INTER-AMERICAN TROPICAL TUNA COMMISSION

SCIENTIFIC ADVISORY COMMITTEE

15TH MEETING

La Jolla, California (USA)
10-14 June 2024

DOCUMENT SAC 15-12

A CLIMATE CHANGE WORKPLAN FOR THE IATTC

Dan Crear, Jon Lopez, Leanne Fuller and Alexandre Aires-da-Silva

CONTENTS

EXECUTIVE SUMMARY

Over the last decades, research has begun to show the direct and indirect impacts of climate change on marine species, ecosystems, and fishing communities. In recognition of these impacts on the fisheries and conservation and sustainability of target and non-target species covered by the Antigua Convention, the IATTC has adopted a Resolution on climate change in 2023 (Resolution C-23-10). This paper summarizes

the current work that the IATTC staff is undertaking to understand, monitor, and prepare for the effects of climate change in the eastern Pacific Ocean (EPO), and reviews the many tools and frameworks developed by various countries and international organizations to understand and account for climate change in fisheries science and management. This review is then used to propose a workplan that promotes climate-resilient tuna fisheries in the EPO. To date, only two projects in the SSP investigated climate change impacts while a small number of other projects are considered relevant. Based on the small amount of work done on climate change at IATTC, an opportunity is present to develop a workplan that guides the Commission through various phases, components, and activities required to promote climate-resilient fisheries. The proposed phases are five: i) planning, ii) deciding on a scope and objectives, iii) developing a framework, iv) creating tools, and v) tool application and/or management implementation, while the three components include i) the framework, ii) tools, and iii) management considerations. The framework, a pivotal component in every climate change workplan reviewed, is a set of steps that guide and support decisions and actions that will lead to climate-ready fisheries. In the review, five frameworks are highlighted, which are starting to be adopted by various countries and organizations. The majority of these frameworks are iterative and follow common steps such as scoping, which is where a conservation target (i.e., species, fisheries, community) is identified, the geographic and temporal extent are determined, and key partners involved are identified. Subsequent steps consist of assessing and understanding the impacts of climate change on the conservation target, developing potential tools managers could use to account for these impacts, and implementing the best strategies and tactics that promote climate-resilient fisheries. To achieve the steps mentioned above numerous tools will need to be developed by IATTC staff, the Commission, and other relevant stakeholders through multiple participatory projects, meetings and workshops. Fortunately, tools have already been developed by other organizations and are described in the review as examples for the IATTC. The review covers a range of tools and case studies, from species distribution modeling and climate vulnerability assessments to climate change integration into management strategy evaluation and spatial management. These tools will ultimately lead to the third component and last phase of the workplan, where management considerations are introduced, and management actions are implemented. As illustrated in this workplan, the timeframe will likely extend beyond 2028 to accommodate future management actions that take the rapidly changing climate into consideration. Taking all the above into consideration, this document describes a workplan developed by the IATTC staff to promote climate-resilient fisheries for the IATTC.

1. BACKGROUND

At the 101st annual meeting in Victoria, B.C., Canada in August 2023, the IATTC adopted a resolution on climate change (Resolution C-23-10). The resolution recognizes the impacts climate change is having on target and non-target species as well as the fisheries and the potential effects these impacts may have on the long-term conservation and sustainability of fish stocks covered by the Antigua Convention. The resolution states that the Working Group on Ecosystem and Bycatch (EBWG), the Scientific Advisory Committee (SAC), and the Commission will include climate change as a recurrent agenda item at their respective annual meetings, and in general, "*highlight and consider the best scientific information available on the relationships between climate change, target stocks, non-target species, and species belonging to the same ecosystem or associated with the target stocks.*" As a first step towards addressing this resolution, the IATTC scientific staff aim to develop a workplan to better assess and mitigate these effects. Although climate impacts are currently included in the previous strategic science plan which was extended to 2024 (SSP, IATTC-93-06a, see primarily theme 5 "*Interactions among the environment, ecosystem, and fisheries*"), following the resolution, the staff plans to incorporate additional efforts to understand, monitor, and mitigate the impacts in the next edition of the 5-year SSP. Climate change is a concern for many organizations, and therefore, the IATTC joins the other tuna-regional fisheries management organizations (t-RFMOs), including the Western and Central Pacific Fisheries Commission

(WCPFC), the International Commission for the Conservation of Atlantic Tunas (ICCAT), and the Indian Ocean Tuna Commission (IOTC), that have developed resolutions (Resolution 2019-01, Resolution 22-13, Resolution 22/01, respectively) to prepare for the impacts of climate change on their fisheries.

1.1 Objectives

Given the adoption of IATTC's resolution on climate change, the goals of this document are to:

1. Summarize the current work that IATTC is undertaking to understand, monitor, and prepare for the effects of climate change in the eastern Pacific Ocean (EPO)
2. Review and highlight various tools and frameworks that other countries and international organizations have developed to promote climate-resilient fisheries, and
3. Use this review to propose a climate change workplan for the IATTC's consideration.

This workplan will allow the IATTC and its scientific staff to better understand, monitor, account for, mitigate, and prepare for the impacts climate change may have on fisheries, target species, non-target species, and the broader EPO ecosystem.

2. IATTC'S CURRENT RESEARCH RELATED TO CLIMATE CHANGE

2.1 Projects on climate change

Similar to many other RFMOs, limited work focusing on the impacts of climate change has been completed at IATTC. There are currently two projects in the SSP under Goal N—improve our understanding of the interactions among environmental drivers, climate and fisheries—that explicitly incorporate climate change in their project titles (see e.g., SAC-14-01). Project N.2.a states that scientific staff should develop models to understand the effects climate change may have on pre-recruit life stages of tropical tunas, while N.2.b supports climate-ready and sustainable fisheries using environmental data (SAC-14-01).

To address the objectives of Project N.2.a, experimental studies have been conducted at the IATTC''s Achotines Laboratory from 2004 to present. Climate change variability has been tested in replicated experimental investigations and the effects on growth, survival, and physiology of early life stages of YFT have been estimated. These investigations have studied the effects of ocean warming, acidification, and anoxia on the egg and larval stages of YFT (SAC-15 INF-P), and these studies have produced eight peer-reviewed publications.

2.2 Other relevant research projects

Other work, although not directly linked to climate change, can be leveraged in future climate change research. In recent years, species distribution models (SDMs) have been developed for the three tropical tunas and bycatch species like the leatherback sea turtle using a set of environmental variables and observer data from the purse seine fishery (see e.g., SAC-10 INF-D). In addition to identifying the effects of various environmental conditions on tropical tunas, the SDMs have been used to predict daily species distributions starting in the early 2000s within the Convention Area. Similarly, SDMs have also been developed for various bycatch species caught in the EPO to support ecological risk assessments (ERAs; see e.g., SAC-15 INF-E). These models can be used to better understand how distributions have shifted over time or in response to specific environmental events (e.g., El Niño Southern Oscillation, ENSO) that impact the catches or habitats of tropical tunas (e.g., through shoaling or deepening of the thermocline, Bayliff 1989). Lastly, tagging projects to understand tropical tuna movements, behavior, and habitat utilization have generated data that can inform SDMs and subsequent environmental inquiries (see e.g., SAC-15 INF-E). Additional applications of SDMs will be discussed in a later section.

The IATTC staff has broadly provided ecosystem indicators in its annually-updated *Ecosystem Considerations* document (e.g., time series of incidental catches of non-target species by taxonomic group: marine mammals, sea turtles, sharks, rays, fishes; environmental indices: Oceanic Niño index, ONI, Pacific Decadal Oscillation, PDO; and more specifically ecological indicators output from the Ecopath mass-balance model that together identify changes in the structure of the EPO ecosystem) (see e.g., SAC-14-11). A proposed workplan on developing an ecosystem report card ("EcoCard") of bycatch, ecosystem, and climate indicators, complementary to the workplan presented herein on climate change, will be presented at this year's EBWG (see EB-02-02) as a means to further support progress and operationalization towards ecosystem approaches to fisheries management (EAFM). This type of information can track simple changes in the ecosystem through time, whether it be environmental conditions (e.g., sea surface temperature), fishing effort (e.g., number of sets), or catches of target and non-target species (e.g., total catch of yellowfin tuna). Theoretically, indicators can be used to connect an ecological or fishery response to an environmental change, which can be linked to climate change impacts.

3. TOOLS DEVELOPED FOR CLIMATE-RESILIENT FISHERIES

Tools are strategic or tactical instruments designed to support fisheries management decisions and actions. They are particularly important because they are used to help scientists monitor change as well as assist resource managers on how to implement actions to address the change. Many countries and international organizations have developed tools to help understand and mitigate the impacts of climate change. A review of a variety of tools is described in detail below.

3.1 Oceanographic and climate data

Oceanographic data are often collected through in situ measurements (e.g., ship-borne and buoy measurements) and remote sensing. Using this information, oceanographers can model and predict certain oceanographic variables at various spatial and temporal scales. Recent advancements in computing power have led to increased spatial and temporal resolution throughout our oceans. Areas where data are collected, assimilated, and modeled at a higher spatial and temporal resolution often can produce a surface of environmental predictions at finer spatial and temporal scales.

A wide array of environmental variables can be produced that range from static (does not change through time) to dynamic (changes through time) and from surface, subsurface, to bottom depths. Static variables include, for example, bathymetry (depth) and rugosity (i.e., the bumpiness of the bottom, which can be derived from bathymetry). Common dynamic surface variables include, for example, sea surface temperature (SST), sea surface salinity, sea surface height (altimetry), surface current velocity and direction, surface wind stress, and curl (measure of the rotation of the wind stress), eddy kinetic energy (proxy for mesoscale variability due to eddies), chlorophyll (often a proxy for primary production), and turbidity. Additional variables can be derived from the variables above, such as intensities, anomalies, and standard deviation of SST and sea surface height, which can be proxies for fronts. Some of the subsurface variables include mixed layer depth (depth of surface mixing) and water temperature, salinity, and current velocities at various depth levels. Subsurface variables are not as readily available due to lack of data and understanding of subsurface conditions and often require further processing of the surface data. Lastly, if biogeochemical models are developed for specific regions, then variables such as dissolved oxygen and nitrate are available, however, these types of models have a very high spatial-temporal resolution and are typically available in very specific, well-studied bodies of water (e.g., Chesapeake Bay; Feng et al. (2015)). Many of these variables are available for various historical and contemporary time periods. Often, a subset of those variables can be projected into the future based on climate projections. All of these variables have been considered when discussing climate impacts on tuna and tuna-like species, because they either directly affect the physiology and behavior of these species or they influence their prey, ultimately affecting their distributions (Hazen et al. 2013, Dell'Apa et al. 2023).

Many oceanographic data products exist globally, but the temporal period and spatial resolution vary substantially. A common product used for contemporary oceanographic data is the Global Ocean Physics Reanalysis (GLORYS, Copernicus Marine Environmental Monitoring Service; Lellouche et al. (2018)), which is a global, in-situ measurements and remote sensing informed, data-assimilating ocean model that produces gap-free daily outputs at 1/12° (~9 km) horizontal resolution and 50 vertical levels. For climate projections, there are many climate models from the Coupled Model Intercomparison Project Phases 5 (CMIP5) and 6 (CMIP6) (IPCC 2023) that provide ocean conditions for various time periods at a horizontal resolution of 1°. On the other hand, NOAA's Geophysical Fluid Dynamic Laboratory (GFDL) developed their CM2.6, which is a high resolution (1/10°) global climate model that resolves ocean circulation along the US shelf and provide expected monthly changes (deltas) in ocean conditions over an 80-year time period (Saba et al. 2016). Unfortunately, high resolution products like CM2.6 have not been developed for all ocean regions. To date, IATTC staff have downloaded many of the variables mentioned above for the EPO from 1995 to 2023 at an often daily temporal resolution and either 1/4° or 1/12° spatial resolution.

Oceanographic data products are used in many climate-resilient fisheries tools. In the various tools sections below, applications of oceanographic data will be highlighted as these data are often a necessary piece of information when determining the effects of climate change on fisheries.

3.2 Species distribution models

Species distribution models (SDMs), also called habitat suitability models, are developed to understand the relationships between the environment and a particular species as well as to predict the distribution of a species over a specific spatial and temporal extent. The species data are obtained from either fishery dependent sources (e.g., observer programs or logbooks) or fishery independent sources (e.g., surveys or tagging data) and consist of spatial information (latitude and longitude) and date/time. To understand the relationship between environmental conditions and a species occurrence or abundance, oceanographic data—extracted from an appropriate ocean product—are linked to the species data based on its location and date, and a model is developed to estimate the relationships. Once those relationships are identified, the species distribution or habitat suitability can be predicted spatially over a particular time period. For example, to predict a species distribution over the EPO for July 2023, the oceanographic data need to be extracted for the same area and time period from one of the many available ocean products. Those data and the relationships developed from the SDM are then used to predict the species distributions. In the climate change context, SDMs are often used to examine how distributions may or may not change in response to various future ocean conditions.

There are many types of SDMs that have been used to understand the impacts of climate change on the distribution of marine species. The most common SDMs use correlative or regressive modeling approaches. This includes semi-parametric models, such as generalized additive models (GAMs) and machine learning models, like random forest or boosted regression trees (BRT). These models often use presence/absence species data and output probability of occurrence. For example, McHenry et al. (2019) used fishery-independent bottom trawl survey data and GAMs to project the probability of occurrence and thus change in distribution under climate change of 125 species along the US Northeast Shelf, while Braun et al. (2023) used fishery-dependent data and BRT to project the changes in the distribution of occurrence of 12 highly migratory species in the Northwest Atlantic Ocean and Gulf of Mexico under climate change. Lastly, Lezama-Ochoa et al. (2023) applied SDMs from 10 highly migratory species in the California Current to project directional and distributional shifts under various climate change scenarios. Changes in the distribution of relative abundance can also be determined using Vector-Autoregressive Spatio-Temporal (VAST) and delta-lognormal models. These methods can consider catch and habitat associations data to derive relative abundances, which may be preferred for certain applications. For example, the delta-lognormal model was used along with long-term ecological survey data to project the shifts in thermal habitat for 686 species under climate change along the North American continental shelf (Morley et al. 2018). For species where the data set is presence-only (e.g., tagging data), pseudo-absences can be created and spatially and temporally randomized so that model outputs are informative. For example, Champion et al. (2021) developed 10,000 pseudo-absences to accompany presence data from a gamefish tagging database and developed a GAM to project distributional shifts under climate change of four recreationally important coastal pelagic fishes off the east coast of Australia. When contemporary and future climate data is available throughout the water column and environmental data is measured and archived while the species is freely swimming in the wild, changes in species distribution can be determined across a 3-dimensional habitat. For example, a depth-integrated SDM was developed for cobia (*Rachycentron canadum*) from archival tagging data and high resolution climate models to assess the shifts in their distribution along the US east coast between contemporary and future time periods (Crear et al. 2020). As mentioned in section 2.2, SDMs have been initially developed for tropical tunas (SAC-10 INF-D) and bycatch species like leatherback sea turtles (BYC-11-01) by IATTC staff and species distributions have been predicted over various time historical and contemporary time scales.

As SDMs build on oceanographic data, many other climate-resilient fisheries tools build on SDM outputs. Often, the most useful outputs from a SDM are maps displaying the species projected distribution given specific ocean conditions and associated metrics measuring change. The integration of SDMs in other tools are described below.

3.3 Indicators

Indicators provide a means to monitor changes over time and ideally have associated thresholds, which may in turn, prompt a response or action from policy makers. Indicators have been developed for climate/environmental data, such as the Oceanic Nino Index (ONI) used to monitor ENSO events or changes in mean SST anomaly for a given body of water. Ecological indicators have been created using fisheries catch and effort data, ecosystem models, or SDM outputs, among others. Examples of fisheries indicators include relative catches of a species for a fishery over time or the latitude-related metrics for a species caught through time. Ecological indices can be output from ecosystem models (e.g., Ecopath), and include trophic indicators (e.g., mean trophic level of the catch), diversity indices (e.g., Shannon's index) and fishing-in-balance indicators (FIB) (see e.g., SAC-10-15). Socioeconomic indicators like price or commercial fishing revenue may also be tracked and help determine targeting of a specific species. A list of indicators either calculated and presented to respective Commissions or proposed by scientists supporting the t-RFMOs are provided in Table 2 in Document EB-02-02. Changes in many of these indicators could be associated to shifts in climate and therefore, monitoring these shifts over time would be important for promoting climate-ready fisheries.

A global synthesis of climate-related indicators conducted on 65 studies found 119 indicators and quantified the type of information used to develop the indicator (e.g., local and expert knowledge vs scientific data), the spatial scale of the indicator (e.g., global vs national), and whether the indicator had an ecological, socioeconomic, or a social-ecological focus (Li et al. 2023). This study identified a major barrier as the gap between countries that have resources and inputs available versus countries that do not have the resources but are in most urgent need of adaptation tools. Despite this, the authors revealed there has been extensive use of indicators in dynamic management and adaptation planning for both ecological and social contexts. Indicators will continue to be useful for climate-resilient fisheries; however, it is important that those developing the indicators are working with the managers and other relevant stakeholders that coordinate the response or action to change to prevent a mismatch. IATTC staff have acknowledged the potential usefulness of indicators in depicting ecosystem status. Consequently, a proposed workplan to create an indicator-based ecosystem report card ("*EcoCard*") and complementary

Ecosystem Status Assessment for the EPO—by linking with stakeholders (i.e., IATTC's EBWG, the SAC, and the Commission) and global experts—will be presented at the 2nd meeting of the EBWG (EB-02-02).

3.4 Climate Vulnerability Assessment

Climate Vulnerability Assessments (CVAs) are a tool to identify relative vulnerability of a specific entity or target, whether it be a species, the habitat or ecosystem, or the fishing community. Vulnerability of a specific entity like a species is a function of its exposure to environmental change, its biological sensitivity to that change given its various traits, and its adaptive capacity and resiliency to deal with that change (Williams et al. 2008, Johnson and Welch 2009, Hare et al. 2016). CVAs are intended to be a rapid approach that can inform researchers and managers where to prioritize their resources. The method in conducting a CVA has taken many shapes and are often given different names (e.g., Climate Risk Assessment), but all follow the general framework of exposure, sensitivity, and adaptive capacity. Examples of CVAs are provided below.

3.4.1 Species and habitats

The method developed by the National Oceanic and Atmospheric Administration (NOAA) Fisheries of the US consists of two main components and has mainly been used to assess the vulnerability of species or stocks to climate change (Hare et al. 2016, McClure et al. 2023). The first component is an evaluation of species biological sensitivities and adaptive capacity (e.g., adult mobility, reproduction, sensitivity to temperature) based on a scientific expert scoring panel. The second component is climate exposure (e.g., SST, pH, oxygen levels), defined as the amount of change a species may be exposed to over a certain time period. The qualitative biological sensitivity score is combined with the quantitative exposure score to get an overall vulnerability rank (e.g., low, moderate, high, or very high) that can be compared across species. To date, CVAs following this method have been conducted in many regions around the US, including the Northeast shelf large marine ecosystem (LME) (82 species) (Hare et al. 2016), South Atlantic (71 species), Gulf of Mexico (75 species), Bering Sea (36 species) (Spencer et al. 2019), California Current LME (64 species; Figure 1) (McClure et al. 2023), and the Pacific Islands (83 species) (Giddens et al. 2022). CVAs have also been developed for specific species groups such as Pacific salmon and steelhead (33 stocks/units) (Crozier et al. 2019), Atlantic highly migratory species (HMS) (58 species/stocks) (Loughran et al. *in prep*) as well as protected species like Atlantic marine mammals (108 species) (Lettrich et al. 2023), Pacific marine mammals (*in progress*), and sea turtles (*in progress*). In addition to an overall vulnerability ranking for each species described above, qualitative scores provided by the scientific expert panel describing the potential for a distributional shift, the directional effect (positive, negative, neutral) of climate change, and a data quality value are determined. A narrative is developed for each species that describes the specific scores and contextualizes these scores with the life history and behavior of the species. These results have informed Endangered Species Act (ESA) documents, risk assessments, scenario planning exercises, and research and data needs. Given the wide use of this CVA method for specific species, other groups have completed similar style CVAs in different parts of the world such as in the Bahamas and Belize (Carroll et al. 2023) and Northeast Atlantic (Kjesbu et al. 2022). Lastly, this CVA method has been adapted for specific habitats as well. Farr et al. (2021) assessed the vulnerability of 52 marine, estuarine, and riverine habitats in the Northeast US to climate change.

In southeastern Australia a different type of CVA was developed using multi-criteria analysis for five coast-pelagic fish species. Champion et al. (2023) used primary literature, available data, and expert knowledge to set criteria that specified species' preferences for certain habitat and environmental conditions and then used those same resources to then weight those environmental conditions based on how important those types of conditions were to a species. Similar to an SDM, this information was used to calculate change in habitat suitability and thus vulnerability and projected spatially, between two time periods. A benefit of this approach is that it is spatially explicit and therefore can inform specific regional management. This method can also be completed for species that may be data poor and a distribution not clearly defined, but where expert knowledge criteria can form the basis for the species distribution.

In the Mediterranean Sea, a different version of a CVA was developed for various fisheries and was termed a climate risk assessment (CRA) (Pita et al. 2021). This study focused on around 100 species that were most important for fisheries in the Mediterranean and used two components, similar to the US CVAs. SDMs were used to determine the species distribution and the climate exposure was calculated based on the change in environmental variables across two time periods. Trait-based biological sensitivities were also identified and scored. The exposure and sensitivity score were combined to get a hazard score for a species (Figure 2a). The species hazard scores were plugged into additional steps to ultimately determine fisheries risk; however, the remainder of the steps will be discussed in section 3.4.2 CVAs specific for fisheries and socioeconomics.

The last CVA approach highlighted was initially developed as a global climate risk index but has been adapted for Canadian fisheries. Boyce et al. (2022) assessed almost 25,000 species globally using SDMs as the base distribution for a species and developed three indices from it: exposure (the species encounter with hazardous climate conditions), sensitivity (susceptibility), and adaptivity (the species resilience to changing conditions), which were combined into species climate vulnerability and then put into climate risk categories (e.g., negligible, moderate, high, critical). The benefit of this approach is that it is spatially explicit, and a climate risk category is provided. The global analysis was conducted on a 1° x 1° global grid, which is rather coarse. However, this approach is being adapted for Atlantic Canadian waters, on ~2,000 species, and 0.25° spatial resolution. Like Pita et al. (2021), the output of this climate risk index is plugged into subsequent steps to assess fisheries vulnerability as a whole. This work will be expanded on in sections 3.4.2 and 4.3.

3.4.2 Fisheries and socioeconomics

Although less common than the species CVAs, fisheries and socioeconomic CVAs have been developed in various regions. As mentioned above, the CRA developed for Mediterranean Sea fishes calculated a hazard score for each species (Pita et al. 2021). A fisheries hazard score was then calculated for each country with vessels fishing in the Mediterranean Sea based on the proportion of catch for each country. A fisheries exposure indicator was then developed for each country from the percentage of workforce in fisheries, the percentage of GDP contributed by seafood landings, and fish protein as a proportion of animal protein (Figure 2b). A vulnerability indicator was also calculated for each country based on three socioeconomic factors: Human Development Index, fisheries subsidies as a percentage of total landings, and number of scientific publications related to fisheries management in proportion to the country's landed tonnage (Figure 2c). The scores for fisheries hazard, exposure, and vulnerability were combined to get an overall fisheries risk value for each country (Figure 2d). This exercise highlighted the stark differences in CRA between the northern and southern Mediterranean countries (Pita et al. 2021). This type of work could be used by regional fisheries bodies to better understand which countries may be the most vulnerable to climate change from a fisheries perspective.

Like the Mediterranean Sea CRA approach, the Canadian CVA approach combines three important components: the ecological (climate risk index; mentioned above in 3.4.1), infrastructure, and management components (Boyce et al. 2023). Under the infrastructure component, the economic vulnerability of fisheries is assessed through the coastal infrastructure vulnerability index (CIVI). CIVI is a national-scale adaptation tool for the Fisheries and Oceans Canada (DFO) to assess harbor vulnerability. Similar to other CVA approaches, CIVI is split into three sub-indices: climate exposure (e.g., sea level change, wind, wave), sensitivity (e.g., harbor condition and protection), and adaptivity (e.g., variability in the cost of replacements from damage). These three scores are combined to get the infrastructure or socioeconomic score (CIVI). For the management component, a survey is being designed and will be sent to fisheries managers to help assess how climate can be considered in management decisions and determine barriers and resources needed to support climate-resilient fisheries. All three components fit into a broader framework developed by Canadian researchers that will be discussed in section 4.3.

Environmental Defense Fund (EDF) is in the process of developing their own stepwise CVA process and is applying it to fisheries in the Bahamas and Belize. Like the previous examples in section 3.4.1, an initial CVA for fishes was developed mirroring NOAA Fisheries CVA method, however EDF's approach allowed the final vulnerability rankings to change based on input from local fishermen (Carroll et al. 2023). Once the adjusted species-specific final vulnerability rankings are generated, those rankings will be inserted as an exposure score in a second level CVA focused on the fishery. A different set of sensitivity attributes will be selected for the fishery CVA to get a sensitivity score and the exposure and sensitivity scores will be combined to generate a fishery vulnerability rank. This CVA will identify which fisheries may be most vulnerable to declines in target species based on fishing strategy, timing, and location. The final fishery vulnerability rankings will be inserted as an exposure score in a third level CVA focused on the fishing community. A new set of sensitivity attributes will be identified for the fishing community CVA so that a sensitivity score can be calculated. Similar to the other levels, the exposure and sensitivity scores will be combined resulting in a fishing community vulnerability rank. The last CVA step will identify which fishing communities are most vulnerable to fisheries decline based on how reliant the community is to fishing and how adaptive the community could be to changes.

3.5 Climate change scenario planning

Scenario planning is a tool to help decision-makers prepare for plausible futures. This tool does not predict the future but rather facilitates presentation of a range of possible futures to prepare for (Schwartz 1996, Peterson et al. 2003). In a climate-resilient fisheries context it can be used to help fisheries managers prepare for the range of ways climate change could impact fisheries, both positive and negative. Scenario planning uses a participatory approach that brings diverse stakeholders together to help shape the plausible futures. This process usually includes the following steps: i) identify key drivers, ii) determine important uncertainties, iii) develop plausible scenarios within the context of those uncertainties, iv) identify actions and recommendations that consider those scenarios, and v) develop key trigger points and monitor for change. Scenario planning has been applied in a variety of fields, but below we focus on a few examples in marine fisheries.

3.5.1 US East Coast case study

Along the US East Coast multiple fisheries management organizations are responsible for managing fish stocks in their specific regions. As climate change causes spatial shifts in species stocks, potential jurisdictional and governance issues arise. For example, how can managers better prepare for a situation where a target species moves into a new region that does not have a fishery management plan in place? What happens to fishers that own a license to fish for a species that no longer occupies their region? The scenario planning exercise was developed by multiple participants and stakeholders within the various management organizations to help these groups better prepare for climate impacts in the next 20 years (MAFMC 2023). First, forces driving oceanographic, biological, and social and economic change were established and shared to stakeholders. Subsequently, a group of 70 stakeholders—ranging from managers, fisheries scientists, fishers, industry workers, and advocates—collaborated in a workshop to develop plausible scenarios within the uncertainty axes: health of stock productivity, predictability of change in ocean conditions and species distribution, and adaptability of the industry (see Figure 3). These scenarios were refined and reduced to four plausible scenarios (MAFMC 2023). In a second workshop, representatives from participating organizations were brought together with the goal of forming governance, management, and monitoring recommendations to address common issues found across scenarios. Recommendations were grouped into high, medium, and low priority actions and two climate leadership groups were created to evaluate and oversee the implementation of any action.

3.5.2 South Africa small-scale fishery case study

A similar scenario planning exercise was developed for a small-scale fishery in South Africa with a stronger focus on the economy (Gammage and Jarre 2021). After identifying drivers of change (i.e., stressors) through qualitative and quantitative survey methods with fishers, structured decision-making tools (SDMTs) were used to provide additional knowledge on those drivers (e.g., changes in currents and optimal SST). SDMTs consist of casual mapping and Bayesian belief networks. For a detailed explanation of these methods, see Gammage and Jarre (2021). This scenario development phase was centered on two crossed main axes: “access to financial capital” and “access to marine resources” and were complemented with two other driving forces: “climate change” and “fish availability.” This resulted in four plausible scenarios (see Figure 6 in Gammage and Jarre 2021). Although a case study, this exercise created the opportunity for a diverse group of stakeholders to interact and visualize marine issues from different perspectives and scales. It also demonstrated that incorporating a bottom-up approach to small-scale fishery management with direct inputs from local and ecological knowledge is important when informing policy makers.

3.5.3 US Atlantic salmon case study

To improve Atlantic salmon populations resilience to climate change NOAA Fisheries applied scenario planning as well (Borggaard et al. 2019). Like the other scenario planning examples, climate/physical and non-climate drivers in freshwater, estuarine, and oceanic environments inhabited by salmon throughout their life cycle were identified. These drivers were described to the scenario planning participants, which included federal experts such as salmon researchers and managers, climate and watershed scientists, and fish physiologists. Climate conditions (warm/wetter vs warm/drier) and freshwater habitat accessibility were selected as the two crossed primary uncertainty axes. This led to four plausible scenarios, in which participants could use to highlight the high priority research and management actions required for recovery to help mitigate the effects of the possible future scenarios.

3.6 Management strategy evaluation

3.6.1 Integrating management strategy evaluation and climate change

Management strategy evaluation (MSE) consists of using simulations to evaluate the effectiveness and robustness of alternative management procedures given a set of objectives (Punt et al. 2016). MSEs can test management procedures under different types of data, multiple analytical approaches, and various specific processes that lead to a management action. Two main approaches have been developed to incorporate climate change and environmental impacts into MSEs: the mechanistic and empirical approaches (Punt et al. 2014). The mechanistic approach uses outputs from global climate models to estimate the relationship between the environment and specific processes in population dynamics to ultimately predict population trends. This involves identifying the mechanisms underlying specific climate impacts on population processes (growth, recruitment, etc), evaluating the proper climate scenario and model to use for the region of interest, accurately downscaling the climate model to the region of interest, incorporating the extracted environmental variables into projection models, and creating projections for which management actions can be drawn. Representing uncertainty is a critical aspect of this process, particularly due to uncertainty in how well environmental variables may predict the parameters in population dynamics and how accurate the actual forecasted climate model may be into the future. The empirical approach uses trends in applying the relationship between climate and various parameters in the operating model, which results in plausible trends rather than projections. The empirical approach is used when the climate or environmental impacts are hypothesized rather than supported by data and can be applied to test which generic management strategies are robust to changing biological parameters.

Punt et al. (2014) described a few common ways climate change can be incorporated into MSEs. These include, the dynamic B_0 (unfished biomass) approach, the moving window approach, and the STARS approach. The dynamic B_0 approach allows the estimated unfished biomass to vary over time to reflect changes over time in biological parameters for processes such as recruitment, growth, or natural mortality. The moving window approach consists of using biomass reference points based on recruitment estimates over a specific number of years (e.g., 25 years). This approach results in a range of biomass reference points that ideally reflect the variety of environmental conditions experienced through time. The sequential t-test analysis of regime shifts (STARS) approach (Punt et al. 2014) uses an algorithm to delineate regimes based on how different subsequent years are from the current regime. If enough years are similar to each other but different from the current regime a new regime is set. Biomass reference points when applying the harvest control rules would be based on the set of years from the most recent regime.

3.6.2 Case studies

Mixed results have been shown from incorporating climate impacts into MSEs. Punt et al. (2013) used an empirical approach to evaluate the performance of a management strategy for rock lobster in Australia that tested changes of natural mortality and growth over time and found no change in performance. A mechanistic study compared two management strategies for Gulf of Alaska walleye pollock where one strategy reflected uncertainty related to linking SST and precipitation with recruitment, the parameter values from those relationships, and the predictions of the variables from multiple climate models (A'mar et al. 2009). They found the results were largely driven by the climate model, and the dynamic B_0 strategy was not substantially better than the strategy that did not incorporate the effects of climate on recruitment. Tommasi et al. (2017) used seasonally forecasted SST anomalies to compare relative stock biomass of Pacific sardines. Harvest guidelines where SST anomaly predictions informed stock biomass predictions led to improvements in stock biomass and yield and decreases in the probability of the biomass and yield from falling below allowable socioeconomic and ecological levels. Another study used MSE to help inform spatial management for bycatch mitigation in the swordfish drift gillnet fishery along California (Kaplan et al. 2021, Smith et al. 2021). Swordfish catch and leatherback sea turtle and blue shark bycatch were simulated in response to static and dynamic closed areas and 10 performance metrics were generated such as total swordfish catch per fishing season and the number of turtles caught per swordfish caught. They found that the highly dynamic closed area performed better under the assumption of substantial data availability, and a dynamic species habitat. Also along the US west coast, sablefish recruitment is known to be related to large-scale climate forcing through sea level and zooplankton communities. Haltuch et al. (2019) determined through MSE that despite small fluctuations in recruitment due to future sea levels, sablefish stock does not fall below the stock size that would initiate a fishery closure. A final example used MSE to inform bilateral management of the hake fishery between the US and Canada (Kaplan et al. 2021). The sensitivity of the performance of the harvest control rule was determined under varying climate-driven movements and changes in the age-dependent selectivity of the two countries' fisheries. Simulation testing showed that the current harvest control rule was robust enough to the climate scenarios.

3.7 Climate-informed stock assessments

Stock assessments use species demographic and fisheries information to evaluate the effects of fishing on fish populations, while accounting for uncertainty. This process can result in a stock status determination, projected future catch levels, and recommended yields or fishing intensities. Scientists make recommendations on sustainable harvest levels or fishing mortalities based on the outputs of stock assessments, so that fishery managers can make informed decisions on management actions. Although previous IATTC stock assessments provided projections, current IATTC stock assessments do not provide future projections.

3.7.1 Integrating stock assessments and the environment

In recent years multiple approaches have been developed that try to incorporate the environment and ecosystem into the stock assessment process. Climate tools like CVAs and indicators can help prioritize the species for which to conduct stock assessments. Environmental variables have been used to inform historical trends in biological processes like recruitment, growth, abundance, and distribution as well as anomalies and uncertainties in assessments (Pepin et al. 2022). Incorporating oceanographic and ecological variables into stock assessments have been more common compared to incorporating climate forcing variables. In 2011 the IATTC held a workshop on Using Oceanography for Fisheries Stock Assessment and Management and produced a draft manuscript summarizing the state of the science (Maunder et al. unpublished).

The IATTC has conducted several studies investigating the use of environmental data in fisheries stock assessment and related analyses. For example, Maunder and Watters (2003) developed a statistically rigorous approach for including environmental data into stock assessment models and conduct hypothesis tests, particularly when combined by the random-effects/state-space approach advocated by Maunder and Deriso (2003). Hinton (1996) developed a mechanistic approach for accounting for environmental, behavioral, and physiological factors when standardizing CPUE data by taking into account the depth of longline gear and habit preference of the species. They applied the approach to blue marlin. Maunder et al. (2006) put the approach in a statistical framework and (Maunder and Hinton 2006) implemented the approach using a neural network. The stock assessment program, Stock Synthesis (Methot Jr and Wetzel 2013), allows for inclusion of environmental variables for biological (e.g. recruitment, growth, natural mortality) and fishing processes (selectivity and catchability).

Spatial Ecosystem and Population Dynamics Model (SEAPODYM) is a numerical model developed to examine the physical-biological interactions between fish populations and the pelagic ecosystem (Lehodey et al. 2008). Although it is not a stock assessment model, SEAPODYM can be used for tuna stock management with regards to climate and ecosystem variability. It has been applied in WCPO.

More complex quantitative approaches, which require more data and resources, attempt to link the environment or ecosystem directly with a stock parameter or indices. If the relationship between the environment and a stock's dynamics is tightly coupled, if data is available, if there is a way to incorporate that relationship into the stock assessment process, and if the relationship can be forecasted with relatively little uncertainty, then it may be appropriate to expand the stock assessment to include an environmental or ecosystem variable (Lynch et al. 2018).

Stock assessments are generally robust to changes in recruitment, which is the major source of changes in abundance, because they estimate annual (or quarterly in the case for tropical tunas) recruitment. Particularly, if combined with dynamic management (e.g., dynamic reference points). Therefore, climate change impacts on recruitment are unlikely to bias stock assessments. However, few stock assessments, particularly those for tropical tunas, have reliable time varying estimates of growth, natural mortality, or the length-weight relationship. Therefore, stock assessments may not be robust to climate driven changes in these processes. Stock assessments can be robust to changes in availability, catchability, and/or selectivity, but it is likely to be application specific. In addition, climate driven changes in the stock-recruitment relationship may not be detectable and management may not be robust to these changes.

The contemporary approaches to develop indices of abundance and associated composition data used in stock assessments could be robust to climate change because they are based on spatial-temporal models.

However, as the spatial distribution of the stock changes, the data needs to cover the whole distribution of the stock (e.g., the survey area needs to change). For indices based on CPUE data, this means that the fishery must move to where the fish are. This highlights the need for monitoring programs that are robust to climate change.

Care needs to be taken when including climate variables in stock assessment models or in the standardization of CPUE data. Annual values can be completely confounded with stock abundance. Therefore, it is more robust to use spatial-temporally stratified covariates in CPUE standardization. However, it is important to correctly specify if the environmental covariate is related to abundance or catchability.

Since climate change is most likely to influence the spatial distribution of highly mobile and highly fecund pelagic spawning species like tunas, any monitoring and assessment methods need to take into consideration possible spatial shifts in the stock's distribution. Given that the spatial range for tunas makes surveys impractical, and the fishery, which can be used to generate CPUE based indices of relative abundance, may not necessarily follow the spatial shifts, alternative approaches need to be considered to monitor and assess tuna stocks in the face of climate change. This is particularly relevant since the longline fisheries, that have been traditionally used to create indices of abundance, have been contracting their spatial range.

Tagging has been promoted and implemented as a candidate approach to develop information on abundance of tunas but has been relatively unsuccessful, particularly for tropical tunas, due to several factors including the limited opportunities to tag fish and nonmixing of tags with the whole population. Close Kin Mark-recapture can overcome many of the problems with traditional tagging but has had limited application and is limited to estimating abundance of the adult population, while many tuna fisheries (e.g., purse seine) capture juveniles. Therefore, information on juvenile abundance may be essential to monitor and assess tuna stocks.

A recent approach that uses spatial-temporal modelling methods to account for the nonmixing of tags has shown promise to estimate absolute abundance of tuna stocks. Estimation of absolute abundance is orders of magnitude more informative than approaches based on indices of relative abundance that require the influence of catch on the index to scale absolute abundance or several assumptions to derive absolute abundance from composition data. The spatial-temporal tagging model explicitly models the movement of tags based on environmental data. Therefore, it also has the potential to deal with changes in the spatial distribution of the environment, and consequently the stock, caused by climate change. In addition, because it also uses information from archival tags to inform movement, it can account for movement of fish outside the range of the fishery where conventional tags are not recaptured. Therefore, it has the potential to provide a monitoring and assessment approach that is robust to climate change.

This approach has been used to estimate absolute abundance for skipjack tuna in the EPO (SAC-15 INF-G). These estimates are based on limited tagging data, but already an estimate with a CV of 30% has been produced, which is a game changer given it is an estimate of absolute abundance. The approach could be used with current data to also produce estimates for EPO stocks of bigeye and yellowfin tunas. Improved tagging data through future tagging cruises would produce even more reliable estimates and provide climate change robust monitoring and assessment.

3.7.2 Case studies

Inclusion of environmental forcings on stock assessment processes has occurred in instances. Off the US East Coast, bottom temperature was incorporated in the butterfish and scup stock assessment (NEFSC 2015, Adams 2018). Specifically, hindcasted bottom temperature was used to develop a habitat suitability index or thermal habitat model. Then the proportion of available suitable habitat sampled by the scientific survey was calculated, which informed the survey catchability parameter. A similar habitat suitability model was developed for multiple life stages of grouper species in the Gulf of Mexico which overlapped with red tide events. A red tide severity index was then incorporated as a variable influencing natural mortality (SEDAR 2019). Because of its short lifespan, the neon flying squid is strongly influenced by the environment, therefore an environmentally dependent surplus production model was developed for its stock assessment. Specifically, carrying capacity was influenced by the variability in favorable spawning habitat driven by temperature, and intrinsic growth rate was affected by variability in feeding habitat attributed to different temperature ranges. The inclusion of temperature improved the model fit and led to more conservative reference points compared to the conventional model (Wang et al. 2016). Across Canadian stock assessments, 21% (38/178) incorporated environmental variables (Pepin et al. 2022). In population models, time-varying parameters like natural mortality were estimated to account for predation, or growth and catchability estimated to account for changing ocean conditions. Other stock assessments used actual environmental variables, like bottom temperature, as covariates in statistical models used to predict recruitment, spawning stock biomass, or productivity (Pepin et al. 2022). In some cases, CPUE was standardized by an environmental variable to improve indices of abundance or make catchability time-varying. The effects of environmental variables on variation in migrations or spawning habitat availability was also considered. Lee et al. (2017) used simulation analysis to investigate climate driven temporal variation in movement of bluefin tuna. Of the environmental variables, oceanographic and ecological variables were applied the most often compared to climate forcing variables. For example, long- and short-term climate forcing variables, such as the Pacific Decadal Index, were applied to anadromous species (Pepin et al. 2022).

3.8 Flexible Management Systems

Fisheries management is setup to maintain sustainability, often making it difficult for managers to adjust to changing conditions. There are several ways future management can increase flexibility in response to shifts in species, fishers behavior, or markets. One tool that managers use to achieve conservation targets is the creation of static closed areas and marine protected areas. Although closed areas can be effective, they are a blunt tool that is not responsive to shifts in ocean conditions, species distributions, fishing practices, and management regulations. In contrast, dynamic ocean management is a spatial management tool in which closed areas are dynamic and adaptive in space and time. They are often informed from SDMs and recent historical or future environmental conditions. A few voluntary spatial management tools, such as EcoCast (Hazen et al. 2018) and TurtleWatch (Howell et al. 2015), have been created, mostly aiming at protecting certain vulnerable species. Daily maps are produced from these tools and provided to fishers via different digital platforms. These maps show areas that are projected to be better (i.e., target species are located along with minimal to no bycatch species) or poorer (i.e., bycatch species may be extensive in these areas) for fishing, based on bycatch to target catch ratios. Although these tools do not require fishers to follow the recommended areas, studies have shown that if followed, the dynamic closed areas would prohibit fishing in a fraction of the area, while having the potential to protect more bycatch species, while maintaining target catch compared to a static closed area, including the tuna purse seine fishery in the EPO (Hazen et al. 2018, Pons et al. 2022). In Australia, dynamic ocean management was used to generate different zones of fishing every two weeks based on a bluefin tuna SDM and projected SST (Hobday and Hartmann 2006). Fishers were required to follow these zones based on the level of observer coverage and the amount of tuna quota they were allocated. Seasonal forecasts (3-4 months in advance) were also produced and shared with fishers so that the industry could prepare for various environmental shifts (Hobday et al. 2011). The temporal scale of this type of tool, whether it be daily, weekly, monthly, or annually is based on the management target and whether voluntary or mandatory dynamic closed areas are preferred.

Other aspects of management would also benefit from being more flexible and adaptive. For example, quotas may need to fluctuate more often within a specific management region or across management regions or seasons. Many fishermen are tied to a specific gear type based on their fishing strategy and licenses. Creating a way to make licenses transferrable or more accessible as resources shift will allow fishermen to adapt easier. Allocation of quota between jurisdictional boundaries either intra- or international will certainty need to be adaptable to reflect shifts in species distributions, hopefully leading to an increase in transboundary management agreements. A recent study examined eight transboundary fishery arrangements and found that none mentioned climate change in the original agreement and only three allocating significant resources to ecosystem fisheries management and climate science (Koubrak and VanderZwaag 2020). The US and Canada currently have a joint management agreement for Atlantic cod and yellowtail flounder, and it has been found that as climate change intensifies the management regimes will become less stable (Sumaila et al. 2020). Pinsky et al. (2018) suggest that management bodies should plan ahead and develop reliable species projections that can be shared. In addition, global tuna distributions are projected to shift due to long term warming (Erauskin-Extramiana et al. 2019). Management bodies would benefit from routinely and objectively updating allocations of catch and effort to reflect distribution changes while considering tradable fisheries access that could occur across political boundaries. These issues are expected to increase and many of the tools mentioned above can be used to help develop arrangements. These topics will be critical as the conversation in Marine Area Beyond National Jurisdiction (ABNJ) advances, particularly in the context of climate change. It is likely that RFMOs, as major regional fisheries bodies, will be involved in coordinating among countries that are undertaking climate change efforts.

When applying flexible management systems, it is important to consider the timeframe of interest. Do managers want to prepare for projected multidecadal climate change impacts? Are they concerned whether their management structure is robust enough to handle the climate variability across a decade? Or do they prefer to be flexible relative to multi-annual cycles (ENSO) or seasonal patterns? These types of decisions are made as part of a climate workplan which is described in detail in section 5.

4. CLIMATE-RESILIENT FISHERIES FRAMEWORKS

The tools described above outline approaches to better assess and mitigate the impacts of climate change on species, ecosystems, and fisheries. To ensure these tools are applied in a fisheries management context, it is critical to have a framework for these tools to feed into the fisheries management process. Often, tools are developed and are not framed properly to answer the management questions, are not properly communicated to fisheries managers, or it is unclear to managers how these tools can be directly applied into management. To avoid these potential undesired outcomes, a working framework should be developed—ideally prior to tool development—so these tools can properly be incorporated into management. A framework provides an organized workflow consisting of operational steps that are often iterative to go from a set of objectives to accomplishing those objectives. As such, some organizations and countries have begun to develop climate-resilient fisheries frameworks to promote climate-resilient fisheries. Five examples are described below.

4.1 Climate smart conservation cycle

Climate Smart Conservation was designed to provide guidance on resource management under climate change (Stein et al. 2014). It was developed by multiple US federal, state, and non-governmental organizations and can be organized into a cycle consisting of seven steps (Figure 4). Each step in the cycle feeds into the next step while also creating opportunities to go back and make improvements. The process is intended to be iterative and adaptable while managing for change rather than assuming the status quo. The process is designed to recognize the variability in the system, while being intentional and transparent about assessing climate vulnerabilities, identifying adaption plans, and implementing the plans that reduce those vulnerabilities. At the same time, it is intended to meet proactive conservation and management goals. NOAA Fisheries is currently working to integrate the tools it has developed into this framework. For example, scenario planning, CVAs, SDMs, indicators, and ocean data can be used to assess climate impacts and vulnerabilities (step 2), while scenario planning and MSEs can be used to review conservation goals and objectives (step 3), identify possible adaptation options (step 4), and evaluate and select adaptation actions (step 5). To implement priority adaptation plans (step 6) spatial management tools, harvest control rules, and other flexible management systems can be applied to transboundary stock management. Tools like indicators and SDMs can track action effectiveness and ecological response (step 7). For more information, see the guidance document published in Stein et al. (2014) and Figure 4.

4.2 Framework for Integrated Stock and Habitat Evaluation (FISHE)

FISHE (https://fishe.edf.org/) is a step-by-step framework developed by EDF to help managers assess and develop sustainable fisheries under climate change and is particularly designed for data-limited fisheries. FISHE has 11 steps (Figure 5), many of which require stakeholder engagement. The final output of FISHE is an adaptive fishery management plan. Along each step of the way, the framework includes tools and an entire workbook with fillable worksheets to help the user complete the step. For example, the first step focuses on projecting future fishery conditions, as these conditions will inform the subsequent steps, and so on. EDF has developed multiple tools to project future conditions, like CVAs and ecosystem risk assessment models. For the second step, "Goal Setting," common goals and objectives are provided and divided into "Fishery Sustainability Goals" and "Climate Resilience Goals." Throughout the next few steps, a series of tools have been developed to qualitatively assess current ecological risk (step 3), evaluate stock vulnerability (step 4), calculate fishery assessment metrics (e.g., estimates of fishing mortality; step 5), prioritize species (step 6), and develop performance indicators and reference points to determine when a management action is required (step 7). Harvest control rules are created for plausible futures, which would eventually be triggered by specific reference points (step 8). This may or may not lead to a more detailed fishery assessment determined by data availability (step 9). Results of the fishery assessment are interpreted (step 10) and harvest control measures informed by the harvest control rules are implemented and eventually adapted for change over a specific timeframe (e.g., annual; step 11). As more data are collected in subsequent years, it is important to reassess each step in the cycle. The entire process has been applied to a hypothetical case study on a nearshore tropical multispecies reef fishery (https://fishe.edf.org/case-study/fishe-tool-action).

4.3 Climate Adaptation Framework for Fisheries (CAFF)

CAFF is a framework designed to support climate resiliency in Canadian marine fisheries (Boyce et al. 2023). Specifically, CAFF assesses climate vulnerabilities across various components of fisheries, including the harvest species, the fishing industry's infrastructure, and fisheries management (Figure 6). The description of each component can be found in section 3.4. CAFF consists of 20 indices/data sources that fit into the three components mentioned above. Climate vulnerabilities are assessed, barriers to adaptation are identified, and ways to overcome these barriers are determined across the three components. Outputs from CAFF can help fisheries scientists and managers prioritize research, assist municipal planners and coastal communities identify which harbors are most at threat to climate change, and help decision makers develop actionable climate adaptation strategies. Additionally, outputs can be fed into other tools such as scenario planning or climate-informed stock assessments. DFO is planning to develop an online dashboard where users can access the climate vulnerability outputs across the three components, at either a higher Canadian fisheries level or a more detailed level of information regarding each component. CAFF is designed to be rapid, reproducible, and flexible for a wide range of fisheries.

4.4 Climate Adaptation Handbook

The Climate Adaptation Handbook was developed by researchers, managers, and the fishing industry in Australia to understand the sensitivity of fishers to physical and ecological change, how easily the fishery can adapt to change, and whether a more elaborate process of changing management plans and methods is needed to accommodate change (Fulton et al. 2020). The handbook outlines a pre-risk assessment, a three-step risk assessment, and a post-risk assessment (Figure 7). The pre-risk assessment is where the scope of the assessment is determined, including objectives, species of interest, stakeholders, and scale as well as the level of the risk assessment, which depends on available data, costs, etc.

The first step in the three-step risk assessment focuses on the physical drivers and their impacts on species and ecosystems. Various tools such as CVAs, SDMs, and scientific research can be applied to understand how sensitive a species abundance, distribution, phenology, and physiology is to climate change. From this information an ecological risk score is determined using qualitive scores (low, medium, high) and a fillable table. The second step in the three-step risk assessment focuses on fishery risk through the development of three surveys designed to elicit advice from stakeholders about autonomous adaptation (actions fishers can take within the current management structure). Advice would include the potential adaptation responses, the likelihood of implementing those responses, and their potential economic and social impacts. Similar to ecological risk, qualitative scoring criteria and a fillable table are used to determine the fishery risk score. The third step determines management risk. The handbook explains five agency management functions to accomplish objectives of fisheries legislation, which can affect the impact of climate change on species abundance, distribution, phenology, and physiology through the management of catch, effort, gear, spatial, or temporal restrictions. Examples might include adjusting the total allowable catch limit or encourage new entrants to the fishery and changing the fishing area. The number of management tools, costs, implementation time, and level of accountability are used to determine management risk using the same format as above.

The post-risk assessment is where the final risk scores are used to provide recommendations, operationalizing those recommendations, and promoting adaptive management. From the detailed risk assessment, sensitivities of the fishery to physical and ecological change should be known, the adaptability of the industry to change should be identified, and whether/how management plans and policies need to change. This information can also help inform other tools like MSEs and stock assessments. This process can be repeated with the addition of new data, or if there are changes in productivity, if an indicator threshold is reached, or if changes in fish availability occur. The fillable tables and a comprehensive hypothetical example are provided within the handbook.

4.5 Food and Agriculture Organization (FAO) Framework

The FAO have put together multiple documents that provide information on how fisheries should adapt to climate change (Barange et al. 2018, Bahri et al. 2021). Through a review of case studies, they identified a list of broad adaptation tools that fall into three main categories: institutional and management, livelihoods, and risk reduction and management for resilience (Figure 8). Under institutional and management, FAO states that, with some modifications, many of the tools fisheries managers have at their disposal—like information gathering (e.g., stock assessments), input controls (e.g., gear restrictions), and output controls (e.g., catch share programs)—can be used to maintain sustainable fisheries management, despite dealing with climate change. Some of those modifications include being more participatory, adaptive, and flexible. With management changes, it is likely necessary that we see changes in existing public policies and legal frameworks through enhanced knowledge, transparency, incentives, and adaptation. For livelihood adaptation, a common strategy is diversifying livelihoods within a sector so that fishers can switch target species due to shifting distributions or market requirements. FAO highlights the need to focus new adaptation strategies on small-scale fishers who lack the adaptive capacity. Tools that can be used for risk reduction and management for resilience are the development and use of early warning and information systems to detect temperature anomalies or market changes. It is also recommended to improve responses to climate change impacts through economic compensation and the development of disaster response strategies.

In Bahri et al. (2021), FAO developed criteria for good practices in climate adaptation measures, which include: 1) explicitly addressing climate-related risks, 2) provide sufficient evidence to infer/assess effectiveness or robustness, 3) be a win-win or lose-win option, 4) "be flexible or responsive, and 5) be socially acceptable. From the case study review Bahri et al. (2021) also provides a review of good practice adaptation measures (Figure 9). Some of these adaptation measures include: adjusting spatial scale of monitoring to reflect shifting stocks, applying flexible fishing seasons, applying tradable fishing rights/allocations to allow flexibility between multiple countries, and applying in-season management to be responsive to climate-driven changes.

5. IATTC CLIMATE CHANGE WORKPLAN PROPOSAL

Based on the review made in this document of the relevant tools and frameworks, the IATTC staff has developed a proposed workplan for consideration of the Commission. This work plan comprises a series of phases and components and its goal is to ensure that fisheries under the Antigua Convention are climate-ready and climate change resilient in the nearest future. This workplan may be expected to be reviewed and revised by the EBWG, the SAC, and the Commission itself. Its implementation will require, among others, coordination within the Commission, between the Commission and its staff, and within the Secretariat, across multiple programs, including the Ecosystem and Bycatch Program, the Stock Assessment Program, and the Policy and Compliance Division.

Prior to describing the proposed workplan, which is also complementary to the workplan on developing an EPO EcoCard (EB-02-02), key terms are defined below:

1. **Workplan**: the hierarchical structure of phases, components, and associated activities to accomplish the main goal.
2. **Phase**: a period of time in which specific actions are taken.
3. **Component**: a major requirement needed to reach the main goal.
4. **Framework**: a set of operational steps, often iterative, that guide and support decisions and actions.
5. **Activity**: the actions required to accomplish the goals of a specific component.
6. **Tool**: strategic or tactical instrument used to support management decisions and actions.
7. **Strategic tool**: a scientific instrument used to support management and address *what* scientists will do to assess, monitor, and track the performance and/or status of a specific concern (e.g., CVA, SDM, climate models and projections, ecological indicators, ecosystem models, ecological risk assessments).
8. **Tactical tool**: an operational instrument used to support management and address *how* resource managers will implement management actions for a specific concern (e.g., implementing harvest control rules, spatial management, catch limits, fishery closures, gear requirements, bycatch mitigation techniques, prioritization of research to fill data gaps).

The staff has divided the IATTC workplan proposal into five phases and three main components. Figure 10 and Table 1 break down parts of the workplan (i.e., those five phases and main components) over the next 4+ years.

The five phases are: i) planning, ii) deciding on a scope and objectives, iii) developing a framework, iv) creating tools, and v) tool application and/or management implementation.

The three components include the i) framework, ii) tools, iii) and management considerations (blue boxes in Figure 10), all of which are iterative requirements to reach the goal of climate resilient fisheries (gray box in Figure 10). The purpose of the components is also included and described in yellow boxes in Figure 10. Multiple activities will need to be completed to accomplish these components, either through meetings, workshops or by the IATTC staff (green boxes in Figure 10). The recommendations associated with the appropriate components will be presented to the EBWG, SAC, and the Commission for consideration and potential adoption (red boxes in Figure 10).

A more detailed description of the phases and components is below.

The first phase (planning), which is already underway, considers educational processes where IATTC staff will engage with Members and Cooperating non-Members (CPCs) to discuss the potential effects of climate change on fishes and associated species and ecosystems, fisheries, and their communities, the ongoing projects to assess these effects, and the tools available for assessing and mitigating climate impacts. In addition to presenting ongoing research that assesses the potential effect of climate change on key species, this phase will provide a review of the tools and frameworks that are being used by other groups and national and international organizations to promote climate-resilient fisheries, along with a specific workplan proposal for input from the EBWG, the SAC, and, ultimately, the Commission, as needed (i.e., this document). As required, the staff will also develop terms of reference (TORs) for the upcoming dedicated workshops.

The second phase consists of scoping, a crucial initial stage for all groups trying to develop climate resilient fisheries. During scoping, many questions are to be answered: What decisions are this climate change plan intended to support? Who will be implementing the plan? What are the conservation targets such as, species, habitats, fisheries, or communities? What is the geographic and temporal scope of the plan? Who are the key partners and stakeholders and how are they involved? What resources are available and how will they be covered? Working through these questions will probably require organization and holding dedicated climate change workshops, in addition to the internal discussions among the staff, as well as at the Commission level, including with relevant stakeholders. As the next steps are developed, and although some backbone is important and needed for the success of the process, scoping requires a degree of flexibility including the need to reassess to adapt to the changing climate and to meet the ever-evolving needs, priorities, and requirements of the Commission.

Once the scoping questions are addressed, a framework will need to be designed and approved (Phase 3). Results of the interactions between the IATTC staff and relevant stakeholders (e.g., dedicated workshops) will be presented at the EBWG, the SAC and the annual meeting of the Commission for its consideration. Like the frameworks described in section 4, multiple climate adaptation tools are developed and plugged into various steps within the framework. Two types of tools exist; strategic tools help scientists and managers identify what we are going to do, and tactical tools address how we are going to do it. Strategic and tactical tools are related in that both are applications used to support management advice but differ in their means of doing so. For example, a strategic tool could be a climate vulnerability assessment that suggests oceanic whitetip sharks are highly vulnerable to climate change, so in turn a further improved protection of this species is needed. Subsequently, a tactical tool could be the development of a spatial management area that would improve oceanic whitetip protection. The tool development phase (Phase 4) will likely take a longer time and may require multiple iterations of tool development and discussions at various levels, therefore the timeframe for this phase is subject to change but is roughly estimated to be four years at this stage. Multiple dedicated workshops are envisioned to be held and will be designed to identify and develop tools with stakeholder input. In addition to these workshops, the IATTC scientific staff will work to develop strategic and tactical tools that will address the required steps in the selected framework. The results from the tools will be presented to the EBWG, the SAC, and the Commission, as appropriate. Based on the framework selected, tool development may also overlap with the last phase, where tactical tools are applied and actions are implemented. To identify initial and potential future management action, a dedicated workshop is envisioned to brainstorm and discuss ideas with the members. The results of this potential workshop will also be presented at the EBWG, the SAC, and the annual meeting of the Commission for consideration and potential adoption as the first management action to promote climate resilient fisheries. IATTC staff anticipate that some of these processes will be iterative, and the efforts will necessarily go beyond 2028 to accommodate future management actions that take climate change into consideration.

6. TABLES

Phase	Activities	2024				2025				2026				2027				2028				2029			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1) Planning	Review of and share available frameworks and tools	■	■																						
	Develop white paper of review and workplan proposal	■	■																						
	SAC/Comission Meeting: Share climate change resources and proposal with members		■	■																					
	Establish Terms of Reference (TOR) for climate change workshops			■																					
2) Decide on scope and goals	Workshop to develop scope				■																				
	SAC/Comission Meeting: Share/adopt scope						■	■																	
3) Develop framework	Workshop to develop framework				■																				
	SAC/Comission Meeting: Share/adopt framework						■	■																	
4) Creating tools	Strategic tool development					■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				
	Workshop for sharing and developing strategic tools							■																	
	Tactical tool development									■	■	■	■	■	■	■	■	■	■	■	■				
	SAC/Comission Meeting: Share newly developed strategic tools										■	■													
	Workshop for sharing and developing strategic and tactical tools											■													
	SAC/Comission Meeting: Share newly developed strategic and tactical tools														■	■									
	Workshop to identify tactical tools and management action															■									
Tool Implentation & Action	SAC/Comission Meeting: Recommend tool implementation/ management action																		■	■					
	Implementation																					■			

TABLE 1. Timetable of activities for the proposed workplan. The timeframe is flexible, often iterative, and subject to change.
TABLA 1. Calendario de actividades del plan de trabajo propuesto. El calendario es flexible, a menudo iterativo y está sujeto a cambios.

7. FIGURES

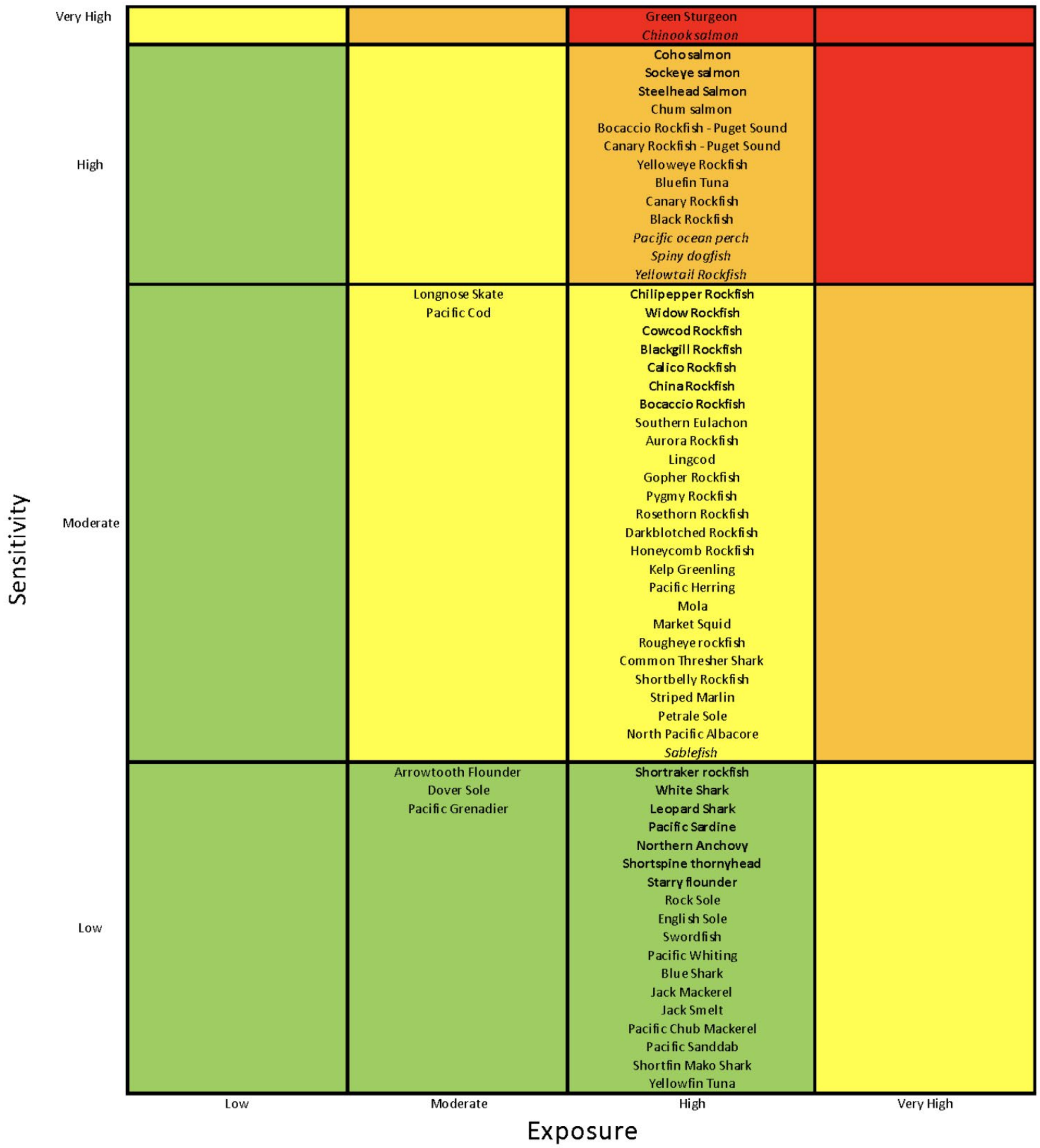

FIGURE 1. Vulnerability categorization for California Current large marine ecosystem (LME) species. Vulnerability categories are colored from green (Low) to red (Very High). Species or stocks in **bold** had a >25% chance of being placed in the next highest vulnerability category in the bootstrap analysis; those in *italics* had a >25% chance of being placed in the next lowest vulnerability category in that analysis. From McClure et al. (2023).

FIGURA 1. Categorización de la vulnerabilidad de las especies del gran ecosistema marino (GEM) de la Corriente de California. Las categorías de vulnerabilidad están coloreadas de verde (baja) a rojo (muy alta). Las especies o poblaciones en **negritas** tuvieron una probabilidad de >25% de ser colocadas en la siguiente categoría de vulnerabilidad más alta en el análisis de *bootstrap*; las que aparecen en *cursiva* tuvieron una probabilidad de >25% de ser colocadas en la siguiente categoría de vulnerabilidad más baja en dicho análisis. Tomada de McClure *et al.* (2023).

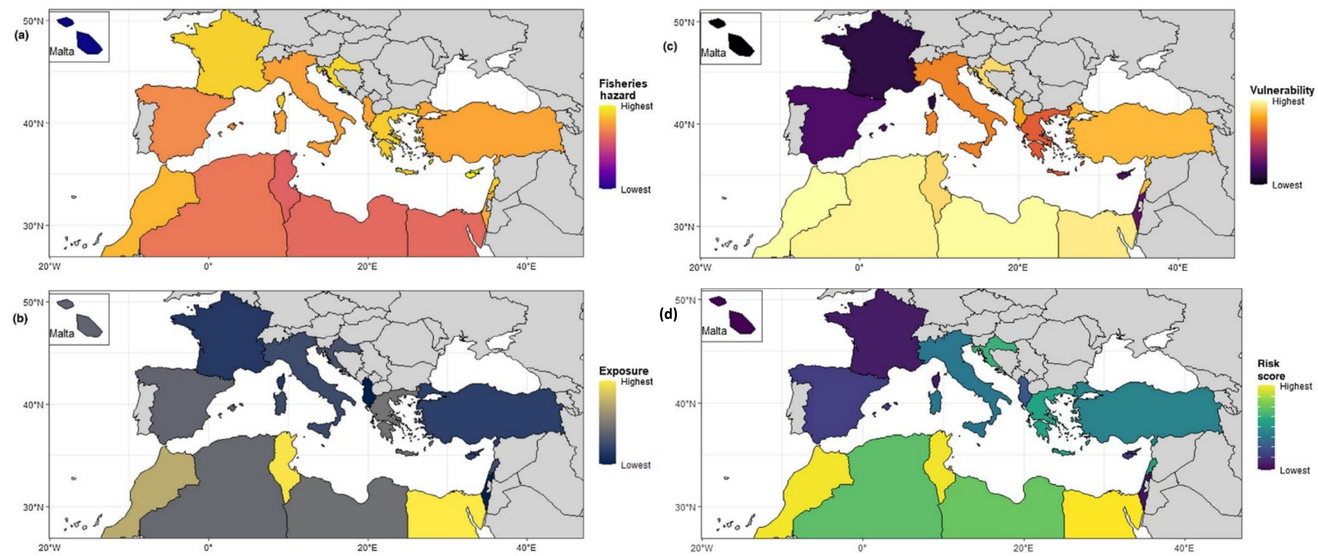

FIGURE 2. Adapted from Pita et al. (2021). Geographical distribution of the 16 studied Mediterranean countries for the three components of fisheries risk: (a) fisheries hazard, (b) exposure, and (c) vulnerability. Combining the three components resulted in the (d) fisheries risk scores amongst the 16 studied countries under the RCP8.5 climate change scenario by 2050.

FIGURA 2. Adaptada de Pita *et al.* (2021). Distribución geográfica de los 16 países mediterráneos estudiados para los tres componentes del riesgo pesquero: (a) peligro pesquero, (b) exposición y (c) vulnerabilidad. La combinación de los tres componentes dio como resultado las puntuaciones de riesgo pesquero (d) entre los 16 países estudiados en el escenario de cambio climático RCP8.5 para 2050.

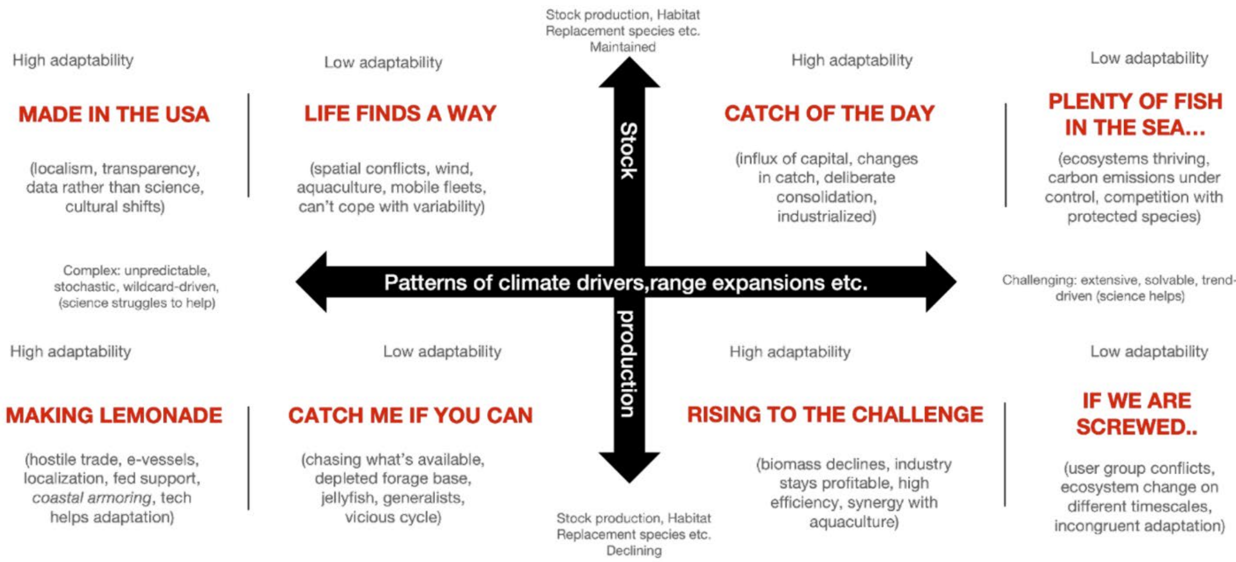

FIGURE 3. The scenarios created during the first workshop from three uncertainty axes: health of stock productivity, predictability of change in ocean conditions and species distribution, and adaptability of the industry, from MAFMC (2023).
FIGURA 3. Los escenarios creados durante el primer taller a partir de tres ejes de incertidumbre: salud de la productividad de la población, previsibilidad del cambio en las condiciones oceánicas y la distribución de las especies, y adaptabilidad de la industria, de MAFMC (2023).

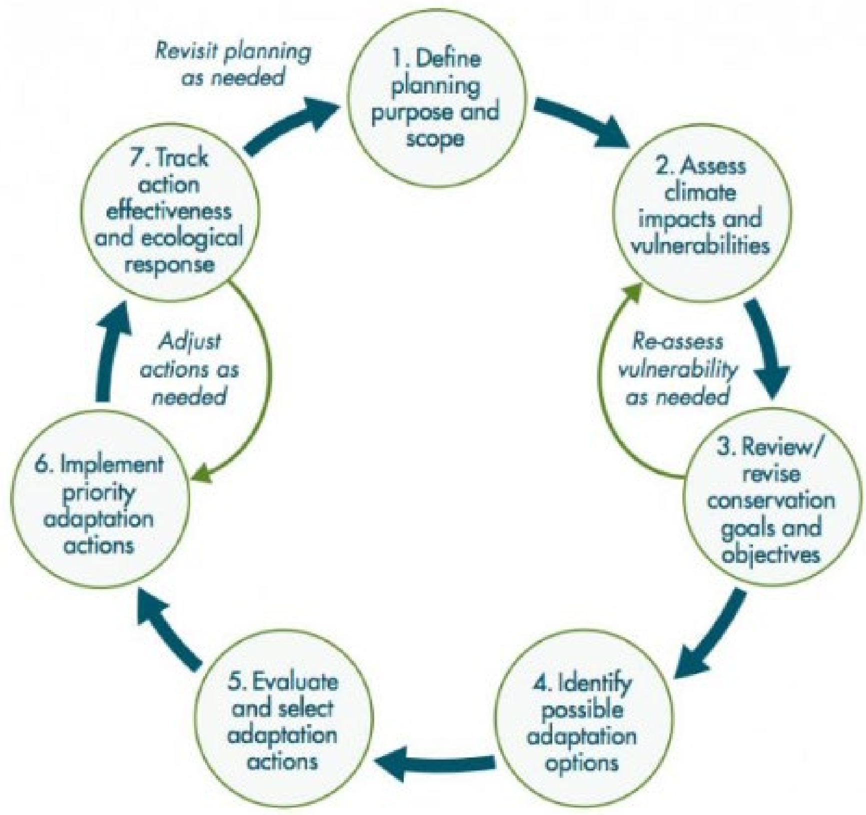

FIGURE 4. The Climate-Smart Conservation Cycle, a general framework for adaptation planning and implementation.
FIGURA 4. El ciclo de conservación climáticamente inteligente, un marco general para la planificación e implementación de la adaptación.

FIGURE 5. FISHE's (https://fishe.edf.org/) 11-step framework to promote sustainable fisheries under climate change.
FIGURA 5. Marco de 11 pasos de FISHE (https://fishe.edf.org/) para promover pesquerías sostenibles ante el cambio climático.

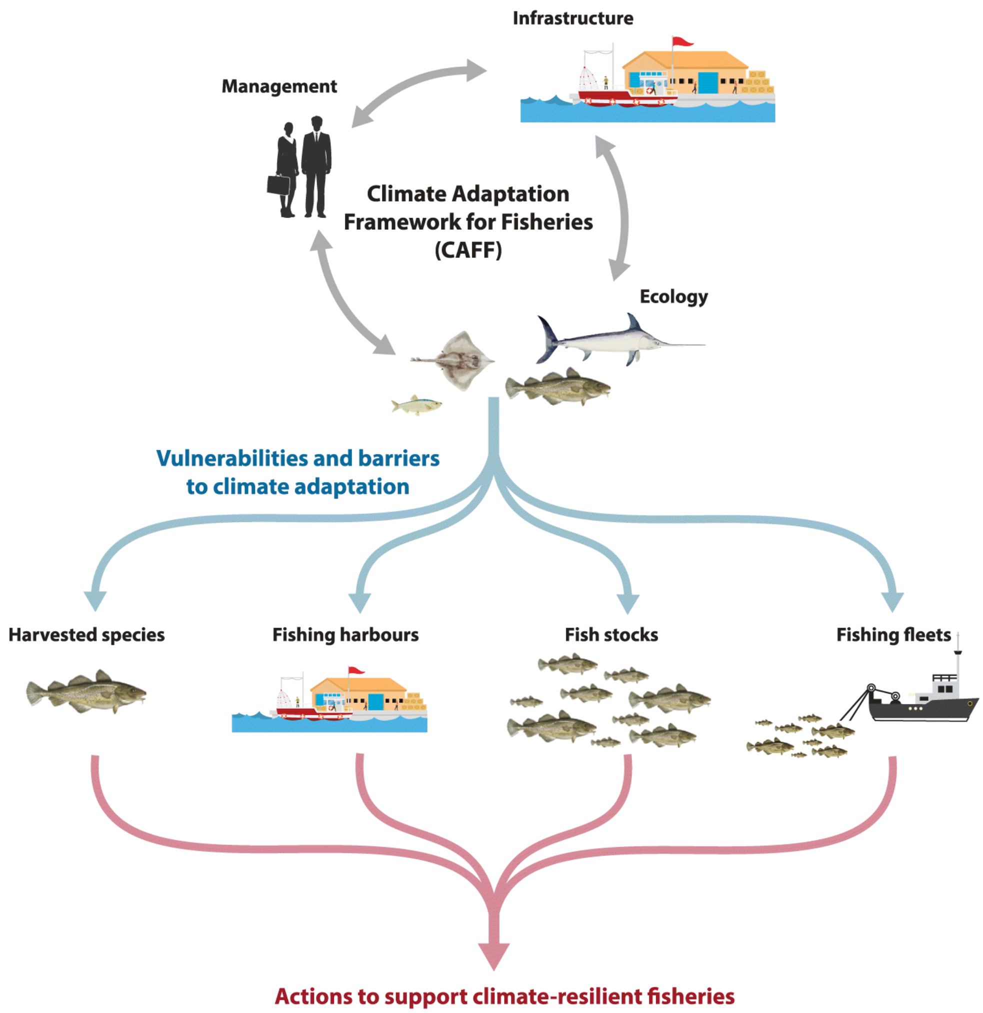

FIGURE 6. The graphic abstract describing CAFF from Boyce et al. (2023).
FIGURA 6. Resumen gráfico que describe el CAFF de Boyce *et al.* (2023).

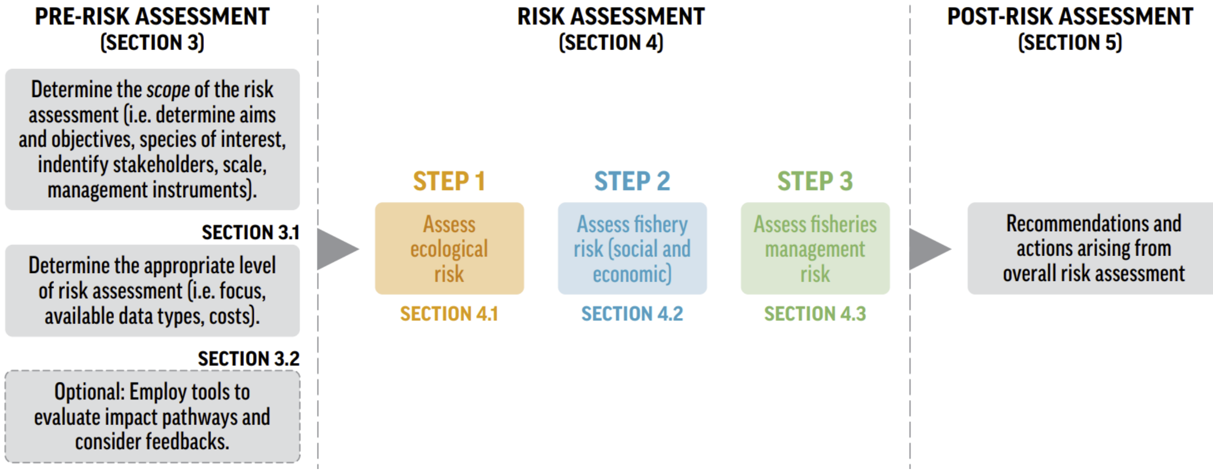

FIGURE 7. The structure of the Climate Adaptation Handbook from Fulton et al. (2020).
FIGURA 7. Estructura del Manual de adaptación al cambio climático de Fulton *et al.* (2020).

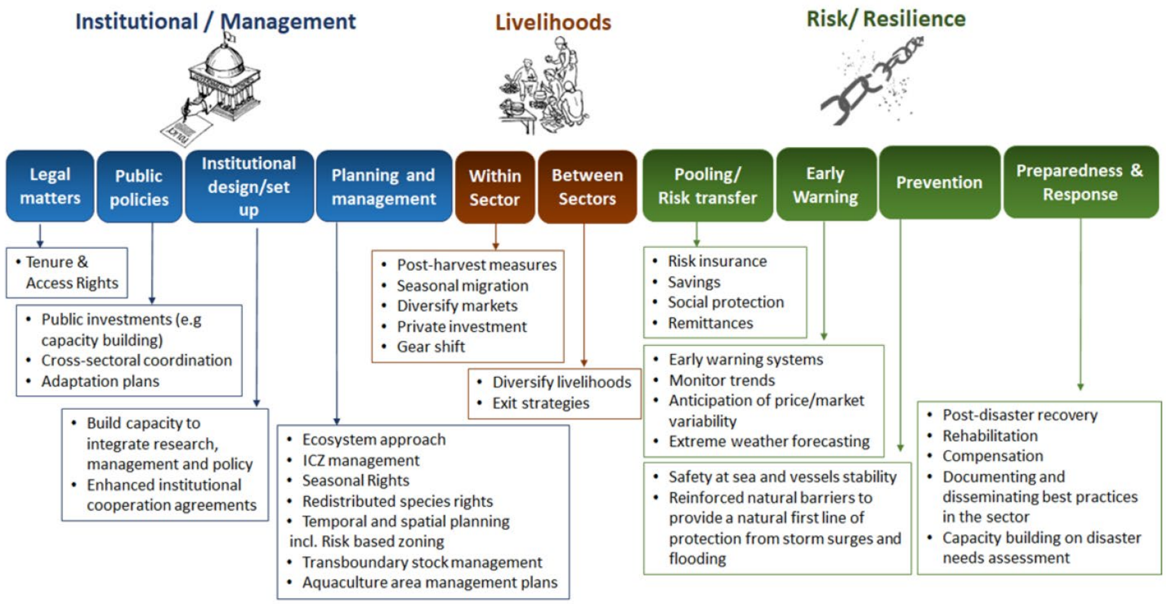

FIGURE 8. Types and selected examples of adaptation tools and approaches in capture fisheries from Barange et al. (2018).

FIGURA 8. Tipos y ejemplos de enfoques y herramientas de adaptación en pesquerías de captura, tomada de Barange *et al.* (2018).

#	Good practice adaptation measure	Reference	Climate impact(s) on fisheries resources addressed	Page no.
1	Enhance monitoring programmes through community-based approaches	Defeo *et al.* (this volume); Fogarty and Pecl (this volume)	Distributional change; productivity change; species composition change	40
2	Incorporate environmental variables and risk into fisheries assessment and management advice	Clarke *et al.* (this volume); Duplisea *et al.* (this volume); Grant *et al.* (this volume); Sharma *et al.* (this volume)	Distributional change; productivity change	42
3	Adjust spatial scale of monitoring to be responsive to shifting stocks	Hollowed and Sundby (2014); Watson and Haynie (2018); Sharma *et al.* (this volume)	Distributional change	45
4	Establish early warning systems for extreme events	Defeo *et al.* (this volume)	Distributional change; productivity change; species composition change	47
5	Apply flexible and adaptable fishing seasons	Defeo *et al.* (this volume)	Productivity change	50
6	Apply tradable fishing rights/ allocations to allow flexibility in response to stocks shifting across international borders	Clarke *et al.* (this volume)	Distributional change	52
7	Close fishery during climate-driven events to support resilience and recovery	Caputi *et al.* (2019); Defeo *et al.* (this volume)	Productivity change	55
8	Apply in-season management systems that are responsive to rapid climate-driven stock changes	Caputi *et al.* (2019); Clarke *et al* (this volume); Defeo *et al.* (this volume); Fogarty and Pecl (this volume); Grant *et al.* (this volume); Oliveros-Ramos *et al.* (this volume); Sharma *et al.* (this volume)	Productivity change; distributional change; species composition change	58
9	Relocate fishery species to compensate for changes in productivity	Fogarty and Pecl (this volume)	Productivity change	61
10	Conserve keystone species complexes to avoid ecological tipping points and related changes in target species abundance	McClanahan *et al.* (2012, 2015); Karr *et al.* (2015); Steneck, *et al.* (2019);	Productivity change; distributional change; species composition change	63
11	Relocate landing and processing practices	Fogarty and Pecl (this volume); van der Lingen (this volume)	Distributional change; productivity change; species composition change	65
12	Develop new fishery opportunities to capitalize on distributional shifts or enhanced productivity (including for 'new' species)	Fogarty and Pecl (this volume); Gücü *et al.* (this volume); van der Lingen (this volume)	Distributional change; productivity change; species composition change	67
13	Source more diverse supplies of seafood for processing facilities	van der Lingen (this volume)	Distributional change; species composition change	70
14	Develop new products and markets to maximize fishery value as catches decline	Defeo *et al.* (this volume); van der Lingen (this volume)	Distributional change; productivity change; species composition change	72
15	Develop insurance schemes that protect fishers against loss and damage after climate events or due to 'forced' practice changes or exit from the industry	Pongthanapanich *et al.* (2019)	Distributional change; productivity change; species composition change	74

FIGURE 9. Summary of good practice adaptation measures described by Bahri et al. (2021) from the case studies and selected literature and the main climate-related impacts on fisheries they address.
FIGURA 9. Resumen de buenas prácticas de medidas de adaptación descritas por Bahri *et al.* (2021) a partir de estudios de caso y bibliografía seleccionada, así como los principales impactos relacionados con el clima en las pesquerías.

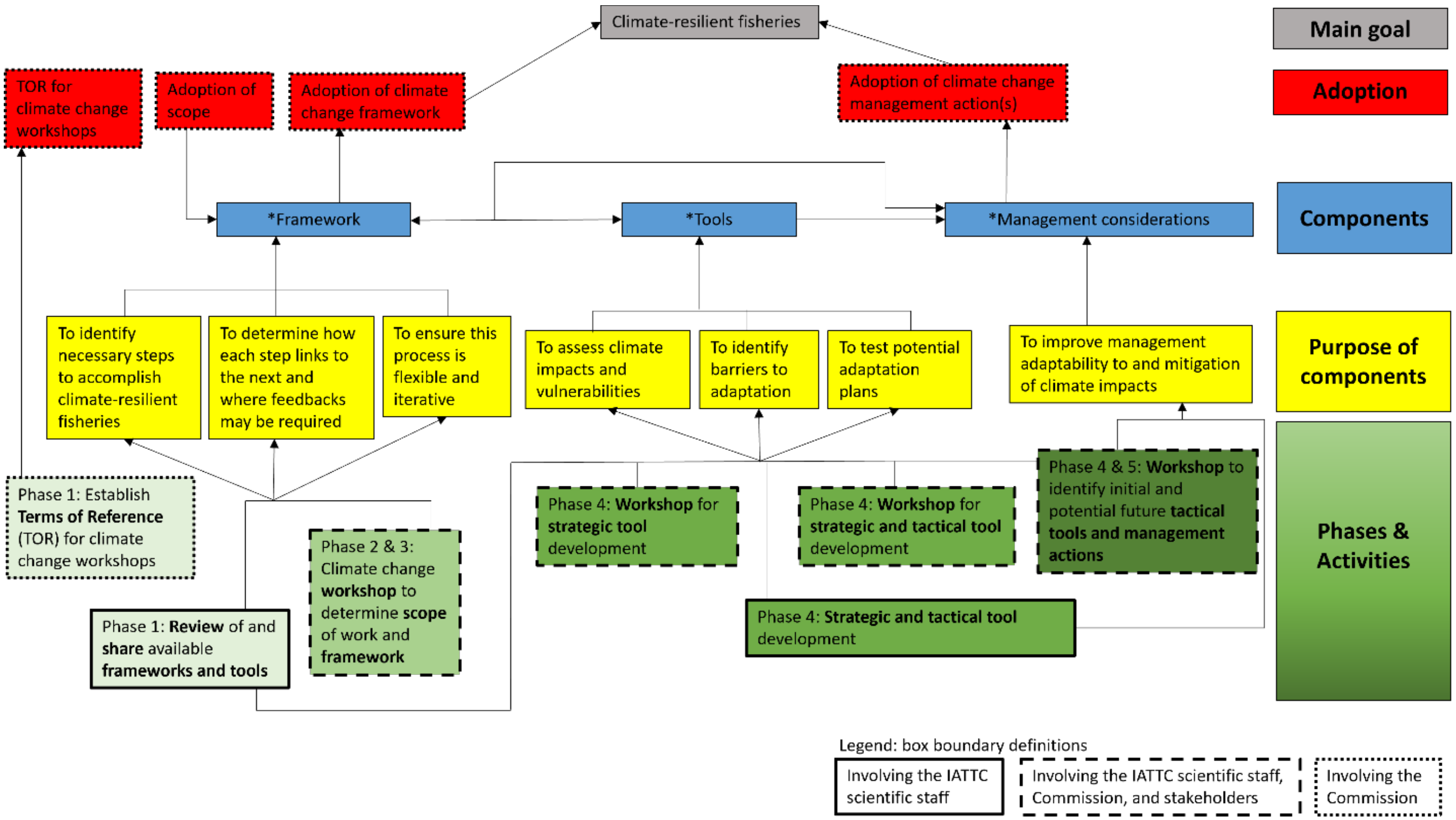

FIGURE 10. The proposed workplan for the implementation of climate-resilient fisheries for IATTC. The five phases that correspond to the chronogram are as follows: 1) Planning; 2) Deciding on scope and goals; 3) Developing a framework; 4) Creating tools; 5) Tool implementation. * indicates that each component is iterative, meaning adjustments and improvements can be made as climate changes, more data are collected, and management needs shift. Therefore, the framework may need to change, additional workshops may need to be conducted, and new tools may need to be developed.

FIGURA 10. El plan de trabajo propuesto para la implementación de pesquerías resilientes al clima para la CIAT. Las cinco fases del cronograma son las siguientes: 1) Planificación; 2) Decisión sobre el alcance y los objetivos; 3) Desarrollo de un marco; 4) Creación de herramientas; 5) Implementación de herramientas. Los * indican que cada componente es iterativo, lo que significa que pueden introducirse ajustes y mejoras a medida que cambia el clima, se recolectan más datos y cambian las necesidades de ordenación. Por lo tanto, es posible que haya que modificar el marco, organizar más talleres y desarrollar nuevas herramientas.

8. REFERENCES

A’mar, Z. T., A. E. Punt, and M. W. Dorn. 2009. The evaluation of two management strategies for the Gulf of Alaska walleye pollock fishery under climate change. ICES Journal of Marine Science **66**:1614-1632.

Adams, C. F. 2018. Butterfish 2017 stock assessment update. Page 31. US Dept Commer, Northeast Fish Sci Cent.

Bahri, T., M. Vasconcellos, D. J. Welch, J. Johnson, R. I. Perry, X. Ma, and R. Sharma. 2021. Adaptive management of fisheries in response to climate change. Fisheries and Aquaculture Technical Paper No. 667, FAO, Rome.

Barange, M., T. Bahri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith, and F. Poulain. 2018. Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. Fisheries and Aquaculture Technical Paper No. 627, FAO, Rome.

Borggaard, D., D. M. Dick, J. Star, M. Alexander, M. Bernier, M. Collins, K. B. Damon-Randall, R. Dudley, R. Griffis, S. Hayes, M. Johnson, D. Kircheis, J. Kocik, B. Letcher, N. Mantua, W. E. Morrison, K. Nislow, V. Saba, R. L. Saunders, T. Sheehan, and M. D. Staudinger. 2019. Atlantic Salmon Scenario Planning Pilot Report. Greater Atlantic Region Policy Series [19-05]. NOAA Fisheries Greater Atlantic Regional Fisheries Office. 89.

Boyce, D. G., N. Shackell, P. Greyson, and B. Greenan. 2023. A prospective framework to support climate-adaptive fisheries in Canada. 2371-1671.

Boyce, D. G., D. P. Tittensor, C. Garilao, S. Henson, K. Kaschner, K. Kesner-Reyes, A. Pigot, R. B. Reyes Jr, G. Reygondeau, and K. E. Schleit. 2022. A climate risk index for marine life. Nature Climate Change **12**:854-862.

Braun, C. D., N. Lezama-Ochoa, N. Farchadi, M. C. Arostegui, M. Alexander, A. Allyn, S. J. Bograd, S. Brodie, D. P. Crear, and T. H. Curtis. 2023. Widespread habitat loss and redistribution of marine top predators in a changing ocean. Science Advances **9**:eadi2718.

Carroll, G., J. G. Eurich, K. D. Sherman, R. Glazer, M. T. Braynen, K. A. Callwood, A. Castañeda, C. Dahlgren, K. A. Karr, and K. M. Kleisner. 2023. A participatory climate vulnerability assessment for recreational tidal flats fisheries in Belize and The Bahamas. Frontiers in Marine Science **10**:1177715.

Champion, C., S. Brodie, and M. A. Coleman. 2021. Climate-driven range shifts are rapid yet variable among recreationally important coastal-pelagic fishes. Frontiers in Marine Science **8**:156.

Champion, C., J. R. Lawson, J. Pardoe, D. O. Cruz, A. M. Fowler, F. Jaine, H. T. Schilling, and M. A. Coleman. 2023. Multi-criteria analysis for rapid vulnerability assessment of marine species to climate change. Climatic change **176**:99.

Crear, D. P., B. E. Watkins, V. S. Saba, J. E. Graves, D. R. Jensen, A. J. Hobday, and K. C. Weng. 2020. Contemporary and future distributions of cobia, Rachycentron canadum. Diversity and distributions **26**:1002-1015.

Crozier, L. G., M. M. McClure, T. Beechie, S. J. Bograd, D. A. Boughton, M. Carr, T. D. Cooney, J. B. Dunham, C. M. Greene, and M. A. Haltuch. 2019. Climate vulnerability assessment for Pacific salmon and steelhead in the California Current Large Marine Ecosystem. PLoS ONE **14**:e0217711.

Dell'Apa, A., R. Boenish, R. Fujita, and K. Kleisner. 2023. Effects of climate change and variability on large pelagic fish in the Northwest Atlantic Ocean: Implications for improving climate resilient management for pelagic longline fisheries. Frontiers in Marine Science **10**:1206911.

Erauskin-Extramiana, M., H. Arrizabalaga, A. J. Hobday, A. Cabré, L. Ibaibarriaga, I. Arregui, H. Murua, and G. Chust. 2019. Large-scale distribution of tuna species in a warming ocean. Global Change Biology **25**:2043-2060.

Farr, E. R., M. R. Johnson, M. W. Nelson, J. A. Hare, W. E. Morrison, M. D. Lettrich, B. Vogt, C. Meaney, U. A. Howson, and P. J. Auster. 2021. An assessment of marine, estuarine, and riverine habitat vulnerability to climate change in the Northeast US. PLoS ONE **16**:e0260654.

Feng, Y., M. A. M. Friedrichs, J. Wilkin, H. Tian, Q. Yang, E. E. Hofmann, J. D. Wiggert, and R. R. Hood. 2015. Chesapeake Bay nitrogen fluxes derived from a land-estuarine ocean biogeochemical modeling system: Model description, evaluation, and nitrogen budgets. Journal of Geophysical Research: Biogeosciences **120**:1666-1695.

Fulton, E., E. van Putten, L. Dutra, J. Melbourne-Thomas, E. Ogier, L. Thomas, R. Murphy, I. Butler, D. Ghebrezgabhier, A. Hobday, and N. Rayns. 2020. Adaptation of fisheries management to climate change Handbook. CSIRO, Australia.

Gammage, L. C., and A. Jarre. 2021. Scenario-Based approaches to change management in fisheries can address challenges with scale and support the implementation of an ecosystem approach to fisheries management. Frontiers in Marine Science **8**:600150.

Giddens, J., D. R. Kobayashi, G. N. Mukai, J. Asher, C. Birkeland, M. Fitchett, M. A. Hixon, M. Hutchinson, B. C. Mundy, and J. M. O'Malley. 2022. Assessing the vulnerability of marine life to climate change in the Pacific Islands region. PLoS ONE **17**:e0270930.

Haltuch, M. A., Z. T. A'mar, N. A. Bond, and J. L. Valero. 2019. Assessing the effects of climate change on US West Coast sablefish productivity and on the performance of alternative management strategies. ICES Journal of Marine Science **76**:1524-1542.

Hare, J. A., W. E. Morrison, M. W. Nelson, M. M. Stachura, E. J. Teeters, R. B. Griffis, M. A. Alexander, J. D. Scott, L. Alade, and R. J. Bell. 2016. A vulnerability assessment of fish and invertebrates to climate change on the Northeast US Continental Shelf. PLoS ONE **11**:e0146756.

Hazen, E. L., S. Jorgensen, R. R. Rykaczewski, S. J. Bograd, D. G. Foley, I. D. Jonsen, S. A. Shaffer, J. P. Dunne, D. P. Costa, and L. B. Crowder. 2013. Predicted habitat shifts of Pacific top predators in a changing climate. Nature Climate Change **3**:234.

Hazen, E. L., K. L. Scales, S. M. Maxwell, D. K. Briscoe, H. Welch, S. J. Bograd, H. Bailey, S. R. Benson, T. Eguchi, and H. Dewar. 2018. A dynamic ocean management tool to reduce bycatch and support sustainable fisheries. Science Advances **4**:eaar3001.

Hinton, M. G. 1996. Standardizing catch and effort statistics using physiological, ecological, or behavioral constraints, and environmental data, with applications to blue marlin (Makaira nigricans) and swordfish (Xiphias gladius) of the Pacific Ocean. University of California, San Diego.

Hobday, A. J., and K. Hartmann. 2006. Near real-time spatial management based on habitat predictions for a longline bycatch species. Fisheries Management and Ecology **13**:365-380.

Hobday, A. J., J. R. Hartog, C. M. Spillman, O. Alves, and R. Hilborn. 2011. Seasonal forecasting of tuna habitat for dynamic spatial management. Canadian Journal of Fisheries and Aquatic Sciences **68**:898-911.

Howell, E. A., A. Hoover, S. R. Benson, H. Bailey, J. J. Polovina, J. A. Seminoff, and P. H. Dutton. 2015. Enhancing the TurtleWatch product for leatherback sea turtles, a dynamic habitat model for ecosystem-based management. Fisheries Oceanography **24**:57-68.

IPCC. 2023. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland.

Johnson, J. E., and D. J. Welch. 2009. Marine fisheries management in a changing climate: a review of vulnerability and future options. Reviews in Fisheries Science **18**:106-124.

Kaplan, I. C., S. K. Gaichas, C. C. Stawitz, P. D. Lynch, K. N. Marshall, J. J. Deroba, M. Masi, J. K. Brodziak, K. Y. Aydin, and K. Holsman. 2021. Management strategy evaluation: allowing the light on the hill to illuminate more than one species. Frontiers in Marine Science **8**:624355.

Kjesbu, O. S., S. Sundby, A. B. Sandø, M. Alix, S. S. Hjøllo, M. Tiedemann, M. Skern-Mauritzen, C. Junge, M. Fossheim, and C. Thorsen Broms. 2022. Highly mixed impacts of near-future climate change on stock productivity proxies in the North East Atlantic. Fish and Fisheries **23**:601-615.

Koubrak, O., and D. VanderZwaag. 2020. Are transboundary fisheries management arrangements in the Northwest Atlantic and North Pacific seaworthy in a changing ocean? Ecology and Society **25**.

Lee, H.-H., K. R. Piner, M. N. Maunder, I. G. Taylor, and R. D. Methot Jr. 2017. Evaluation of alternative modelling approaches to account for spatial effects due to age-based movement. Canadian Journal of Fisheries and Aquatic Sciences **74**:1832-1844.

Lehodey, P., I. Senina, and R. Murtugudde. 2008. A spatial ecosystem and populations dynamics model (SEAPODYM)–Modeling of tuna and tuna-like populations. Progress in Oceanography **78**:304-318.

Lellouche, J.-M., E. Greiner, O. Le Galloudec, G. Garric, C. Regnier, M. Drevillon, M. Benkiran, C.-E. Testut, R. Bourdalle-Badie, and F. Gasparin. 2018. Recent updates to the Copernicus Marine Service global ocean monitoring and forecasting real-time 1/12◦ high-resolution system. Ocean Science **14**:1093-1126.

Lettrich, M. D., M. J. Asaro, D. L. Borggaard, D. M. Dick, R. B. Griffis, J. A. Litz, C. D. Orphanides, D. L. Palka, M. S. Soldevilla, and B. Balmer. 2023. Vulnerability to climate change of United States marine mammal stocks in the western North Atlantic, Gulf of Mexico, and Caribbean. PLoS ONE **18**:e0290643.

Lezama-Ochoa, N., S. Brodie, H. Welch, M. G. Jacox, M. P. Buil, J. Fiechter, M. Cimino, B. Muhling, H. Dewar, and E. A. Becker. 2023. Divergent responses of highly migratory species to climate change in the California Current.

Li, Y., M. Sun, K. M. Kleisner, K. E. Mills, and Y. Chen. 2023. A global synthesis of climate vulnerability assessments on marine fisheries: methods, scales and knowledge co-production. Global Change Biology.

Lynch, P. D., R. D. Methot, and J. S. Link. 2018. Implementing a Next Generation Stock Assessment Enterprise. An Update to the NOAA Fisheries Stock Assessment Improvement Plan. NOAA Tech Memo NMFS-F/SPO-183, U.S. Dep. Commer., NOAA Tech. Memo.

MAFMC. 2023. East Coast Climate Change Scenario Planning. Mid-Atlantic Fisheries Management Council, Dover, DE.

Maunder, M. N., and R. B. Deriso. 2003. Estimation of recruitment in catch-at-age models. Canadian Journal of Fisheries and Aquatic Sciences **60**:1204-1216.

Maunder, M. N., and M. G. Hinton. 2006. Estimating relative abundance from catch and effort data, using neural networks.

Maunder, M. N., M. G. Hinton, K. A. Bigelow, and A. D. Langley. 2006. Developing indices of abundance using habitat data in a statistical framework. Bulletin of Marine Science **79**:545-559.

Maunder, M. N., and G. M. Watters. 2003. A general framework for integrating environmental time series into stock assessment models: model description, simulation testing, and example.

McClure, M. M., M. A. Haltuch, E. Willis-Norton, D. D. Huff, E. L. Hazen, L. G. Crozier, M. G. Jacox, M. W. Nelson, K. S. Andrews, and L. A. Barnett. 2023. Vulnerability to climate change of managed stocks in the California Current large marine ecosystem. Frontiers in Marine Science.

McHenry, J., H. Welch, S. E. Lester, and V. Saba. 2019. Projecting marine species range shifts from only temperature can mask climate vulnerability. Global Change Biology **25**:4208-4221.

Methot Jr, R. D., and C. R. Wetzel. 2013. Stock synthesis: a biological and statistical framework for fish stock assessment and fishery management. Fisheries Research **142**:86-99.

Morley, J. W., R. L. Selden, R. J. Latour, T. L. Frölicher, R. J. Seagraves, and M. L. Pinsky. 2018. Projecting shifts in thermal habitat for 686 species on the North American continental shelf. PLoS ONE **13**:1-28.

NEFSC. 2015. 60th Northeast Regional Stock Assessment Workshop (60th SAW) Assessment Report. US Dept Commerce, Northeast Fish Sci Cent.
Pepin, P., J. King, C. Holt, H. Gurney-Smith, N. Shackell, K. Hedges, and A. Bundy. 2022. Incorporating knowledge of changes in climatic, oceanographic and ecological conditions in Canadian stock assessments. Fish and Fisheries **23**:1332-1346.
Peterson, G. D., G. S. Cumming, and S. R. Carpenter. 2003. Scenario planning: a tool for conservation in an uncertain world. Conservation Biology **17**:358-366.
Pinsky, M. L., G. Reygondeau, R. Caddell, J. Palacios-Abrantes, J. Spijkers, and W. W. Cheung. 2018. Preparing ocean governance for species on the move. Science **360**:1189-1191.
Pita, I., D. Mouillot, F. Moullec, and Y. J. Shin. 2021. Contrasted patterns in climate change risk for Mediterranean fisheries. Global Change Biology **27**:5920-5933.
Pons, M., J. T. Watson, D. Ovando, S. Andraka, S. Brodie, A. Domingo, M. Fitchett, R. Forselledo, M. Hall, and E. L. Hazen. 2022. Trade-offs between bycatch and target catches in static versus dynamic fishery closures. Proceedings of the National Academy of Sciences **119**.
Punt, A. E., T. A'mar, N. A. Bond, D. S. Butterworth, C. L. de Moor, J. A. De Oliveira, M. A. Haltuch, A. B. Hollowed, and C. Szuwalski. 2014. Fisheries management under climate and environmental uncertainty: control rules and performance simulation. ICES Journal of Marine Science **71**:2208-2220.
Punt, A. E., D. S. Butterworth, C. L. de Moor, J. A. De Oliveira, and M. Haddon. 2016. Management strategy evaluation: best practices. Fish and Fisheries **17**:303-334.
Punt, A. E., F. Trinnie, T. I. Walker, R. McGarvey, J. Feenstra, A. Linnane, and K. Hartmann. 2013. The performance of a management procedure for rock lobsters, Jasus edwardsii, off western Victoria, Australia in the face of non-stationary dynamics. Fisheries Research **137**:116-128.
Saba, V. S., S. M. Griffies, W. G. Anderson, M. Winton, M. A. Alexander, T. L. Delworth, J. A. Hare, M. J. Harrison, A. Rosati, and G. A. Vecchi. 2016. Enhanced warming of the northwest Atlantic Ocean under climate change. Journal of Geophysical Research: Oceans **121**:118–132.
Schwartz, P. 1996. The art of the long view: planning for the future in an uncertain world. Currency.
SEDAR. 2019. SEDAR 61 - Gulf of Mexico Red Grouper Stock Assessment Report. Page 285. SEDAR, North Charleston.
Smith, J. A., D. Tommasi, H. Welch, E. L. Hazen, J. Sweeney, S. Brodie, B. Muhling, S. M. Stohs, and M. G. Jacox. 2021. Comparing dynamic and static time-area closures for bycatch mitigation: a management strategy evaluation of a swordfish fishery. Frontiers in Marine Science **8**:630607.
Spencer, P. D., A. B. Hollowed, M. F. Sigler, A. J. Hermann, and M. W. Nelson. 2019. Trait-based climate vulnerability assessments in data-rich systems: An application to eastern Bering Sea fish and invertebrate stocks. Global Change Biology **25**:3954-3971.
Stein, B. A., N. E. Glick, and A. Staudt. 2014. Climate-Smart Conservation: Putting Adaptation Principles into Practice. National Wildlife Federation, Washington, D.C.
Sumaila, U. R., J. Palacios-Abrantes, and W. W. Cheung. 2020. Climate change, shifting threat points, and the management of transboundary fish stocks. Ecology & Society **25**.
Tommasi, D., C. A. Stock, K. Pegion, G. A. Vecchi, R. D. Methot, M. A. Alexander, and D. M. Checkley Jr. 2017. Improved management of small pelagic fisheries through seasonal climate prediction. Ecological Applications **27**:378-388.
Wang, J., W. Yu, X. Chen, and Y. Chen. 2016. Stock assessment for the western winter-spring cohort of neon flying squid (Ommastrephes bartramii) using environmentally dependent surplus production models. Scientia Marina **80**:69-78.
Williams, S. E., L. P. Shoo, J. L. Isaac, A. A. Hoffmann, and G. Langham. 2008. Towards an integrated framework for assessing the vulnerability of species to climate change. PLoS Biology **6**:e325.