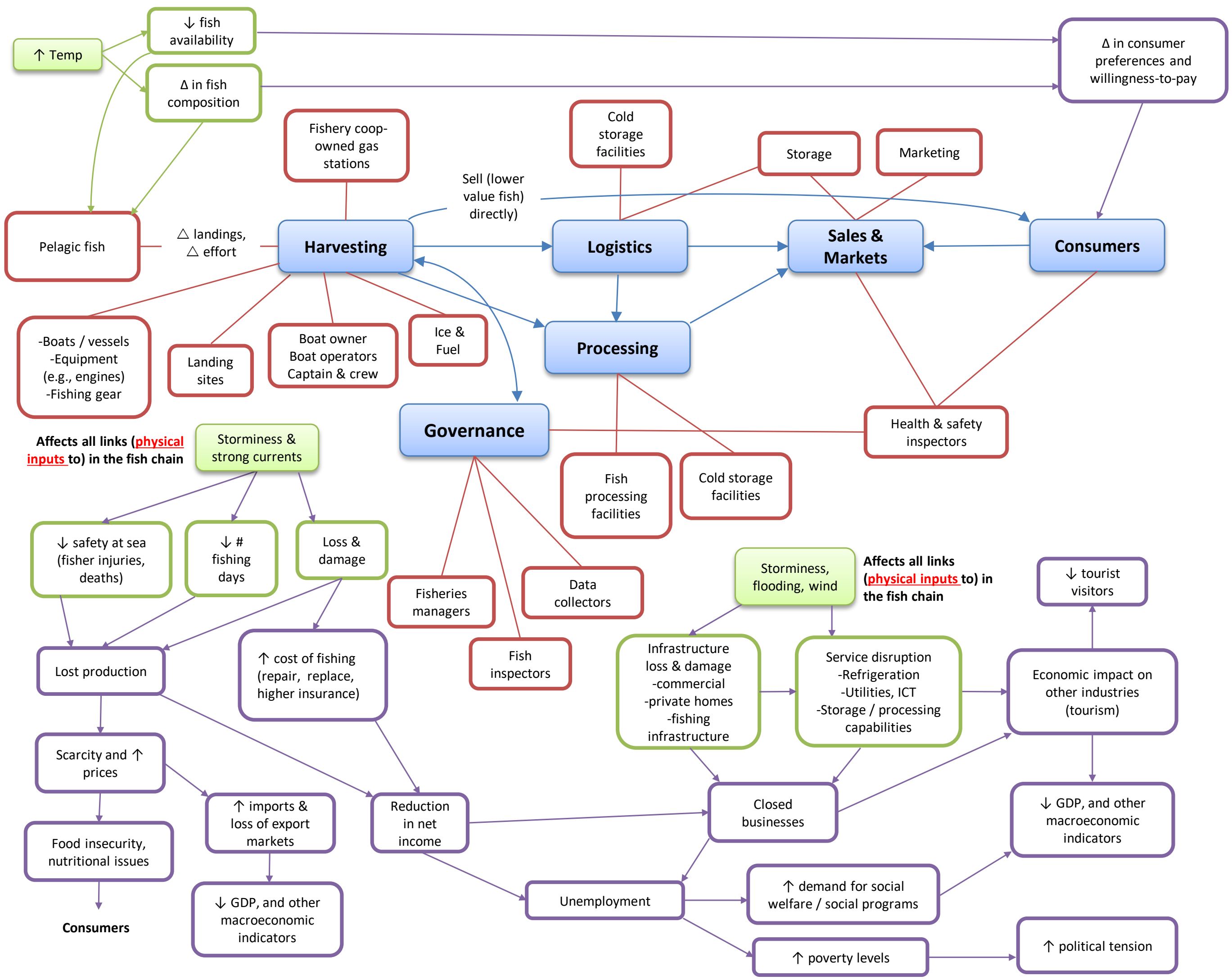


Figure 10: Conceptual models of the (A) seagrass-mangrove-coral reef fisheries and (B) pelagic fisheries visualized using PowerPoint. Blue shaded boxes represent the key fisheries-sector activities, boxes outlined in red represent assets and inputs into these activities; green shaded boxes and outlines represent climate- drivers and direct impacts; boxes outlined in purple represent social and economic consequences of the direct impact

APPENDIX II: Situational Awareness Question Template – Monitoring (by Country)

These fisheries monitoring questions aimed at documenting the current situation are drawn from ESSA's experience in past projects as well as questions recommended for guiding assessment of fisheries management practices in the FishPath decision-support tool (Dowling *et al*., 2016). We include them as an appendix in case the CRFM and / or member countries wish to replicate this type of assessment in a few years' time, in an attempt to evaluate changes in monitoring capacity.

Existing Monitoring Programs

1. What monitoring programs are currently in place? For each one, record:

a. Name and Implementing Agency

- Name of program and implementation agency

b. Description

- Description of the program (e.g., overall aim and related monitoring activities – e.g., piezometers to monitor groundwater)

c. Indicators

- List the indicators resulting from the monitoring program, focusing on those of most relevance to the Big Questions. May include…
- Fishery *Dependent:*
    - Catch (total landings)
    - Effort / CPUE
    - Discarded catch
    - Size / weight
    - Size distribution
    - Geographic distribution
    - Sex composition
    - Smallest/average/largest size (or other percentiles related to reference point proxies) of fish in catch
    - Approximate relative proportions of size of fish in catch (small, medium, large)
    - Multispecies fisheries: For each "key" species, what data is available? Is species composition or ratios of species composition informative?
- Fishery *Independent:*

If fishery independent surveys are available, what types of data are available? May include:

- Total biomass thresholds
- Size data from survey—mean, maximum (or other percentiles related to reference point proxies)
- Habitat mapping

- Is there any data collection or assessment integrating social, bio-ecological, and economic considerations of fisheries? (Salas *et al*. 2007)

d. Response Design (how data is collected)

- There are different approaches to obtaining the same estimate. Approaches often differ in cost, spatial coverage and precision, one is usually improved at the sacrifice of the other. Include frequency of data collection.
- Include references (links) to program protocols if available and ensure they are uploaded in the Dropbox folder

e. Data Format & Accessibility

- What forms of data are currently available? May include:
    - Logbooks
    - Port monitoring
    - Observers
    - Surveys
    - Snapshots
- Is the data readily accessible (e.g., are there potential legal/ bureaucratic hurdles)?
- How is the information collected and stored (e.g., paper, electronic database)?

Use a table or spreadsheet template to record results as follows:

Monitoring Program	Description	Indicators	Response Design (how they are acquiring the monitoring data, protocols with references)	Data Format & Accessibility

Existing Monitoring Capacity

1. **Enabling Structures:** What legal, policy or other institutional requirements (e.g., international reporting) compel or support monitoring activities?
2. **Decision Making:** What decision making processes are in place to make use of fisheries and environmental monitoring data?
3. **Learning Culture:** What processes are in place to take the results from analysis of monitoring data and make adjustments to management, programs or projects? How is learning encouraged as an organization?
4. **Responsibilities:** Who is responsible for which aspects of monitoring and data management? For all aspects of monitoring, identify who is responsible.
5. **Assets:** What assets (people, skills, IT and software) are available for collecting, analyzing, or using fisheries and environmental data? E.g.,
    - # of people dedicated to field data collection
    - # of people dedicated to fisheries (NRM, harvest and post-harvest) extension and communication with communities and value chain actors
    - # of people with statistical analysis capacity (e.g., use of R)
    - # of people with GIS capacity and types of GIS tools used (e.g., ArcGIS, QGIS)
    - If you have used GIS then which tools do you have experience with - ArcGIS, QGIS, or other tools?
    - IT setup
    - # of people with capacity in social science methods (e.g., household surveys, value chain analysis, economic analysis)
6. **Capacity Challenges:**

What are the biggest capacity challenges for collecting, analyzing, or using fisheries and environmental data? Capacity challenges could be: financial, lack of people, lack of training, lack of infrastructure.

- Are home ports/landing sites and markets numerous / spatially disaggregated / variable over time, such that representative sampling would be difficult to obtain given the available capacity
- What kind of institutions are in place that could help with monitoring and research (e.g., Government, universities, fishery cooperatives, NGOs)?

- What types of training could make the biggest difference in improving capacity for collecting, analyzing, or using fisheries and environmental data?

7. **Funding:** What is the funding source for fisheries and environmental monitoring? What is the funding cycle? For example, annual funding from government appropriations or 3-year projects?
8. **Data Management:** What is the data management strategy? How are the data stored (e.g., relational data base, filing cabinet)? Where are data stored (cloud, someone's hard-drive)? Who is responsible for managing these data? What standards are in place for data formats and data sharing?

D. Identifying Potential Climate Change Adaptation Strategies for the Fisheries Sector

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1. INTRODUCTION

Once assessment tools have helped to characterize the nature of climate change vulnerabilities and impacts, the next step is to identify adaptation strategies that might help to manage these effects (USAID, 2009). As with any management problem, it is best to begin by first considering a range of management options or alternatives and how each might help to achieve the desired management objectives.

This chapter summarizes the current state of knowledge on possible climate change adaptation actions for the fisheries sector, drawing on a range of regionally-oriented resources including peer-reviewed literature, government reports, documentation of past adaptation initiatives, and input from national fisheries representatives from the case-study countries for this project. Many of the potential climate change adaptation actions that have been identified for the fisheries sector are variants of more general coastal management, fisheries management, and sustainable development strategies that have been modified to account for the anticipated effects of climate change (West *et al.*, 2016, Parker *et al.*, 2017, Poulain *et al.*, 2018, IFAD, 2014).

The types of climate change adaptation actions identified fall into three broad classes:

- Habitat Management Actions: These adaptation actions help to reduce cumulative non-climate stressors on marine habitats which helps to improve overall coastal ecosystem health, preserve the provision of coastal ecosystem services to the fisheries sector, and ultimately increase coastal ecosystem resilience to climate change.
- Harvest Management Actions: These adaptation actions help to modify fisheries practices to ensure ongoing yet sustainable levels of harvest in light of the anticipated effects of climate change to ensure the persistence of fisheries stocks and the benefits they provide into the future.
- Sustainable Livelihoods and Economic Diversification Actions: These adaptation actions focus on protecting the physical assets that fishing communities require to pursue their livelihoods and supporting fisherfolk throughout the value chain as they transition to new, climate-resilient practices and livelihoods.

For each action presented in this chapter, we provide profiles that include a rationale for the action within the climate change context, linkages to broad adaptation objectives for the fisheries sector, linkages to monitoring systems, and practical considerations for implementation in the Caribbean context. Once the portfolio of potential actions has been defined, managers must then evaluate and select the most appropriate actions to implement in light of current management priorities as well as capacity constraints (USAID, 2009). A framework for evaluating and selecting among these potential adaptation options is outlined in Chapter F of this report.

Although this chapter focuses on targeted measures to reduce specific climate change impacts or vulnerabilities, there is also a need for overarching institutional strategies to foster an enabling governance, planning, and policy environment within which the actions outlined here can be successfully implemented (Poulain *et al.*, 2018). Two policy documents guide the creation of this enabling environment for the fisheries sector in the Caribbean. One is the Regional Strategy and Action Plan for Climate Change Adaptation and Disaster Risk Management in Fisheries and Aquaculture (CRFM, 2013). Also, the region recently developed a Protocol on Climate Change Adaptation and Disaster Risk Management in Fisheries and Aquaculture[20], building on the existing Caribbean Community Common Fisheries Policy (CCCFP) (CRFM, in press).

2. POTENTIAL ADAPTATION OPTIONS

2.1 Habitat Management Actions

Overview: Adapting to a changing climate includes a variety of strategies for protecting, restoring, and even creating valuable habitats for economically-important fish and invertebrate species. Reducing other cumulative stressors on critical habitats for fished species will help these marine ecosystems be more resilient to the effects of climate change and improve their ability to sustain existing and future fisheries. Adaptation actions in this class may be applied to either land or marine sites, and simple decision-rules can help to determine whether land-based management strategies will be more effective than ocean-based management strategies for promoting ecosystem recovery (Saunders *et al.*, 2017). In general, land-based restoration actions are more effective where most vegetation within coastal watersheds has already been lost or degraded but marine ecosystems are not declining at a rapid rate, while ocean-based restoration actions are more effective where most coastal watershed restoration is intact yet marine ecosystems continue to decline (Saunders *et al.*, 2017).

2.1.1 Reduce Landscape Stressors on Coastal Habitats

Rationale: Coastal habitats facing stress from direct effects of climate change will be more vulnerable to the negative consequences of harmful inputs from land-based activities, particularly sedimentation and excessive nutrient loads. Reducing undesirable inputs to the marine environment is an important component of reducing cumulative stressors on coastal environments which can provide near term benefits and help these habitats be more resilient to climate change (Bell *et al.*, 2018, Andersson *et al.*, 2019). Moreover, reducing these cumulative stressors can help to achieve the maximum possible benefits from other adaptation options, including marine protected areas (Suchley and Alvarez-Filip, 2018) and habitat restoration initiatives (Björk *et al.*, 2008; McLeod and Salm, 2006; Spalding *et al.*, 2014).

Activities within this class include upland vegetation management for erosion control and sediment trapping (e.g., planting for slope stabilization, riparian buffers), improving sediment management practices during coastal development, reduction of marine dredging activities, and reductions of untreated wastewater discharge into coastal waters. These activities will have the added benefit of mitigating increased hazards related to more frequent and severe rainfall, flooding, and landslides, anticipated under future climate scenarios.

These types of adaptation actions have been described as win-win scenarios (Bell *et al.*, 2018), insofar as they provide both short-term (improving coastal water quality and preserving existing ecosystem productivity) and long-term benefits (increase ecosystem health and resilience to future climate change).

[20] The Protocol is a result of technical cooperation between the Caribbean Regional Fisheries Mechanism (CRFM) and the Global Environment Facility (GEF)-funded Climate Change Adaptation in the Eastern Caribbean Fisheries Sector (CC4FISH) Project of the Food and Agriculture Organisation of the United Nations (FAO).

Objectives met: Adaptation to losses of productive fish habitats.

Considerations for Implementation: Vegetation management strategies will be among the simplest of these actions to implement at a range of scales, while implementing broader changes in coastal development practices and land use may first require regulatory reform that will be much more challenging. Site selection for implementation should be guided by a spatial site prioritization assessment using all available data on current habitat distributions, land use, and water quality. Implementation at priority sites will require stakeholder input and support as well as political will to counteract the perceived drawbacks of potential restrictions on land development and increased regulations on land-based activities (e.g., logging, resort development, land conversion to agriculture).

Information Needs & Monitoring Connections: At a minimum, coastal managers can use direct observations of coastal erosion and terrestrial runoff into marine environments to identify potential implementation sites. Where available, coastal habitat maps, land use maps, precipitation maps, and marine water quality monitoring data (e.g., turbidity, nutrient levels and pH) can also be compared to more effectively identify and prioritize areas where action is needed or likely to be needed. Additional information from climate change projections of future precipitation and extreme weather patterns can help to refine lists of priority areas by considering how shifts in precipitation patterns, storm frequency and intensity, and coastal hydrology will affect both (1) runoff of terrestrial inputs and (2) the longevity and effectiveness of adaptation interventions under a future climate (West *et al.*, 2016). Explicitly incorporating these climate-smart design considerations will help to extend the useful lifetime of interventions under a future climate.

Following implementation, measures of turbidity and nutrient levels in key habitats, particularly before and after land-based management has been implemented, will provide observable evidence that these actions are working as intended to improve coastal habitat quality.

Monitoring Card 2 (Changes in Critical Habitats for Fished Species) provides guidance on water quality indicators and metrics, including temperature, pH, suspended solids and turbidity.

2.1.2 Protect Critical Coastal Habitats Supporting Fisheries Species

Rationale: Coastal habitats including mangroves, seagrasses, and coral reefs are expected to experience adverse effects due to rising temperatures, decreasing pH, and an increasing frequency and severity of extreme weather events anticipated under a future climate. However, not all of these habitats will experience the same level of climate change risk due to natural variation in levels of exposure and vulnerability that can be exploited to increase climate resilience. For example:

- Some areas of marine habitats may benefit from reduced exposure to climate change due to their location in the seascape, such as coral reefs and seagrasses at greater depths (Bongaerts *et al*., 2010, Smith *et al.*, 2016), mangroves in areas that will allow for landward migration (McLeon and Salm, 2006), or any of these organisms occurring in small-scale variations in physical ocean conditions (microclimates) that are less sensitive to broader trends in temperature or pH (Woodson *et al.*, 2018)..
- Other areas of marine habitat may have already adapted to warmer temperatures or sea-level rise through natural phenotypic plasticity or evolutionary adaptation (McLeod and Salm, 2006, Howells *et al.*, 2016, Osman *et al.*, 2018).

Once identified, these habitats could be prioritized for protection to help contribute to future fisheries production and act as source populations to provide propagules for recolonization of broader coastal ecosystems (but see Smith *et al.*, 2016). However, some research cautions that climate refugia should be part of a broader portfolio that maximizes habitat diversity across protected area networks (McLeod and Salm, 2006, Björk *et al.*, 2008, Walsworth *et al.*, 2019). Protected area networks with greater habitat

diversity were found to facilitate evolutionary adaptation among corals and achieve better conservation outcomes than protected area networks including only climate refugia sites. This is partly because this diversity helps to hedge against environmental variability that may cause refugia locations to shift over time.
Objectives Met: Adaptation to a changing physical environment. Adaptation to losses of productive fish habitats.

Information Needs & Monitoring Connections: Implementation of this management option will depend on a sufficient diversity, spatial resolution, and temporal resolution of physical monitoring data to identify climate change refugia, ensure these anomalies persist over time, and inform site selection. In many cases, this might be possible using existing remote sensing and monitoring data. For example:

- existing maps may be used to delineate refugia based on broader geographic characteristics (e.g., depth characteristics, such as the use of bathymetric maps to delineate mesophotic zone refugia;
- long-term field monitoring data could indicate areas that appear to be less affected by extreme climate events, perhaps experiencing greater short-term (diurnal) fluctuations but less sensitivity to regional patterns (e.g., Woodson *et al.*, 2019) and
- habitat suitability map projections under future climate scenarios from the earlier impact assessment in this project (Cheung *et al.*, 2019) could provide a starting point for identifying refuge regions at larger spatial and temporal scales.

After implementation, ongoing assessment data of habitat status would be valuable to confirm the site's ongoing suitability as a refuge.

Monitoring Card 1 (Changes in the Physical Environment) and 2 Monitoring Card 2 (Changes in Critical Habitats for Fished Species) provides guidance on relevant indicators and metrics to identify candidate climate change refugia and monitor selected sites' continued suitability. Additionally, physical monitoring data can be used alongside reports of habitat and distribution of fishes (Monitoring Card 3: Changes in Fished Species Distributions) data to assess the effectiveness of climate change refugia in avoiding or reducing losses of productive fish habitat.

Considerations for Implementation: Protected area planning should consider the protection of climate change refugia as one part of a broader strategy emphasizing the protection of a diverse portfolio of marine and coastal habitats (Beyer *et al.*, 2018). Adding or modifying new protected areas to existing networks may require adjustments to existing protected area networks which might be difficult to achieve under the current regulatory frameworks for delineating conservation areas, which are often cumbersome, slow-moving, and spatially fixed.

The success of any protected area strategy depends strongly on the capacity, resources, and political will to effectively enforce protected status so that the intended benefits of these protections are realized. Where these conditions are lacking, managers may consider implementation of community-based protected area management initiatives for additional support, or consider alternative adaptation strategies until these conditions are met.

2.1.3 Restore Critical Coastal Habitats Supporting Fisheries Species
Rationale: Coastal habitats provide important ecosystem services contributing to climate change resilience, including as habitat for economically-important fisheries species, as coastal defenses against extreme weather, and as "blue carbon" sinks. Given that many of these habitats have been significantly degraded or lost across the Caribbean region, costal habitat restoration represents a key climate change adaptation strategy for the coastal fisheries sector (Guannel *et al.*, 2016, Wilson and Forsyth, 2018).

Mangroves: Mangrove forests are most vulnerable the impacts of effects of sea-level rise and extreme weather anticipated under future climate projections (McLeod and Salm, 2006). Beyond protecting the remaining healthy mangrove habitats, mangrove restoration can help to offset some anticipated climate change impacts on this type of habitat. Mangrove restoration can include (1) restoring hydrological function, flow, and sediment supply to existing but degraded mangrove habitats through excavation or backfilling and (2) planting seedlings as part of reforestation initiatives. There are numerous examples of successfully community-based mangrove restoration initiatives across tropical nations (McLeod and Salm, 2006).

Seagrasses: With regards to climate change, seagrasses are most vulnerable to increasing temperatures, which can cause extensive diebacks, and extreme weather, during which storms can uproot large areas of seagrass habitat. Moreover, these effects can be greatly exacerbated by poor water quality due to untreated sewerage discharge, land use practices, runoff and sedimentation (Björk *et al.*, 2008). In many cases, improving water quality is sufficient to encourage regrowth and expansion of damaged seagrass beds, and such measures can also be supplemented by seeding or transplantation of seedling or mature plants from donor beds. However, seagrass replanting projects are recognized as being labour intensive and having highly variable rates of success and may not be as cost-effective as improving water quality, which would have spin-off benefits for other coastal habitats (Björk *et al.*, 2008).

Corals: As with seagrasses, corals are most vulnerable to increasing temperature and ocean acidification anticipated with climate change, and these impacts can be exacerbated by poor water quality due to land use practices. Where water quality issues have been successfully addressed, artificial propagation of corals is one way some countries have sought to stem habitat loss due to coral bleaching and disease, and has been considered a cost-effective alternative to engineering-based approaches to coral reef restoration such as the installation of artificial reefs (Lirman and Schopmeyer, 2016). This ‘coral gardening’ approach is already being used for basic habitat restoration in many places; one study, published in 2012, documented over 60 individual coral gardening projects in Caribbean countries (Young *et al.*, 2012). This general habitat restoration strategy can be adapted to achieve more climate-resilient outcomes through assisted selection. In this scheme, fragments collected from local coral communities are propagated in aquaria under higher temperatures and/or lower pH to identify the most tolerant strains. These strains are then selected for propagation and outplanting to priority coral reef restoration sites. Adding an artificial selection component to existing or new coral gardening initiatives can help to make these types of projects more resilient to future climates (van Oppen *et al*., 2015; Morikawa and Palumbo, 2019). However, it is also important to bear in mind the potential drawbacks and unintended consequences that might arise in any strategy involving ‘assisted evolution’ (Filbee-Dexter and Smajdor, 2019).

Objectives Met: Adaptation to a changing physical environment. Adaptation to losses of productive fish habitats.

Information Needs & Monitoring Connections: Implementation of this restoration action should begin with site selection and prioritization assessments. These assessments will rely on information about past and present habitat distribution and conditions to identify and prioritize sites where environmental quality is sufficient to ensure the success of restored habitats. Practical guidelines on site selection criteria and other aspects of restoration vary by habitat and are available for mangroves (McLeod and Salm, 2006), seagrasses (Björk *et al*., 2008), and coral reefs (Grimsditch and Salm, 2006, Lirman and Schopmeyer, 2016, Frias-Torres *et al*., 2018).

Following implementation, the condition of restored communities should be monitored over time using, for example, standard reef health protocols measuring indicators such as coral cover, growth rates, physical damage, disease, and associated fish community diversity and abundance. Long-term field monitoring data from these ‘tolerant’ reefs and other habitats can then be compared to data from outplanted reefs that did not use assisted selection and to natural reefs as controls to measure the benefits of assisted selection. More recent studies have also recommended monitoring indicators to assess the socio-economic benefits of coastal habitat restoration programs, including enhancing conservation awareness, local stewardship and livelihood opportunities (Hein *et al.* 2017).

Monitoring Card 2 (Changes in Critical Habitats for Fished Species) provides guidance on habitat indicators (area and quality) and related metrics, including total area where mangrove forest, shallow reef, and seagrass beds are present; coral reef / mangrove / seagrass habitat area by EEZ that is degraded or dysfunctional.

Considerations for Implementation: Straightforward and 'low-tech' coastal habitat restoration activities can be labour-intensive but achievable at small scales. The most accessible and inexpensive form of restoration will be mangrove restoration through planting in shallow coastal habitats easily reached on foot or by small vessels (Bayraktarov *et al.,* 2016). More challenging and costly forms of coastal restoration will include propagation and outplanting of deeper seagrasses and corals. Restoration in underwater areas will require access to equipment and expertise for SCUBA diving to access restoration sites which is not readily available in all communities. Notably, restoration of terrestrial vegetation first can help to improve outcomes for marine-based habitat restoration later on (Hernández-Delgado *et al*., 2014, Bayraktarov *et al*., 2016).

Implementing an assisted coral selection and outplanting strategy at scales expected to yield significant benefits will require more substantial resources, personnel, and existing or acquired expertise in artificial coral propagation. Artificial propagation and assisted selection could potentially be carried out at a suitable central location (e.g., laboratories at the fisheries agency or a local university), and the resulting coral fragments distributed out to local community groups for further propagation and outplanting (van Oppen *et al.*, 2015). This type of community-based coral gardening has been successfully implemented in Jamaica as part of the C-FISH project, and can help to provide alternative employment and facilitate local ownership of solutions (C-FISH 2016).

Some of the costs of habitat restoration can be significantly offset using volunteer and/or community-based approaches (Hernández-Delgado *et al.*, 2014, Bayraktarov *et al.*, 2016), and there are also opportunities to finance restoration of coastal vegetation through blue carbon project financing initiatives (Hejnowics *et al.*, 2015) and tourist visitor fees (Lachs and Oñate-Casado, 2020).

2.1.4 Managed Realignment of Coastal Vegetation

Rationale: Mangrove forests and seagrass beds provide important habitat for economically-valuable fisheries species. Future sea-level rise may increase the likelihood of flooding and inundation of low-lying land, which creates opportunities for landward migration of coastal vegetation. In many areas, this natural landward migration will be prevented by coastal land use and infrastructure, but there is increasing interest in undertaking 'managed realignment' where landward migration is guided in a controlled way. This strategy is a useful alternative to more costly installation, fortification, or maintenance of artificial coastal defenses such as seawalls (Spalding *et al.,* 2014). Promoting managed realignment during landward migration of mangroves and other coastal vegetation will help to maintain access to important spawning and rearing habitats for many economically important species (Bell *et al*., 2018). This strategy will also provide "blue carbon" sequestration services (Duarte *et al.*, 2013, Serrano *et al*., 2019) and increase the resilience of coastal lands to uncontrolled flooding and erosion during storms (Chang, 2006; Spalding *et al*,. 2014), because mangroves stabilize coastal sediments. The benefits of mangrove forests are enhanced when seagrasses and fringing corals are also present, pointing to the value of an integrated coastal zone management strategy (Guannel *et al*., 2016).

This adaptation strategy has been described as a lose-win scenario (Bell *et al*., 2018), because benefits will primarily accrue in the future as precipitation increases, and sea levels continue to rise, and flooding becomes more frequent.

Objectives Met: Adaptation to losses of productive fish habitats.

Information Needs & Monitoring Connections: Site selection for managed realignment would be identified from both historical and current flood maps and vegetation habitat maps developed using field surveys and/or remote sensing data. Schill *et al.* (2014, pp. 16-18) illustrate a simple approach to identifying potential sites for implementation based on existing mangroves and land characteristics. Progress towards project objectives could be monitored by tracking the establishment of new habitat locations, the increase in total habitat, and public use of new habitats through, for example, adoption as new fishing areas.

Monitoring Card 2 (Changes in Critical Habitats for Fished Species) provides guidance on indicators and metrics related to mangrove extent and quality.

Considerations for Implementation: Areas of intact coastline with a high likelihood of coastal flooding should be earmarked for protection from future development. Where coastal infrastructure currently blocks the influx of water, channels, bridges, and other bypasses should be planned or modified to allow for more controlled coastal flooding that will allow landward migration of mangroves and seagrasses. These actions may require substantial capital works and higher costs, which can potentially be offset through regional or international adaptation funding programs. As with more general forms of habitat restoration, successful implementation of managed realignment will depend on political will and community support in the face of potential restructuring of existing infrastructure and restrictions on coastal land development that may be perceived as disruptive to local communities and businesses.

2.2 Harvest Management Actions

Overview: Climate change is expected to influence both the productivity and the distribution of many Caribbean fish species. Decreases in productivity will require actions to avoid excessive fishing pressure on stocks with reduced capacity to sustain levels of harvest that may have been sustainable in the past. Shifts in distribution may reduce fishing opportunities in some regions but create new opportunities in other regions. Adaptation to these changes will require actions that influence the amount, composition, and distribution of harvests. Reef-dependent fishes and benthic invertebrates are, in general, expected to be more vulnerable than pelagic species due to greater cumulative stressors from land-based activities. As a result, some harvest-based adaptation strategies include shifting fishing efforts toward pelagic species. Because climate change impacts on fisheries are expected to occur at broad spatial scales, there will also be a need to coordinate some adaptation strategies across affected nations. All these actions fall within the scope of existing fisheries management frameworks, and there is increasing recognition that improving regional capacity, rigor, and effectiveness in fisheries management will go a long way towards offsetting many of the anticipated negative effects of climate change on fisheries (Gaines *et al.*, 2018, Gourlie *et al.*, 2018). However, it should also be noted that the simplest fishing regulations will also be the easiest to effectively enforce, and so fisheries managers should strive for adequate enforcement of existing regulations before adding new regulatory requirements.

2.2.1 Use Regulations to Protect Vulnerable Fish Populations

Rationale: A changing climate brings a new set of stressors to fish populations already under pressure from coastal pollution, habitat loss, and fishing. One way to help mitigate the effects of climate change is to reduce other stressors, including fishing pressure where populations are presently fully or over-exploited. To some degree, changes in everyday fisheries management can help to offset the declines in productivity caused by a changing climate, while allowing some fishing to continue. In particular, managing fishery harvest in ways that maintain diversity within a fish population can improve the resilience of these populations to climate change. Diversity can result from a greater range of ages or sizes of fish in the population, more genetic variation (sub-populations), and abundance across a wide spatial range. Harvest regulations such as size limits, catch limits, seasonal and spatial closures, and restrictions on types of gear to be used, are all tools that can be used to maintain or increase diversity of exploited fish populations. Importantly, the potential benefits of harvest regulations strongly depend on effective enforcement.

Objectives Met: Adaptation to declines in growth and productivity of harvested species, and to changes in the distribution of fishing effort.

Information Needs & Monitoring Connections: General indicators of population status including abundance, age/length composition, and spatial distribution of species of concern can be used to determine the need for regulation changes and indicators of fishing effort can subsequently indicate whether adequate protection has been provided.
Monitoring Card 3 (Changes in Fished Species Distributions) provides guidance on indicators and metrics related to occupancy and abundance, whereas Monitoring Card 4 (Changes in Species Growth and Productivity) includes guidance on indicators and metrics related growth (e.g., size distribution) and productivity (e.g., size at maturity).

Considerations for Implementation: Successful implementation will depend on four key factors:
(1) availability of assessment data to inform decision makers of the need for regulations for different fisheries;
(2) ability to evaluate which regulatory changes are most likely to produce the desired outcomes (e.g., through conceptual models, simulations, or comparisons with other jurisdictions);
(3) adequate consultation with fishing communities to ensure that the measures are understood and broadly supported;
(4) sufficient capacity to enforce the prescribed regulations, either by governments or using self-policing fishers cooperatives or other community-based organizations.

Bell *et al*. (2018) offer a broad list of suggestions for implementation of regulatory strategies at both the community and national level, and Melnychuk *et al.* (2014) discuss the merits of flexibility in the timing of season openings and closings to better adapt to uncertainty about future climate.

2.2.2 Adjust Assessments and Harvest Control Rules to Account for Climate Vulnerability

Rationale: Climate change will affect the growth, distribution, survival rates, and vulnerability to capture of numerous exploited fish species in ways that influence the level of harvest that can be sustainably removed from exploited populations. For managed species where suitable harvest levels are determined by stock assessments and the application of a harvest control rule, these management procedures should be revised to account for the forecasted effects of future changes to climate on population dynamics and fishery operations. Some species are expected to experience altered growth and mortality patterns in the future, as indicated by analyses presented in an earlier phase of this project. Ecosystem effects of climate change may also change the operational characteristics of fisheries (e.g., catchability, size/age-specific vulnerability), which influence interpretation of assessment data and consequently the specification of a sustainable harvest rule. There is evidence that some types of harvest control rules (i.e., where mortality rates vary with assessed stock biomass or environmental conditions) are more resilient to climate change effects on productivity than rules that are more rigid (i.e., where mortality rates are fixed at some reference point) (Kritzer *et al.*, 2019).

Objectives Met: Adaptation to declines in growth and productivity of harvested species, and to changes in the distribution of fishing effort.

Information Needs & Monitoring Connections: Some form of stock assessment, including credible estimates of stock biomass and fishing rates, is essential for application of a harvest control rule. This level of monitoring information is only likely to be available for the most valuable fisheries in countries with relatively high assessment capacity (e.g., conch and lobster).

Monitoring Card 4 (Changes in Species Growth and Productivity) includes guidance on indicators and metrics related growth (e.g., size distribution) and productivity (e.g., size at maturity, spawn timing). For example, information on the distribution of fishes capable of spawning can be used to adjust size-based harvest control rules to ensure the fishery is not targeting sizes of fish that are still expected to be immature.

Considerations for Implementation: This adaptation strategy is only relevant to relatively well-developed, intensive fisheries for which harvest control rules are used to guide management. For these fisheries, modeling should be used to evaluate the performance of alternative policies in the face of uncertainty about future fishery characteristics under future climate scenarios (e.g., by accounting for relative changes in growth and survival rates across species as in Kritzer *et al.*, 2019). Once a robust strategy has been identified using simulation, or experience from other, similar fisheries, implementation will depend on maintenance of an informative assessment program, and the ability to enforce changes to the harvest policy.

2.2.3 Diversify Catches to Relieve Pressure on Vulnerable Populations

Rationale: Vulnerability to climate change varies widely across fisheries species. Reducing fishing pressure on those species projected to be "first and worst" affected by climate impacts will help to mitigate the climate impacts on these fish populations. However, more restrictive regulations intended to protect vulnerable species (see above) will not mitigate the impacts on the fishers that depend on these species. Another strategy is to encourage the diversification of harvests to include greater use of less vulnerable species that should be able to sustain higher exploitation rates, and less use of more vulnerable species (Bell *et al*,. 2018). Having a diverse portfolio of fishing opportunities (species, habitats) improves outcomes for fishers during times of change (e.g., Cline *et al.,* 2017, Young *et al.,* 2018).

One prominent example of this strategy is encouraging a shift in fishing effort from reef-dependent species to offshore pelagic species through the use of fish aggregating devices (FADs), which help to concentrate pelagic species in a small area and improve harvest efficiency. This has been described as a 'win-win' strategy because it increases access to fish in the near term, and sets the stage for communities to continue to fill a gap in access to nearshore coastal resources as coral reefs and the inshore stocks they support continue to degrade (Bell *et al*., 2018). FAD fishing programs have been successfully implemented as part of broader climate change adaptation initiatives for fisheries in several Pacific Island Countries and Territories (Bell *et al*., 2018), and has also been implemented in several Caribbean states including Guadeloupe, Martinique, Dominica (Mathieu *et al*., 2014) and Haiti (Valles, 2014). In this case, diversifying catches may also help to diversify livelihoods as many pelagic fish may also be targeted through guided recreational fishing as part of the tourism sector (C-FISH 2016, diversification of livelihoods discussed further later in this chapter).

Objectives Met: Adaptation to declines in growth and productivity of harvested species and to changes in the distribution of fishing effort

Information Needs & Monitoring Connections: Decisions about where fisheries effort should be reduced or increased require an understanding of both the current status of fished species and their anticipated vulnerability to climate change under future climate projections. Information on current status can be obtained through general fisheries monitoring programs, which collect data on age/length composition, spatial distribution, and indices of abundance (also see Monitoring Card 4). Information on future vulnerability of each species under climate change can be obtained from model forecasts from the vulnerability and impact assessment phase of this project (e.g., species-specific values for the climate vulnerability index and climate risk index). Information on the climate sensitivity of different species at different trophic levels is also useful, but remains poorly studied outside of short-term, small-scale experiments (Ullah *et al.*, 2018). These sources of information can help managers to craft harvest diversification strategies that reduce pressure on more vulnerable species and shift effort towards species whose populations are currently considered robust and are expected to remain so under future climates.

As harvest diversification strategies are implemented, monitoring data on catch composition and fishing effort will help to track the effectiveness of these interventions for diverting harvest away from more vulnerable species and habitats. Data collected by implementing guidance in Monitoring Card 5 (Changes in the Distribution of Fishing Effort) and Monitoring Card 6 (Change in Fisheries Dependence and Diversification) can be used alongside catch data for these purposes.

Considerations for Implementation: Strategies for diversifying harvests are very flexible and can be adapted in their scope and scale to fit within the capacity constraints of implementing agencies.

Implementation of these interventions typically requires incentives to change existing fishing practices, which might include training in new fishing methods, exchange programs or subsidies to support acquisition of different fishing gear, or subsidies for fuel to offset increased travel time to offshore fishing grounds (Bell *et al.*, 2018). Research on past initiatives suggests that without incentives, changes to fishing practices may be less than hoped for (Matthieu *et al*., 2014). Section 2.3.4 outlines complementary measures post-harvest.

Encouragement of new fishing methods and areas must be carried out with careful consideration for unintended consequences. For example, studies in Guadeloupe, Martinique, and Dominica have shown that the anticipated benefits of FAD initiatives are constrained by competition for limited number of FADs, increased market saturation for pelagic fish, greater variability in fishing success due to seasonal migrations of pelagic species and loss of FADs in strong seasonal currents, and increased fuel prices, which led many fishers returning to the harvest of benthic species (Mathieu *et al*., 2013). The authors of these studies concluded that FAD initiatives alone are not sufficient to reduce pressure on inshore resources without simultaneous implementation of regulations to directly reduce inshore fishing effort.

2.2.4 Precautionary Management of Emerging Fisheries

Rationale: Shifts in the distributions of some marine species may result in the development of new fisheries opportunities around species or locations not historically targeted. In light of likely declines in other fishing opportunities, there may be a risk of excessive exploitation of these new populations before they are successfully established in an opportunistic ‘race to fish’ where alternative opportunities are limited. Fisheries managers can use information on the projected distributions of species under future climates to proactively identify and plan for likely emerging fisheries (Karp *et al.*, 2019). A precautionary approach has been recommended for these emerging fisheries to allow the population to increase to levels where long-term sustainable harvest is possible. A temporary moratorium on emerging fisheries may be the most effective option, potentially followed by an experimental fishery to assess population abundance and appropriate harvest levels (Pinsky *et al*., 2014). Although not related to climate change, this approach has been implemented for the emerging sea cucumber fishery in Jamaica which developed rapidly in response to new export market opportunities in Asia. Following an initial period of opportunistic fishing, the fishery was closed for assessment, followed by issuance of experimental fishing permits associated with strict monitoring requirements to explore sustainability of the fishery (per A. Murray, Jamaica Fisheries Division). This model could be repeated over time as new fishing opportunities may arise due to shifting species distributions under a future climate, and can help to protect the establishment of stocks that could be important in the future.

Objectives met: Adaptation to shifts in species distributions.
Information Needs & Monitoring Connections: Fisheries-independent monitoring of species occurrence and fisheries-dependent monitoring of catch composition will be essential to detecting new species as they begin to establish populations and will also help to validate climate projections of species range shifts produced in earlier phases of this project. Monitoring Card 3 (Changes in Fished Species Distributions) provides guidance on indicators and metrics related to species occupancy and abundance. Data from implementing such guidance can be used in conjunction with catch data to inform management decisions and related outreach that promote effective adaptation to shifts in species distributions.

Considerations for Implementation: Catch data should be regularly assessed for evidence of new species in the harvests or trends in the relative abundance of previously-rare species in the harvests. When this occurs, a rapid early response in the forms of moratoriums or other fishing restrictions on these species will be critical to minimizing the negative effects of precautionary management (i.e., investment in gear that is subsequently subject to restrictions) until safe levels of exploitation can be determined. At the same time, outreach efforts to inform fishers of emerging new opportunities and training in suitable harvesting techniques will help to manage expectations and sustainably capitalize on opportunities as they arise.

2.2.5 Adjust Management Areas to Reflect Changes in Species Distributions

Rationale: The benefits of some marine protected areas (including no-take and limited-take areas) for their intended conservation purpose may be expected to decline over time due to species range shifts under future climate scenarios (e.g., Davies *et al.*, 2016; Woodson *et al.*, 2019). As the impacts of climate change at local scales become more apparent through long-term monitoring, some boundaries may need to be re-evaluated and moved, or there may be a need to transition to a more flexible spatial management framework, to maintain conservation benefits under future climate scenarios. When establishing new management areas, or refining zones within existing management areas, it will be important to explicitly address climate resilience as part of the decision-making process (e.g., Keller *et al*., 2009, Davies *et al*., 2016). Establishment of effective management area networks with a high degree of connectivity across broader regions can help to mitigate against localized climate change effects.

Objectives Met: Adaptation to shifts in species distributions.

Information Needs & Monitoring Connections: Local-scale assessment of habitat conditions, species distributions, and how they change over time will inform the need for changes in management area boundaries, particularly when examined in the context of knowledge about habitats that are resilient to climate change (see 2.1.1 above). Monitoring Card 2 (Changes in Critical Habitat for Fished Species) and Monitoring Card 3 (Changes in Fished Species Distributions) provide guidance to enable collection and analysis of data for these purposes.

Considerations for Implementation: Improving the climate resilience of management area networks requires spatial analysis to examine overlaps between area boundaries, the distribution of species and habitats of conservation concern, and indicators of future climate change resilience. In their simplest form, these types of analyses have used general indicators of reef resilience (e.g., depth, structural complexity, coral cover) as proxies for climate resilience (e.g., Davies *et al.*, 2016). In the case of the Caribbean, existing management area boundaries can instead be overlaid with high-resolution projections of species range shifts under future climate scenarios produced earlier in this project for a more direct assessment of anticipated conservation effectiveness in light of climate change. These types of information can be used as inputs to spatial conservation decision-support software like MARXAN to produce data-driven recommendations for refining protected area network boundaries to optimize their effectiveness under future climate scenarios (Davies *et al.*, 2016; also see Chapter B). In considering the role of climate change considerations in protected area planning, a review of case studies from multiple geographic regions concluded that strictly protected reserves are the best option for climate resilience when faced with an uncertain future, and provide added value as scientific reference sites for studying climate change effects in the absence of other stressors (Hopkins *et al*., 2016). As noted earlier in this section, successful implementation of this strategy relies entirely on sufficient capacity and commitment to strong enforcement of protected areas.

2.3 Sustainable Livelihoods and Economic Diversification Actions

Overview: Many of the anticipated impacts of climate change on marine habitats, fish and shellfish populations, and the fisheries that rely upon them will have significant social and economic repercussions for harvesters, fishing communities and national and regional economies (Bell *et al*., 2018). In addition, many of the conservation-oriented adaptation strategies being proposed for the fisheries sector, such as increased fisheries regulation, come with their own challenges that may in some cases cause further hardships to fishing communities unless they are mitigated through complementary socio-economic adaptation strategies (Shaffril *et al.,* 2017; Savo, 2017, Cinner *et al*., 2018). Socio-economic adaptation strategies for the fisheries sector fall into five broad areas (Cinner *et al.*, 2018):

1. Protecting existing assets and providing new assets to draw on in times of need
2. Increasing flexibility to change livelihood strategies
3. Supporting community organization and collective action
4. Supporting learning and information-exchange to inform decision-making
5. Empowering communities with agency through participatory decision-making

These types of adaptation strategies are explored further in the remainder of this section.

2.3.1 Protect Existing Assets Against Climate-Related Impacts

Rationale: Sea-level rise as well as an increasing frequency and severity of extreme weather anticipated in the future are expected to have significant impacts on coastal infrastructure important to the fisheries sector by causing damage and loss of physical assets. Many existing assets within the fisheries sector are vulnerable to physical damage due to sea level rise and extreme weather, including fishing gear, vessels, piers, processing facilities and markets, as well as transportation infrastructure. Adaptation strategies to better protect these assets include:

- enhancing natural coastal defenses including mangroves, seagrasses, and coral reefs through restoration and the creation of green belts and buffer zones (Spalding *et al*., 2014, Guannel *et al.,* 2016, described previously in this chapter),
- managing realignment to guide redistribution of the shoreline around critical resources (Duarte *et al*., 2013, Spalding *et al*., 2014, described previously in this chapter),
- implementing coastal development setbacks to prohibit infrastructure development in high-risk coastal areas (Mycoo and Chadwick, 2012; Mycoo, 2018),
- maintaining, reinforcing, or building soft or hard coastal defenses including groynes, seawalls, revetments, and emergent or submerged breakwaters, to ‘hold the line’ or ‘advance the line’ of coastal protection (Mycoo and Chadwick, 2012; Mycoo 2018), and
- investing in the development of safe harbours and anchorages, vessel haul-out and storage facilities, as well as adopting the use of bumper rails and fenders at piers to reduce weather-related damage and loss of fishing vessels and help to lower marine insurance premiums (Tietze and van Anrooy, 2018).

Objectives Met: Adaptation to a changing physical environment.

Information Needs & Monitoring Connections: Setting priorities for asset hardening requires an understanding of vulnerability and risk. This can be accomplished by first mapping land use vulnerability, incorporating data from historical maps, land use maps, asset distribution maps, remote sensing and aerial photography, shoreline erosion rates, and damage assessments from past storms. This information can then be used to carry out a broader climate change vulnerability assessment of specific land uses, sites, and development plans that can be used to select and prioritize among the above adaptation strategies (Elsharouny, 2016). Governments undertake post-disaster damage and loss assessments, which reveal relative vulnerabilities to hazard events.

Monitoring Card 9 (Changes in Uptake of Climate Risk Management) provides guidance to track the use of climate-responsive tools, instruments, strategies or activities, which includes measures to protect or harden physical and natural assets from the impacts of climate change and variability. Overlaying penetration rates of asset protection and hardening measures over mapped information on exposure to climate-related hazards can be used to identify potential risk management shortfalls and capacity gaps. Data collected on uptake of this adaptation option along with information on new programs (objectives, intended beneficiaries, area of influence) can support effectiveness monitoring.

Considerations for Implementation: Strategies for protection of coastal infrastructure should ideally be implemented as part of a broader coastal zone management strategy, and are most effective when using several complementary approaches (Mycoo and Chadwick, 2012).

Natural coastal defenses are preferred for their additional benefits in providing supporting habitat for important fisheries species. While managed realignment is also an attractive nature-based solution, a high degree of coastal development and property investments coupled with limited landmass for relocation across many Caribbean island states is likely to lead to strong economic and political resistance to this strategy (Mycoo and Chadwick, 2012).

Artificial coastal defenses may be necessary in some circumstances, but care should be taken to consider their higher initial and long-term costs as well as their impact on natural ecosystems. Depending on their location, hard shoreline defenses can contribute to coastal squeeze during landward migration of mangroves, seagrasses, and sandy beaches (Mycoo and Chadwick, 2012, Elsharouny, 2016).

A range of guiding documents and protocols are available to enable accounting for climate change risk in the design of individual physical assets (e.g., Scott *et al*., 2013).

2.3.2 Improve Safety at Sea

Rationale: Climate change is expected to increase the frequency and severity of poor weather conditions at sea, including extreme weather events, with significant implications for both catches and the safety of fisherfolk while at sea. These increasing risks are expected to be further multiplied as more fishers travel farther from the coast to pursue pelagic fish species in an effort to diversify their catch in the face of shifting fish populations (ILO, 2014; Monnereau and Oxenford, 2017). Adaptation measures to reduce this risk include:

- Inspections to verify maintenance records and assess seaworthiness of vessels, which may also be set as a condition of licensing or obtaining insurance (Tietze and van Anrooy, 2018), with due attention to small-scale fishing vessels.
- Training in engine repair, vessel maintenance and the implementation of safety-at-sea practices, protocols, and equipment to prepare for maritime emergencies (Monnereau and Oxenford, 2017). These types of training sessions are already offered by fisheries authorities in many Caribbean nations, and many others have been provided across the region by various international and non-governmental organizations (Monnereau and Oxenford, 2017; Tietze and van Anrooy, 2018).
- Purchase and use of dedicated safety equipment including VHF radios, navigation lights, compass and charts or navigational global positioning systems (GPS), vessel monitoring systems (VMS), rain gear, life vests, flares, and fire extinguishers to use during emergencies (Monnereau and Oxenford, 2017; C-FISH, 2016; Tietze and van Anrooy, 2018). Among these, VHF radios are particularly

important to reduce the current reliance of many fisherfolk on mobile phones, which cease to be an effective mode of emergency communication once more than a few miles from shore (Tietze and van Anrooy, 2018).

- Implementation of early warning systems to alert fishers of maritime emergencies in time to take countermeasures (e.g., not going out to sea, securing vessels and gear). The Fisheries Early Warning and Emergency Response (FEWER) ICT Solution provides essential web-based dashboard and mobile app components of an appropriate early warning system, which has recently been launched in the Caribbean as a deliverable under the Investment Plan for the Caribbean Regional Track of the Pilot Program for Climate Resilience (PPCR) (CRFM, 2018). FEWER includes modules to record and report current weather conditions, receive emergency alerts, contact emergency services, and report damages and missing persons following emergencies. The mobile app component streamlines safety at sea information and services into a single channel that is expected to improve fisher use of these services to prepare for and respond to emergencies at sea.

Objectives Met: Adaptation to a changing physical environment.

Information Needs & Monitoring Connections: The range of options described above to improve safety at sea is vast and the potential benefit of implementing each will be context-specific. Designing new programs will require baseline information on knowledge, attitudes and behaviour regarding safety at sea practices, segmented by different target audiences (e.g., large-scale versus small-scale fishers), to identify gaps in compliance and opportunities to enhance safety. Several resources exist to help design interventions based on social change (see, for example, Rare, 2019). Setting priorities requires weighing expected benefits of implementation with related costs. Appraisal techniques that allow comparison across different attributes (e.g., human health and safety outcomes, financial investment), such as Multi-Criteria Decision Analysis introduced in Chapter F, are more appropriate than techniques aiming to reduce each criterion to the same metric. Once key interventions are selected and implementation occurs, information gleaned from implementation and effectiveness monitoring can help identify needed course corrections.

Monitoring Card 9 (Changes in Uptake of Climate Risk Management) provides guidance to track the use of climate-responsive tools, instruments, strategies or activities, which includes measures to enhance safety at sea. Data collected on uptake of this adaptation option, changes in social outcomes compared to the baseline, along with information on the intervention (objectives, intended beneficiaries, area of influence) support effectiveness monitoring.

Considerations for Implementation: Where resources are limiting, training is the least resource-intensive adaptation option to improve safety at sea. General safety-at-sea training has been implemented as part of a number of adaptation projects throughout the Caribbean, particularly those promoting shifting effort to offshore fisheries (e.g., C-FISH, 2016). More specialized training in the proper use of early warning systems is also desirable and was recently undertaken as part of the launch of the FEWER early warning ICT Solution (CRFM, 2018). Trainings, including refresher courses, should be offered regularly to account for limited capacity, turnover in the fishing fleet, and forgetting what was learned over time. Some of the techniques and protocols taught in these types of trainings will require specific supplies, and additional funding can be invested in the purchase and distribution of safety equipment across the fishing fleet, either through fisheries cooperatives or to individuals. However, donations of physical assets must be considered carefully and accompanied by follow-up incentives, monitoring, training, or reporting requirements to ensure they are being used as intended. For example, safety-at-sea training and equipment are prerequisites for fisher/captain registration in some areas (per E. Mohammed, Fisheries Division Trinidad) and is proposed as requirements for obtaining insurance on fishing vessels (Tietze and van Anrooy, 2018).

2.3.3 Facilitate Access to New Assets in Times of Need

Rationale: As climate change progresses, the fishing sector will require access to new assets to help them adapt to gradual changes in sector operations as well, help them recover from acute losses following extreme weather events, and help them undertake broader community-scale adaptation projects.

Broadening access to credit is an extremely important financial measure for helping fishers acquire new fishing gear and vessels to adapt to new fishing opportunities and can also be helpful for replacing lost assets (Shaffril *et al.* 2017). However, many fishermen have difficulties accessing credit through formal institutional arrangements due to barriers including illiteracy, high bureaucratic burden, lack of adequate collateral, inability to arrange a co-signer, inflexible repayment schedules, and fear of losing assets. As a result, fishermen may prefer to resort to informal credit arrangements through family and social networks to enable adaptation until formal credit becomes more accessible and flexible to meet the needs of the small-scale fisheries sector (Haque *et al.*, 2015). Because access to some fishing opportunities may increase travel distances and fuel consumption, duty-free concessions on more fuel-efficient engines and fuel subsidies from governments and/or fisheries associations can also help to offset the costs of travelling farther to fish (CANARI, 2015, Young *et al.*, 2018). While subsidies can be a useful tool, they should involve very clear goals linked to positive contributions to fisheries management, transparent implementation, and regular monitoring to prevent unintended consequences including illegal, unreported and unregulated fishing, maladaptation, dependence, and overcapacity which can lead to overexploitation of fisheries stocks (Khan *et al.*, 2006, Bell *et al.*, 2018).

Access to affordable insurance and social assistance programs is most important for replacing vessels, equipment, and income lost following extreme weather events which may prevent fish harvesters, processors, or sellers from earning income (Shaffril *et al*., 2017, Tietze and van Anrooy, 2018). However, much of the Caribbean's small-scale fisheries sector has limited or no access to affordable insurance (Monnereau and Oxenford, 2017). A recent review of insurance needs in the wider Caribbean fisheries sector found that 97% of fishing vessels and assets were not insured despite the availability of marine insurance and that less than 20% of fishers had health or life insurance policies, where the primary reason given by fishers for not obtaining insurance was because they could not afford it (Tietze and van Anrooy, 2018). What might be considered affordable varies across Caribbean nations, but was reported as being an average of 2.6% of total insurable asset value among fisherfolk surveyed (Tietze and van Anrooy, 2018).

At broader scales, regional and national adaptation funds (e.g., the Community Disaster Risk Reduction Fund of the Caribbean Development Bank) can help communities to implement larger-scale adaptation projects, such as purchasing freezers to store fish, funding the installation and maintenance of FADs, or implementing coral reef restoration programs (Shaffril *et al*., 2017). Several important multilateral funds in this class were established under the United Nations Framework Convention on Climate Change (UNFCCC) regime to support adaptation projects and include the Least Developed Countries Fund (LDCF), the Special Climate Change Fund (SCCF), the Adaptation Fund (AF), and the Green Climate Fund (GCF). A retrospective analysis of awards from these funds shows they have been used to finance several adaptation projects in the fisheries sector, including some in the Caribbean, making up roughly 6% of all adaptation projects funded. The types of projects funded have included modification of laws or policies, assessing projected climate change impacts on fisheries, operationalizing fisheries monitoring systems, reducing ecosystem and fishing-related stressors on fish stocks, and improving fishing communities' resilience in terms of food security and livelihoods (Guggisberg, 2018). However, these funds do not currently provide a harmonized and searchable marker dedicated to fisheries-related adaptation. This can make it harder for nations to know these funds can be used for fisheries-related adaptation projects and more difficult for organizations to track regional progress towards climate change adaptation in the fisheries sector (Guggisberg, 2018).

In the absence of these financial support systems, an inability to cope with the increasing costs of implementing adaptation measures may force some individuals and businesses to close and some fisherfolk to migrate and/or seek employment in other sectors (ILO, 2014).

Objectives Met: Adaptation to a changing physical environment and adaptation to variations in fishery production

Information Needs & Monitoring Connections: Loss and damage assessments and results of studies on the economic consequences for fisher welfare of lower catches and more intense storms due to climate change can help define the magnitude of financial assistance currently needed to recover from extreme weather and the magnitude of potential finance shortfalls in the future. However, understanding of risk profiles at various scales (household, community, national) is also critical, as is the need to appraise the range of potentially-applicable financial instruments in the context of their role in disaster preparedness, response, recovery and adaptation to long-term change. Information on the potential interplay between institutional interventions and informal social safety nets is also important to consider. Lessons on the application of micro-finance to reduce vulnerability to climate risk in the development world (CARE International, 2019; PPCR, 2018) are starting to emerge and can guide the design of new interventions.

Monitoring Card 9 (Changes in Uptake of Climate Risk Management) provides guidance to track the use of climate-responsive tools, instruments, strategies or activities, which includes financial instruments and social safety nets. Monitoring Card 6 (Change in Fisheries Dependence and Diversification) highlights "success rate (frequency) in accessing capital/credit to purchase new gear or equipment when needed" as a secondary metric to monitor flexibility within the sector. Data collected on uptake of this adaptation option, changes in social outcomes compared to the baseline risk profile, along with information on the intervention (objectives, intended beneficiaries, area of influence) support effectiveness monitoring.

Considerations for Implementation: Improving fisherfolk access to assets for facilitating adaptation in times of need will require (1) reforms to application processes that account for the constraints of fisherfolk who may have few physical assets and little formal education as well as (2) financial support from regional and/or multilateral agencies to help make these reforms financially viable for credit and insurance service providers.

Barriers to obtaining credit could be reduced by streamlining application processes for the fisheries sector to provide simplified forms and application assistance for applicants who may not be literate, relaxing requirements for collateral and co-signers, and more flexible repayment schedules that account for the irregularity and uncertainty in fish catches inherent to this sector and more likely to increase under future climate projections (Haque *et al.*, 2015).

Barriers to obtaining insurance have already been reduced to some extent by the launch of the Caribbean Ocean Assets Sustainability FaciliTy (COAST). The Caribbean Catastrophe Fisheries Risk Insurance Facility (CCRIF) coordinates the development and implementation of COAST, which has received financial support from the US State Department. CCRIF supports locally-based marine insurance companies to help offset the costs of settling many simultaneous claims following extreme weather events in exchange for making policies more accessible to those working in the fisheries sector (Tietze and van Anrooy, 2018, www.ccrif.org). This institution's efforts to advance COAST-associated fisheries parametric insurance policies provide coverage for fisherfolk and other players in the fisheries industry to enable them to recover quickly after weather-related events. CCRIF also offers a complementary Livelihood Protection Policy, a type of micro-insurance policy that provides rapid financial support to vulnerable people whose livelihoods are interrupted by extreme weather events. Increasing participation in these insurance programs should be a priority of climate change adaptation initiatives for fishing communities. As one example for incentive, it has been proposed that obtaining insurance could become a requirement for obtaining vessel registrations, and could also carry obligations to engage in climate-smart behavior including proper vessel maintenance and use of safety equipment (Tietze and van Anrooy, 2018).

2.3.4 Enhance Post-Harvest Handling, Processing, and Marketing

Rationale: Even where adaptation measures are successful in maintaining fish harvest, climate change has the potential to impact post-harvest processing and marketing in other ways. Enhancing post-harvest handling, processing, and marketing can help to preserve and extend the benefits of pre-harvest adaptation strategies. Enhancing post-harvest practices can help to significantly extend the shelf life of the catch and maintain market access to fish during interruptions in supply. This class of adaptation strategies includes measures such as (Bell *et al*., 2018; CANARI, 2015; Dunstan *et al*., 2018; Tietze and van Anrooy, 2018):

- food safety training programs (e.g., HAACP),
- purchase of coolers, ice machines, and freezers to bank catches for future use,
- fortifying power infrastructure (e.g., solar power, wind power, generators) to offset the electricity costs of cold storage and protect against power loss that would lead to spoilage of catch, and
- training in traditional methods of food preservation (e.g., smoking, salting, and drying) that do not rely on a power supply.

These measures will help to stabilize the supply of fish, reduce the likelihood of food-borne disease or pathogens affecting fish consumers, and better meet food safety requirements for additional export markets (CANARI, 2015; Dunstan *et al*., 2018).

Where adaptations for maintaining the catch include diversifying catches, additional incentives and support for market promotion may be needed to help promote the consumption of new types of fish not commonly consumed in the past. Appropriate subsidies for processors and markets may help to incentivize adoption of new, more sustainable fish species into the fish value chain (Bell *et al*., 2018).

Objectives met: Adaptation to a changing physical environment, adaptation to variations in fishery production, enhanced post-harvest productivity

Information Needs & Monitoring Connections: The range of options described above to enhance post-harvest handling, processing and marketing is vast and the potential benefit of implementing each will be context-specific. Selecting from among the options will require information on baseline conditions of post-harvest activities, to identify where along the chain to intervene to achieve most impact (in whatever way this is expressed) and who to target. Information on current supply-side inefficiencies or unmet needs, as perceived by consumers, can also help select the most promising intervention approaches.

Monitoring Card 9 (Changes in Uptake of Climate Risk Management) provides guidance to track the use of climate-responsive tools, instruments, strategies or activities, including investments in technologies and infrastructure, as well as training programs. Guidance here can help track progress in implementing the adaptation intervention. Additionally, Monitoring Card 8 (Changes in Post-Harvest Productivity) provides guidance to monitor waste reduction and value addition, which provides the complementary evidence (socio-economic outcomes) to monitor adaptation effectiveness.

Considerations for Implementation: Where resources are limited, training in food safety and traditional methods of preservation may be the most accessible adaptation strategy within this class. Where more resources are available, improving ice production and cold storage infrastructure can be one of the most effective ways to prolong the shelf life of fish catches and stabilize market availability during interruptions in supply. However, these types of infrastructure improvements should proceed only after careful feasibility studies to ensure their long-term viability. Many infrastructure projects built using funds from short-term development projects are likely to fail if they do not adequately account for operating costs (e.g., electric bills) and long-term maintenance needs (e.g., local availability of parts and expertise for repair in case of breakdowns). These types of projects are more likely to be successful where they are implemented in partnership with a local organization (e.g., fishing cooperative, fish market, fisheries authorities) which can oversee long-term maintenance and funding for continued operations.

2.3.5 Diversify Livelihoods

Rationale: Dependence on fisheries and extraction of marine resources is highly relevant to climate change adaptation, as the more dependent fisherfolk households and fishing communities are on fisheries, the harder it will be to bounce back from severe disturbances in production. Diversification within and across economic sectors is a common strategy to improve the adaptive capacity of fisherfolk across the fish value chain (ILO, 2014; Savo *et al*.; 2017; Cinner *et al*., 2018). Diversification within the sector includes diversification of fishing methods, catch, post-harvest processing and marketing as already discussed in prior sections. Diversification across sectors may include engaging in alternative or supplementary economic activities to reduce dependence on fisheries, such as expanding participation in marine tourism, aquaculture, agriculture, or other market opportunities, such as seamoss farming (ILO, 2014; CANARI, 2015). Diversification will not only help communities be more resilient to climate change impacts on fisheries, but it will also reduce the likelihood of vulnerable community members pursuing unsustainable practices to support themselves (e.g., illegal fishing, see Ahmed *et al.*, 2019).

Objectives Met: Adaptation to a changing physical environment, adaptation to variations in fishery production.

Information Needs & Monitoring Connections: Livelihood diversification strategies can be more successful by first conducting surveys to assess interest in a range of alternative livelihoods among those employed in the fisheries sector. Monitoring the types and extent of diversification activities by target communities, as well as perceived barriers, can inform programmatic adjustments. Independent evaluation of the effectiveness and impact of programs and initiatives to support livelihood diversification is also critical and should seek to uncover impact differentiated by sex and social groups that may be underserved in the absence of special accommodations.

Monitoring Card 6 (Changes in Fisheries Dependence and Diversification) provides guidance to track whether and how livelihood diversification is occurring. Indicators include the importance of the marine fishery sector to local livelihoods, the importance of seafood for food security, flexibility within the sector and occupation mobility.

Considerations for Implementation: Diversification of livelihood activities can be extremely challenging and often fail for financial, social, cultural, and environmental reasons. In recognition of these challenges, many practitioners have published lessons learned and best practices for implementation of livelihood diversification initiatives in small-scale fisheries households and communities that are summarized briefly here (Gillett *et al*., 2008; APFIC, 2010).

Those currently employed in the fisheries sector will need significant support to facilitate the transition to an alternative livelihood, including financial assistance, skills development training (including business skills), and mentorship. Without these supports, many in the sector will not be able to make a successful transition to alternative livelihoods. Implementing complementary adaptation strategies that improve access to credit and additional training can help to reduce these barriers (Bell *et al*., 2018, Cinner *et al*., 2018). Even where supports are available, fisherfolk may be reluctant to change occupations. Many fisherfolk ground their sense of self in their fishing occupation, location, and lifestyle that may make it challenging to transition into alternative employment, especially where the alternatives being offered are considered unattractive (Cinner *et al*., 2018). Alternative occupations that share similar skillsets with the fisheries sector (e.g., recreational fishing guide, boat tours, or engine mechanic) may be more attractive options for diversification.

Livelihood diversification often requires long timeframes to achieve profitability and cannot be effectively accomplished through a few short training sessions. Without adequate long-term mentorship and support to work through common start-up challenges, participants are more likely to return to their original occupations after support is withdrawn (Gillett *et al*., 2008). A review of past initiatives has suggested that fostering partnerships with existing businesses may be a more successful long-term strategy for livelihood diversification than encouraging fisherfolk to start new livelihood endeavors from scratch (Gillett *et al*., 2008).

Finally, livelihood diversification must be undertaken in parallel with other enabling reforms of management, governance, and policy frameworks to be most successful. For example, livelihood diversification should occur in parallel with management measures to prevent the continued degradation of the fisheries resource base to ensure that the ecological benefits of this strategy are fully realized (APFIC, 2010).

3. FURTHER CONSIDERATIONS FOR IMPLEMENTING ADAPTATION OPTIONS

The actions outlined above describe *what* could be done to address climate change impacts in the fisheries sector, but more consideration is needed to determine *which* actions are most appropriate for a given management context and *how* those actions should be carried out in a broader institutional and policy context.

3.1 Selection of Adaptation Options for Specific Management Contexts

Selecting among all possible adaptation options requires comparing the options against criteria that give some indication of the expected benefits and likelihood of success of the actions being considered. In general, criteria used for the evaluation of alternative adaptation options fall into four categories (USAID, 2009; Stein *et al.*, 2014; Parker *et al*., 2017; West, 2018):

- *Alignment with Conservation Objectives:* How well does the proposed action align with priority conservation objectives and outcomes?
- *Alignment with Social, Cultural, and Economic Objectives:* How well does the proposed action support sustainable development objectives across the fisheries sector?
- *Feasibility:* Is the proposed action achievable with current finances, capacity, community support, and political will?
- *Climate Resilience:* How resilient is the proposed action and location to climate change? Are the benefits likely to be maintained under future climate scenarios?

Chapter F of this report explores how these and related criteria can be used to select among potential adaptation options in the context of a broader decision-support framework for climate-smart adaptation planning in the fisheries sector.

3.2 Creation of Enabling Conditions to Support Implementation Success

All of the adaptation actions described in this chapter should be undertaken in parallel with broader enabling reforms of management, governance, and policy frameworks to ensure that their benefits will be fully realized (APFIC, 2010).

- First, management frameworks should be strengthened and sufficiently resourced to mitigate continued decline of the habitats and species constituting the fisheries resource base. In the context of the fisheries sector, improving current environmental management measures represents one of the most effective strategies for mitigating the anticipated effects of climate change on fisheries resources (Gaines *et al*., 2018; Gourlie *et al*., 2018).
- Second, governance frameworks should be adapted to promote community organization and participatory decision-making in the fisheries sector. Community organizations such as fisheries cooperatives can help to build capacity for supporting individuals impacted by climate change, strong connections between communities and institutions can help to secure access to resources, information, and technology for facilitating adaptation (Cinner *et al*,. 2018). Similarly, promoting the participation of communities and organizations in participatory decision-making for fisheries management can help to improve acceptance and support for conservation measures that contribute to better environmental management outcomes and increased ecosystem resilience to climate change (Cinner *et al*., 2018).
- Finally, international cooperation across national and regional governments and institutions is needed to effectively monitor impacts, develop adaptation strategies, and implement adaptation programs over the broader geographic scales at which climate change impacts will manifest. Measures in this space may include data-sharing agreements, catch-sharing agreements, trade agreements, and adaptation funding agreements, among others (Pinsky and Mantua, 2014; Pinksy *et al.*, 2018, *Karp et al.*, 2018).

These and other considerations will factor into the update to the 2013 Regional Strategy and Action Plan for Climate Change Adaptation and Disaster Risk Management in Fisheries and Aquaculture (CRFM, 2013) – the final task under this project.

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E. Selecting Adaptation Options and Creating An Action Plan: From The Possible To The Practical

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1. INTRODUCTION

Although several potential climate change adaptation strategies apply to the fisheries sector, not all will be appropriate for every management setting and context. It will be the responsibility of natural resource managers to consider these options, select the most suitable among them given the local context, and begin to design an action plan for implementation - steps 6 and 7 in the planning cycle described in the introduction (Chapter A, Figure 1). This is not an easy task. There are many options to compare, varying degrees of information to determine which options are most needed or appropriate and considerable differences across the region in levels of capacity to implement different options.

General guidance exists for selecting among potential adaptation options and translating these into a robust action plan for climate change adaptation (e.g., USAID, 2009, Stein, 2014, Bolaños *et al.*, 2016, Olazabal *et al.*, 2017). These resources highlight the importance of using a structured approach, informed by careful consideration of goals and objectives to select a wise course of action from a potentially overwhelming set of possibilities.

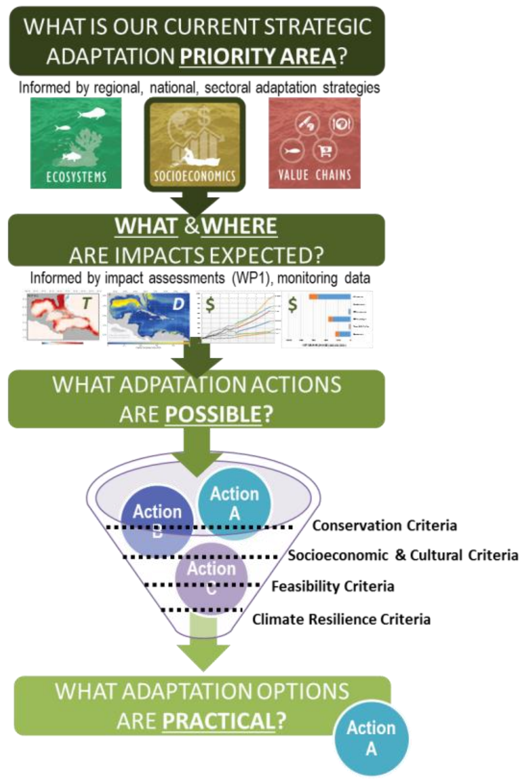

Figure 1: An illustration of the process for selecting among potential adaptation options.

The general nature of this structured approach is illustrated in Figure 1. It involves reviewing adaptation goals and objectives, selecting high-level strategic priorities that align with goals and objectives to focus the scope of action planning, considering the outcomes of prior impact / vulnerability / risk assessments and monitoring initiatives for selected strategic priorities, characterizing the set of potential adaptation actions that address those strategic priorities, and applying a set of prioritization or evaluation criteria to determine which ones are most suitable for implementation. This process can be repeated to address different focal areas for adaptation in the present and repeated when revising plans, as knowledge and conditions change in the future.

2. APPROACH TO PRIORITIZING ADAPTATION OPTIONS

2.1 Review Adaptation Goals and Objectives

The first step in this process is to review the goals and objectives of a broader regional, national, or sectoral adaptation plan or strategy, such as those contained in CRFM (2013). All choices about actions to implement should be, first and foremost, governed by whether there is a realistic expectation that the action will result in an outcome that contributes to achieving a stated objective. It is perhaps surprising how often decisions are made without consideration of objectives – if such decisions result in a desirable outcome it is more due to good fortune than good planning.

2.2 Establish Strategic Priorities to Focus Adaptation Planning

Climate change will bring about many effects in the fisheries sector, but some of these may more urgent to address through adaptation than others. Examples include climate change effects that may pose immediate risks to personal safety, key sectoral infrastructure or critical marine habitats. Regional, national, or sectoral adaptation plans or strategies may include guidance on which types of climate change effects should be addressed first.

2.3 Review Current Understanding of Climate Change Effects for Focal Areas

Deciding on a course of action will depend on understanding the mechanism and magnitude of the climate change effect that is expected to occur. This step can draw on insights from other parts of this "Fishery-Related Ecological and Socio-Economic Assessments of the Impacts of Climate Change and Variability and Development of an Associated Monitoring System" project, including the regional climate change impact assessments carried out as part of the earlier Work Package 1, as well as new data emerging from implementation of the monitoring guidance provided in this publication (Chapter D). If the expected effects are large, or changes observed to date through monitoring suggest the impact is greater than forecasted, the need for action and the scale of response will be greater. However, it is important to note that the inverse does not necessarily imply that no action is required. In some cases, places, species, or practices that are found to be more resilient may be important candidates for adaptation investments.

2.4 Identify Potential Actions to Address Focal Adaptation Needs

Chapter E of this report describes a range of potential adaptation options, and cross references them to specific climate change effects addressed, climate-smart fisheries adaptation objectives they would help to meet, and related monitoring approaches that could be implemented to increase the knowledge base around this climate effect.

2.5 Define and Apply Evaluation Criteria to Potential Adaptation Actions

In this step, the portfolio of potentially relevant adaptation options for a given effect is compared to a set of evaluation criteria to select the subset of actions with most implementation promise. This step can be carried out using a wide range of techniques, from a simple set of qualitative screening questions (e.g., USAID, 2009, Stein *et al.*, 2014), to a semi-quantitative scoring framework used in Multi-Criterion Analysis (MCA) (e.g., Bolaños *et al.*, 2016), to more fully quantitative cost-benefit and physical modelling of alternative management outcomes for specific classes of actions (e.g., Reguero *et al*., 2018). Examples of evaluation criteria typically used in selecting among adaptation options are provided in Table 1. These criteria have been adapted to the Caribbean fisheries context for this chapter.

This will be the most difficult step in the process, as it depends on many factors, some of which can only be judged subjectively. While this step will be challenging, it will also be where the opportunity for creative solutions to emerge, especially ones that involve community empowerment and local ownership of the actions.

Table 1: Example criteria for prioritizing among potential climate change adaptation options (adapted from USAID, 2009, Stein et al., 2014, Bolaños et al., 2016).

Overarching Evaluation Considerations	Evaluation Criteria	Evaluation Sub-Criteria
Conservation Goals How well do the alternatives help achieve agreed-upon marine conservation goals and objectives?	Conservation of critical habitats supporting fisheries production	Improvement in productivity of critical habitat
		Increase in total area of critical habitat
		Increase in spatial protection of critical habitat
	Biodiversity	Reduction in illegal harvests
		Reduction in harvest of vulnerable species
		Diversification of fisheries harvests
	Climate change mitigation potential	Improvement of carbon storage (e.g., via marine vegetation)
		Reduction of carbon emissions from the sector
Societal Goals How well do the alternatives help achieve social, cultural, and economic goals and, or provide co-benefits to other sectors?	Equity and benefits sharing	Generation of employment
		Contribution to economic diversification
		Contribution to co-benefits to other economic sectors occurring in the same area (e.g., tourism)
		Contribution to recovery from climate impacts
	Safety and well-being	Reduces risks to personal safety
		Improves food quality and security
	Physical assets	Reduces risks to coastal infrastructure
Feasibility How practicable or realistic is it to implement the each alternative?	Legal and institutional frameworks	Alignment with existing adaptation strategies
		Compliance with national policy and regulations
		Regulatory complexity (e.g., level of jurisdictional overlap, need for lengthy permitting or legislative reform process)
		Access complexity (e.g., land ownership, access, right of way)
	Stakeholder support	Community support
		Local implementation partners
	Capacity	Access to expertise needed for implementation
		Access to sufficient personnel for implementation, enforcement, and monitoring
	Cost	Implementation costs
		Long-term operating costs
		Cost-sharing opportunities
	Implementation Risk	Data needs
		Technical feasibility
		Likelihood of achieving benefits
Climate-Smart Considerations How robust are the adaptation actions themselves to climate change impacts and variability other than those they are intended to address?	Linkage to impacts and vulnerabilities	Actions linked to known impact pathways
	Time horizons	Relevance to short-term and long-term needs
		Alignment between timing of benefits and timing of anticipated climate impacts
	Robustness to other climate impacts not targeted by the focal action	Robust to changes in the physical environment
		Robust to changes in fish distribution
		Robust to changes in fishing distribution
	Robustness to uncertainty	Robust under multiple climate scenarios
		Robust to variation in funding or capacity over time
		Robust to changes in nearby land ownership and use

3. WORKED EXAMPLE: ADAPTING TO CHANGES IN THE PHYSICAL ENVIRONMENT

A first step in this example would involve reviewing the overarching goals and objectives of a national adaptation strategy to consider how it might apply to the fisheries sector. In this hypothetical example, we can assume that the strategy highlights as a strategic priority mitigating or minimizing the negative effects of increased temperatures. An objective might be to minimize other, avoidable stresses on habitats deemed vulnerable to increased temperatures. Another might be to preserve fishing opportunities in habitats that are less likely to experience elevated temperatures in the near future.

Key questions to address next would include the following:

- Does modelling, particularly using downscaled predictions of future conditions, point to areas where larger changes are expected (vulnerable habitats), or to areas where relatively little change is expected (resistant habitats)?
- Does knowledge of local-scale oceanographic factors (e.g., positions of land masses relative to prevailing wind and current directions) suggest that some areas are likely to be more vulnerable than others?
- Has recent monitoring detected changes in average temperatures and/or pH relative to past observations?

Answers to these questions will help determine which adaptation options are worth considering. For example if there is no evidence available to suggest where habitats resistant to physical changes might be, options related to protecting such habitats do not warrant consideration.

As a next step, we can consider three potential adaptation options discussed in Chapter E that are expected to boost resilience to climate change effects on temperature. First, actions could be taken to reduce landscape stressors on coastal habitats. This would involve restricting or modifying land-use practices to reduce damaging runoff and nutrients into areas already considered critical, improving baseline habitat health and resilience to temperature increases. Second, *in-situ* actions could be taken to protect critical coastal habitats important for supporting fisheries species. This action would also serve to lower additional stresses on habitats already vulnerable to physical environment changes, such as high fishing rates or destructive fishing practices, and could have greater benefits if aligned with known climate refugia. Third, actions could be taken to restore critical coastal habitats. Such actions would aim to create new valuable habitat to offset losses occurring as a result of increased temperature, ideally in areas expected to experience less temperature stress under future climate projections.

Subsequently, we would apply our evaluation criteria to these three actions to determine the most practical one to implement, in this case using simple evaluation questions. To illustrate this step we focus on the first category of action: land-based measures to reduce additional stressors. The first filtering step would be to determine whether there is evidence that runoff is responsible for loadings of nutrients or suspended materials that could add substantial stress to vulnerable habitats, or if this is anticipated to happen in the future in the absence of restrictions on coastal development. Assuming the answer to this is yes, the logical next step would be to identify specific areas of vulnerability through the use of spatial data and analytical tools (e.g., Reiblich *et al.*, 2019, see also Chapter G) to inform candidate site selection. Once candidate adaptation sites or areas are selected, a determination of the institutional capacity to regulate development and enforce rules would need to be made. Depending on this capacity, different scenarios of action could be considered, ranging from strict enforcement of precautionary development restrictions (e.g., on-site water treatment, settling ponds, regional stormwater management infrastructure) to outreach effects aimed at encouraging voluntary compliance based on low-cost solutions such as shoreline vegetation management.

The outcome of this process, aggregated across the range of potential climate effects and adaptation options, would yield a subset of recommended adaptation actions that are practical and focused to the greatest extent possible on meeting the primary objectives articulated at the outset. Once the subset of practical adaptation options is identified, the next step is the development of a detailed implementation plan (including mobilizing funding) to bring the chosen actions into reality.

4. GUIDANCE FOR DRAFTING ADAPTATION PLANS

Detailed implementation plans make aspirational adaptation goals and objectives real, actionable, and more likely to move forward. As with individual actions, detailed criteria have been developed to evaluate the quality of adaptation plans and identify areas for improvement (e.g., Olazabal *et al.*, 2017). In addition to evaluating the proposed actions themselves, the recommended criteria seek to establish:

- Political and Economic Coherence – by evaluating level of funding and personnel commitments, alignment with policies and regulations, and assignment of responsibilities and effective leadership. This includes reflecting climate change adaptation plans and priorities for fisheries within existing fisheries governance institutions and other resource-use management frameworks (e.g., tourism, coastal development and marine transportation).
- Opportunities for Learning – by evaluating the quality of information underpinning the selection of adaptation options, the robustness of the proposed monitoring and evaluation strategy, and the mechanisms put in place to maximize learning and to flexibly adjust strategies in response to new information. A learning orientation, an adaptive approach and a long-term focus are essential responses to confront the added uncertainty climate change brings to fisheries management (e.g., productivity of fish stocks, migration patterns, marine food webs interactions, fisherfolk responses to ecological shifts).
- Legitimacy – by evaluating levels of transparency in priority-setting and resource allocation, stakeholder engagement, accountability and considerations of equity and social justice. In particular, effective and inclusive stakeholder engagement and empowerment in planning and implementation are important properties of fisheries governance that enables climate change adaptation (Poulain *et al.*, 2018).

Successfully completing climate change adaptation planning to the stage of implementation requires a substantial commitment of resources and effort from decision-makers, managers, and members of the public that will be affected by the plan. Since climate change complicates existing approaches to marine resource stewardship and fisheries management, and management agencies are already stretched, the role of non-governmental organizations and communities in the management process is increasingly recognized (Wilson *et al.*, 2017). The process is most likely to result in effective implementation and good outcomes when key stakeholders are engaged from the outset. Once implemented, monitoring is critical to ensuring the interventions are having their desired effects and, if not, to informing course corrections. Additionally, monitoring data are inputs for the design of future adaptation projects. Reporting on implementation progress and sharing lessons learned with affected stakeholders and the broader adaptation community are other activities that promote accountability and continuous learning.

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F. Marine Spatial Planning for Climate Change Adaptation in the Fisheries Sector

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1. INTRODUCTION

The effects of climate change are expected to vary across regions and, as a result, much of the information produced during climate change vulnerability and impact assessments is necessarily spatial in nature. Making the best use of this valuable information in climate change adaptation planning in the fisheries sector will require the use of 'spatial adaptation planning' that can help managers identify management opportunities and allocated limited adaptation resources to those areas that need it most (Mills *et al.*, 2015, Jones *et al.,* 2016).

To date, most applications of spatial methods to climate change adaptation have focused on prioritization for conservation of species and habitats. A review of past studies that have applied this approach revealed that most were carried out with the primary objective of protecting habitats expected to be suitable under future climates (52% of studies) and/or identifying and protecting climate refugia (41% of studies). A smaller proportion of studies focused on optimizing connectivity (24%) or heterogeneity (17%) to facilitate migration and increase resilience to future climate change, and only a minority of studies (2%) incorporated human considerations as part of adaptation planning for ecological resilience (Jones *et al*., 2016). More recent initiatives are increasingly recognizing the social dimensions of spatial adaptation planning for conservation, particularly in tightly coupled socio-ecological systems such as fisheries (Bennett *et al.*, 2019). This generally involves comparing spatial conservation priorities against the spatial distribution of human activities in order to optimize conservation outcomes and support climate resilience of communities and economies.

The application of spatial methods in ecosystem management and adaptation planning has barriers to entry, in particular access to relevant data in usable formats, access to the appropriate geographic information systems (GIS) software, and availability of staff trained in the use of GIS and familiar with management techniques. Despite these barriers there are considerable benefits to incorporating spatial methodologies when planning and implementing resource management policies generally and in particular for managing for climate change adaptation.

This chapter provides a brief overview of current spatial approaches to ecosystem-based management in a fisheries context, describes how these approaches can be used in a climate change adaptation context, introduces the geospatial library to be delivered as part of the data portal component of this project, and suggests types of analyses that can be performed to enhance climate change adaptation planning for CRFM members.

2. BENEFITS OF SPATIAL APPROACHES TO ADAPTATION

The primary advantage of using spatial approaches for marine planning is the ability to address spatial as well as temporal variability in the distribution of resources and impacts. This is particularly relevant in a climate change context, where these distributions are expected to move over time in ways that may not be compatible with more traditional static approaches to marine spatial planning (Gissi *et al.*, 2019). Unlike analyses that make blanket assumptions within jurisdictional bounds, explicitly spatial approaches help to:

- Facilitate analysis and management of cumulative effects,
- Address shifting resource distributions,
- Prioritize distribution of limited management resources to those areas most in need, and
- Improve knowledge transfer and participatory planning within and outside of institutions.

This section provides a brief overview of these benefits in a climate change context.

2.1 Addressing Cumulative Effects

Traditional resource planning exercises have tended to be tied to a newly proposed development, or a newly proposed policy, or a newly understood vulnerability. These targeted approaches can be undermined by the shifting baseline phenomenon, in which each new analysis takes as a given the accumulated impacts of previous developments, policies and environmental shifts.

Analyses that are conducted with spatial methodologies are less likely to suffer from these limitations, because the GIS tools tend by their nature to highlight overlaps. In many cases cumulative effects can become visually apparent simply by importing relevant data into a desktop GIS and inspecting their spatial relationship to each other. There is also a suite of techniques that can be applied to quantify and evaluate those overlaps, some of which are suggested at the end of this chapter.

This benefit is particularly relevant in the case of climate change, which brings with it multiple, spatially variable, and overlapping impacts on the marine environment (e.g., temperature increases, sea-level rise, species range shifts) that can themselves be exacerbated by existing human activities in the coastal zone (e.g., coastal development, pollution runoff, etc.). For this reason, many of the ecosystem-based climate change adaptation strategies identified for the fisheries sector, including those identified in Chapter E in this publication, focus on reducing non-climate cumulative effects on ecosystems to increase their resilience to climate change. Spatial tools can help to identify areas with greater cumulative effects on species and habitats critical for fisheries production and prioritize these areas for management interventions (e.g., Wedding *et al.*, 2018).

2.2 Addressing Shifting Resource Distributions

Prior to the onset of climate change, planning exercises could reasonably assume that the spatial distribution of resources and impacts would vary only cyclically or even remain relatively constant (at least as aggregated over time). This meant that a given analysis could be performed once and the resulting boundaries applied henceforth. Changes in climate mean that static outputs from one-off planning exercises will become less relevant over time as those distributions shift.

Spatial methodologies can help to address this challenge by including documented steps and live tools to readily recreate the analyses as needed as more recent data or parameters become available. Spatial methodologies can also address these challenges by building in assumptions of change over time each time they are performed. Furthermore, where available, climate change projections of anticipated future habitat and species distributions can be used to inform such assumptions about how resource distribution patterns may change over time relative to existing spatial management boundaries. For example, climate change projections have been used in a marine spatial planning context to:

- Identify and protect climate refugia where habitat suitability will change little over time (Graham *et al.*, 2018, Woodson *et al.*, 2019),
- Identify and protect areas expected to become suitable habitats under future climate scenarios (Jones *et al.*, 2018),

- Plan redistribution of fishing effort to maintain access to harvest opportunities while minimizing conflict with future climate adaptation measures (Maina *et al.*, 2015) and
- Predict movements of transboundary stocks that might require amendments to existing catch sharing agreements or creation of new ones to prevent resource use conflicts between fishing nations (Pinsky *et al.*, 2018).

Work Package 1 of this project used species distribution models to project the range shifts of 110 marine species. Both the modelling approach and mapped outputs can be useful to spatial adaptation planning (see Box 1).

Box 1: Species Distribution Modelling – A Key Tool for Producing Spatial Data on Climate Impacts

As part of Work Package 1 of this project, the current and future distributions of the selected 110 marine species were modelled using an environmental niche approach. This method quantifies the environmental preferences (e.g., temperature, salinity, dissolved oxygen) of marine species and projects their potential distribution according to present conditions determined by monitoring data and future conditions determined using earth system models projecting forward under different climate change scenarios.

For this project, changes in species distributions under future climates were evaluated using a combination of four environmental niche models (ENM): the (1) Bioclim and (2) Boosted Regression Trees models from the Biomod2 R package (Thuillier *et al.*, 2008), (3) Maxent (Phillips *et al.*, 2004), and (4) NPPEN (Beaugrand *et al.*, 2011). These models were selected as they are currently the most widely used in the published literature given the type of data accessible for the region (Philips *et al.*, 2004; Thuiller *et al.*, 2009).

To help readers understand how these data are generated for use in spatial analyses, the project team developed a tutorial (see **Chapter B** of this report) that walks readers through an example application of the Biomod2 model using training data for King Mackerel or Kingfish (*Scomberomorus cavalla*) implemented in the open-source statistical programming suite known as R. It requires users to download the R Software (https://www.r-project.org/) and ideally its companion user-friendly user interface R Studio (https://www.rstudio.com/).

Understanding how to use these models would provide regional managers with the ability to update projections of species geographic ranges under future climate scenarios as more accurate input data and updates of earth system modelling efforts are released.

2.3 Prioritizing the Distribution of Adaptation Efforts

Resource management policies are best assessed and applied at the spatial scale at which the resource—or the stressors on the resource—vary. In a hypothetical case in which a resource was distributed equally within the jurisdictional bounds of a managing agency, then it would be appropriate for the agency to develop a single policy for the entire jurisdiction. But in most real-world cases there is considerable variation in both resources and stressors on those resources (Davies *et al.*, 2016, Jones *et al.*, 2016), as well as in a wider range of feasibility criteria that affect how they can be managed (Reiblich *et al.*, 2019).

By prioritizing protection and restoration efforts on areas where the resources and stressors (either new or preferably, cumulative stressors) overlap, the impact of that effort is likely to be greater. This is especially important in small and medium fisheries and in developing states where available resources for implementation of protective policies can be especially limited. As a corollary, by relaxing resource use restrictions in specific areas where a resource is *not* under stress, that resource can remain available for economic utilization. This can increase acceptance by resource users of protection efforts being applied elsewhere and maintain livelihoods. As with increased protection efficiency, this benefit can be especially important in small and medium fisheries where profit margins can be slim and resource users can be particularly vulnerable to reductions in livelihood. This situation may apply more readily to the larger Caribbean island or to mainland states, rather than very small island states.

Beyond resources and stressors, the spatial prioritization process will also need to consider how spatial variation and overlaps in regulatory and policy obligations might affect the feasibility of adaptation options at local, national, and even regional scales. These obligations might include land-use zoning, permits, property rights, environmental protection regulations, jurisdictional boundaries, and regional or international agreements. Conducting this type of exercise can help to surface regulatory barriers to desired adaptation measures and ensure the right parties are engaged to overcome these barriers (Reiblich *et al.*, 2019).

Once a range of spatial data layers are available, they can be used as inputs to spatial conservation prioritization analysis. One of the simplest spatial prioritization analyses is known as spatial multi-criteria decision analysis (MCDA), where rules can be set up to determine whether the values in each layer of information being considered are positive or negative conditions in the overall decision-framework (e.g., per Rikalovic *et al.*, 2013, Tammi and Kalliola, 2014). The result is an output layer that is typically colour-coded to show how suitable different areas might be for a chosen intervention based not only on climate layers, but on other types of geographic information. More advanced applications involve the use of free spatial optimization software (e.g., MARXAN or InVEST) to optimize the boundaries of marine management areas depending on a range of desired climate change adaptation goals (e.g., as in Maina *et al.*, 2015, Davies *et al.*, 2016).

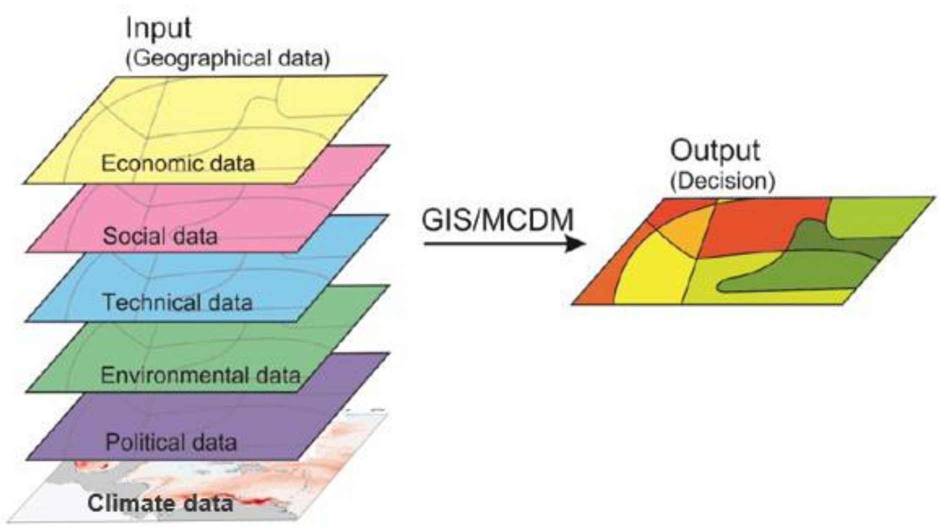

Figure 1: A schematic of the types of spatial information that can be overlaid to carry out a spatial multi-criterion decision analysis (adapted from Rikalovic et al. 2013).

2.4 Improve Communication and Knowledge Transfer

Spatial data repositories and their map-based visualizations provide a useful common language for facilitating knowledge transfer at multiple scales of organization.

- *At Community Scales*: The success of marine planning exercises depends in large part on efficient and accurate communication among technical experts, policy makers, local and sectoral stakeholders and funding agencies. When effective communication is happening, all parties can share more informed feedback during planning stages, and effective implementation is more likely once planning is complete (Le Cornu *et al.*, 2017). Spatial data and maps represent a powerful visual communication tool for sharing potential climate change impacts and adaptation options with communities in a broadly accessible way. Spatial data products can form the basis of participatory mapping exercises to incorporate local and traditional knowledge, guide modifications to the boundaries of existing management areas, and inform site selection for new adaptation interventions (e.g., Baldwin and Oxenford, 2014; Lieske, 2015). The use of visual tools in participatory processes can also help to lower barriers for participation in planning discussions for community members with limited education and literacy skills. Enabling participatory decision-making in this way will empower fisherfolk in the adaptation process and improve buy-in, self-enforcement, and monitoring for those adaptation options that are ultimately implemented. Incorporating fisherfolk input can also be important for avoiding maladaptive spatial planning, for example, by restricting fishing activities to areas were fishers are more likely to be at risk from other aspects of climate change such as extreme weather (Le Cornu *et al.*, 2018).

- *At Institutional Scales*: Spatial data repositories and maps can serve as a centralized conduit for institutional knowledge within organizations. Fisheries management agencies in the Caribbean have expressed common challenges with staff turnover and retention, particularly among technical staff (Eyzaguirre *et al.*, 2018). Staff departures can represent a loss of methodological knowledge, and repeated departures can significantly undermine capacity if methods are not found to transfer that knowledge between generations of employees. So long as processing steps are reasonably well documented and the files they are run on are retained, GIS and other computational operations provide a channel for the collection and transmission of such knowledge. Although documentation and data retention efforts do require some additional effort, and some loss of capacity between staff is inevitable, as long as reasonable efforts are made there is the possibility of a net cumulative gain in capacity over time.

- *At Regional Scales*: The Caribbean Regional Fisheries Mechanism has a distributed capacity for analysis and planning, with collaborating technical staff in place within the fisheries management agencies of multiple member nations. Those staff have access to a variety of data and tool resources. Providing a shared set of "baseline" spatial datasets, processed spatial data products, and suggested spatial analyses built on those datasets can help to facilitate cooperation across member countries to address regional management issues including climate change. A shared set of spatial datasets reflecting a regional picture can also help preserve or support institutional memory at national scales.

3. POTENTIAL CHALLENGES AND OPPORTUNITIES

In order to access the many benefits of spatial adaptation planning, national and regional entities may first need to overcome a number of challenges to the successful implementation of marine spatial planning approaches (Mills *et al.*, 2015).

3.1 Access to and Proficiency with GIS Software

Training staff to become adept with a particular software system requires an investment of time and money by an institution. If it isn't clear whether a particular software will support all of the functions that will be required by that institution into the future, or if licensing costs will be continue to be supportable, this investment may not be warranted.

The availability of the open source QGIS desktop geographic information system makes an investment into training staff much lower risk. QGIS has a robust feature set, comparable to the more costly licensing tiers of ESRI's ArcGIS (arcgis.com) set of tools and superior to the lower cost tiers. The user interface requires an approximately similar level of training to gain comfort, and user interface operations tend to run more quickly on lower-end computers.

If more sophisticated analysis becomes necessary QGIS provides options for integrating plugins and third party geospatial libraries (such as GRASS, originally developed by the U.S. Army Corps of Engineers) and functions can be scripted for repeated application using the Python programming language. In addition, the cartographic system for static map production in QGIS is well developed.

Most importantly, in the 17 years since its original release, QGIS has established a wide community to provide ongoing development and peer support. Numerous online tutorials are available, there is a large and active user-support community, and yearly developer meetings continue to contribute to improvements in the platform. Staff time invested in gaining capacity with QGIS will reliably remain relevant into the future.

3.2 Availability of Geospatial Resources in the Caribbean

As with other types of data, there is a wide range of variation in the number, resolution, and quality of geospatial data products across countries within the Caribbean. This variability reflects both differences in countries' internal capacity to produce geospatial data products and differences in their history of relationships with external partner organizations that have facilitated habitat mapping and other types of spatial data generation in recent years (e.g., TNC, 2016).

There have been several initiatives in recent years to assemble spatial data layers relative to marine ecosystems and human uses in the Caribbean in a common web-based data portal, including the:

- Caribbean Marine Atlas (https://www.caribbeanmarineatlas.net)
- CaribNode (http://www.caribnode.org/)
- Reefs at Risk Portal (https://www.wri.org/publication/reefs-risk-revisited)

Some of the spatial data layers available in these three regional portals are summarized in Table 1. Many of the geospatial resources that are currently publicly available exist at coarse resolutions suitable for regional analysis and planning, with a few exceptions.[21] However, they lack sufficient detail for planning at finer national or community scales, particularly with regard to marine livelihoods in fishing communities. Additional geospatial data from within countries can help to fill in these gaps in resolution and can be used in concert with regional data layers to inform planning at local scales. Although national data portals have been developed to facilitate access to marine spatial data resources in some countries (e.g., via MarSIS in Grenada), broadening public access to spatial datasets in other Caribbean countries should be encouraged for its potential benefits in facilitating spatial climate change adaptation planning for fisheries and other coastal activities.

Table 1: Summary of regional geospatial datasets relevant to the Caribbean fisheries sector, available via the Caribbean Marine Atlas, CaribNode or the Reefs at Risk Portal

Domain	Spatial Data Resources	Source(s)	Web Link
Habitats	Global Distribution of Seagrasses	UNEP-WCMC	http://data.unep-wcmc.org/datasets/7
	Global Distribution of Coral Reefs	UNEP-WCMC	http://data.unep-wcmc.org/datasets/1
	Global Distribution of Mangrove Biomass	UNEP-WCMC	http://data.unep-wcmc.org/datasets/39
	Marine Protected Areas of the Caribbean	MPA Atlas	http://www.mpatlas.org/data/download/
	Downscaled Caribbean Coral Reef Bleaching Vulnerability	Van Hooidonk *et al.*, 2016	https://coralreefwatch.noaa.gov/climate/projections/downscaled_bleaching_4km/index.php
Fished Species	Species Occurrence Records (Note: Records from these sources	Ocean Biogeographic Information System	www.obis.org

[21] For example, see Habitat Suitability Index projections from Work Package 1 of this project, and downscaled climate projections on coral reef bleaching risk from van Hooidonk *et al.*, 2016.

Domain	Spatial Data Resources	Source(s)	Web Link
	have been consolidated for Caribbean species examined in this project and are available via http://climatesmart.fish)	(OBIS)	
		Intergovernmental Oceanographic Commission of UNESCO	www.ioc-unesco.org/
		Global Biodiversity Information Facility (GBIF)	www.gbif.org
		FishBase	www.fishbase.org
		IUCN	http://www.iucnredlist.org/technical-documents/spatial-data
	Species-specific Habitat Suitability Indices and Anomalies Under Future Climate Projections	CRFM (this project)	http://climatesmart.fish/
Fisheries	Historical Catch reconstructions (by country)	Sea Around Us	www.seaaroundus.org
	Cumulative Maximum Catch Potential Indices and Anomalies Under Future Climate Projections	CRFM (this project)	http://climatesmart.fish/
Human Populations and Activities	Latin American and the Caribbean Continental Population Datasets (2000-2020)	WorldPop	https://www.worldpop.org/geodata/summary?id=141
	Cumulative Human Impact	Halpern *et al.*, 2008	http://www.car-spaw-rac.org/?-Maps-and-reports https://www.wri.org/publication/reefs-risk-revisited
	Cumulative Maritime Traffic (large vessels)	Halpern *et al.*, 2008	
	Cumulative Coastal Development Pressure	World Resources Institute (WRI) Reefs at Risk Revisited Project	
	Cumulative Land-based Pollution	World Resources Institute (WRI) Reefs at Risk Revisited Project	
	Cumulative Fisheries Pressure	Stewart *et al.*, 2010 Dunn *et al.*, 2010	

A principal deliverable of this project is the development of an online data portal designed to facilitate publication, discovery, viewing, and downloading of fisheries-relevant data and documents for technical and non-technical users. An offline geospatial repository has also been assembled to facilitate more technical users in performing ongoing spatial analyses. This offline geospatial repository was an input to a Regional Training Workshop that took place in October 2019, with all participants receiving access to it. It can be retrieved from the CRFM data portal ("GIS Data Package"). The offline geospatial resource is composed of:

- offline copies of all of the species-specific Habitat Suitability Index as well as cumulative Maximum Catch Potential map products from earlier phases of this project,
- general reference layers for cartography and context (e.g., national boundaries, EEZs),
- ecological, human use, and land use layers relevant to fisheries from third party sources (including those from Table 1),
- any additional layers of interest provided by fisheries management agencies within the region, and
- a unifying QGIS project file to facilitate access to these layers, so that the simplest way to explore the resource will be to open the project file in QGIS and turn layers on or off in the viewer's table of contents.

3.3 Lack of Capacity to Engage in Effective Spatial Adaptation Planning

Even where spatial data are readily available for use in spatial adaptation planning, lack of institutional capacity or political will can present a roadblock to effective implementation of management initiatives

(Mills *et al.*, 2015). An enabling institutional and policy environment for spatial adaptation planning includes the following elements:

- Adequate resources and expertise for creating and regularly updating spatial data layers,
- Willingness to incorporate local knowledge into spatial data collection,
- Use of spatial information within a broader, participatory decision-making framework,
- Sufficient regulatory flexibility to accommodate dynamic spatial management strategies such as (e.g., flexible management area boundaries, length of fishing season, and gear restrictions over the course of seasons or years), and
- Sufficient resources, personnel, and community support to enable effective enforcement of spatial management areas in the coastal zone.

These and other elements of enabling institutional environments will be explored in greater depth during the final phase of this project, which involves updating the Regional Strategy and Action Plan for Climate Change Adaptation and Disaster Risk Management in Fisheries and Aquaculture (CRFM, 2013).

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