INTER-AMERICAN TROPICAL TUNA COMMISSION

2ND WORKSHOP ON CLIMATE CHANGE

La Jolla, California (USA)
6-8 April 2026
(*by videoconference*)

DOCUMENT CC-02-01

CLIMATE RESILIENT FISHERIES TOOLS OF THE IATTC CLIMATE CHANGE WORKPLAN

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SUMMARY

Climate change is increasingly affecting marine species, ecosystems, and fishing communities, prompting the Inter-American Tropical Tuna Commission (IATTC) to adopt a Resolution on Climate Change (C-24-10) and develop a Climate Resilient Fisheries Framework for the eastern Pacific Ocean (EPO). As part of this framework, the next critical step is to assess climate impacts and vulnerabilities across three levels: ecological/ecosystem, fisheries, and management via strategic (science-oriented) tools. This document reviews the strategic tools available to accomplish that assessment, drawing on successful examples from other regions and organizations, and presents preliminary staff recommendations as a starting point for discussion at IATTC's 2nd Climate Change Workshop. The strategic tools reviewed span a broad spectrum, from **species distribution models** that predict how target and bycatch species may shift their ranges under changing ocean conditions to **scenario planning** which engages diverse stakeholders in preparing for a

range of plausible futures, helping managers develop proactive governance and monitoring responses. **Oceanographic and climate data products** that track environmental variables across space and time and support many of the tools described in this review. **Climate vulnerability assessments (CVAs)** systematically rank species, fisheries, and fishing communities by their exposure and sensitivity to climate change, and have been applied globally from the US and Canada to the Mediterranean and Pacific Islands. **Climate-informed stock assessments** and **management strategy evaluations (MSEs)** integrate environmental variables directly into population models and harvest strategies to test how robust current management measures are to future climate conditions. Finally, **fisheries and management surveys** provide direct insight into how fishers and managers perceive climate risks and the adaptive capacity available to them. Based on this review, the staff recommends prioritizing oceanographic data, SDMs, CVAs, scenario planning, fisheries surveys, and management surveys in the near term, with climate-informed stock assessments and MSEs to follow as foundational data and models mature (note that many of these tools are already being developed by the IATTC staff). The outcomes of workshop discussions will be used to refine these recommendations for presentation to the Ecosystem and Bycatch Working Group (EBWG), Scientific Advisory Committee (SAC), and the Commission later in 2026. Another future document will cover the tactical tools in details, a topic that is scheduled to be discussed in a future workshop.

1. BACKGROUND

In 2023 the IATTC adopted Resolution C-23-10 on climate change as a result of the direct and indirect impacts climate change and the changing environment has on marine species, ecosystems, and fishing communities. As a result of this resolution and subsequent amendments (Resolution C-24-10), the staff developed a climate change workplan to promote climate-resilient tuna fisheries in the eastern Pacific Ocean (EPO) (SAC-15-12), in the understanding that the details of the workplan and its implementation would be elaborated in consultation, as appropriate, with all relevant stakeholders. The workplan, which was welcomed and supported during the 2nd Ecosystem and Bycatch Working Group (EBWG), as well as by the 15th meeting of the Scientific Advisory Committee (SAC; SAC-15 Recommendations), consists of five phases: 1) Planning, 2) Deciding on goal and scope, 3) Developing a framework, 4) Creating tools, and 5) Tool application and/or management implementation. Phase 1 was completed by mid-2024, and by February 2025, the staff organized a three day virtual workshop to discuss Phases 2 and 3. The IATTC's 1st Climate Change Workshop, where over 70 participants including, *inter alia,* representatives from CPCs, NGOs and academia*,* focused on the importance of deciding a goal, scope, and framework clearly for climate change workplans, and specifically what the goal, scope, and framework should be at IATTC. From this successful workshop, the staff produced recommendations to define IATTC's climate change workplan's goal, scope, and framework (SAC-16 INF-P). These recommendations were fully endorsed by the 3rd EBWG, as well as by the 16th meeting of the SAC in June 2025 (SAC-16 Recommendations).

With the completion of Phases 2 and 3 in 2025, in 2026 the staff plans to move on to Phase 4: creating tools. Like many other climate related fisheries frameworks (e.g., Climate Adaptation Handbook: Fulton et al. 2020; Climate Adaptation Framework for Fisheries: Boyce et al. 2023), IATTC's Climate Resilient Fisheries Framework (Figure 1) consists of multiple steps, many of which require multiple types of tools to accomplish. After completion of Step 1 of the framework, *define goal and scope*, IATTC moves on to Step 2, which is *to assess climate impacts and vulnerabilities*. As in other fisheries related climate change frameworks it is important to not only assess the impacts and vulnerabilities of climate and environmental change on the species and ecosystem level, but also on the fisheries and management levels. The three levels are represented in Step 2 in the proposed framework as a mini connected circle in which an assessment of each level is completed to fully understand climate impact, vulnerabilities, risk, and barriers. The staff plans to work with stakeholders to co-create various tools that will help the Commission better understand and prepare for climate impacts on all three levels. Given this may be a large task with numerous research projects and a combination of tools, it is likely that Phase 4 of the workplan (and Step 2 of the framework) will take significantly longer to accomplish compared to the previous three phases.

The purpose of this document is to describe the various climate related tools that exist and that could be considered to accomplish Step 2 (assess climate impacts and vulnerabilities) of the framework, based on successful climate-related fisheries tools developed by other groups or efforts. In addition, this document contains a set of preliminary recommendations on tools by the IATTC staff as a starting point and reference to foster and facilitate discussion between members and relevant stakeholders at the 2nd Climate Change Workshop. Further, this document also reviews the current tools that IATTC staff have already developed and has in hand and could contribute to Step 2 (assess climate impacts and vulnerabilities). The outcome of this informal discussion among workshop participants will be used to revise staff's preliminary recommendations and guide tool development, and the corresponding updates will be presented to the EBWG, the SAC, and later to the Commission, at the annual meetings in 2026.

2. CLIMATE-RELATED TOOLS: STRATEGIC VS TACTICAL TOOLS

Climate-related 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. Specifically, a **strategic tool** is 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/element of interest. A **tactical too**l, however, is an *operational instrument* used to support management and address *how* resource managers will implement management actions for a specific concern/element of interest. In practice, the application of these tools is often iterative and collaborative, with scientists and resource managers working in tandem to refine assessments and adjust management actions as new information becomes available. Additionally, some tools may serve dual purposes, functioning as both strategic and tactical instruments depending on the context in which they are applied. Many such tools have been developed by other countries and organizations and can be adapted for IATTC. Given that strategic tools will be needed to accomplish Step 2 (assess climate impacts and vulnerabilities) of the framework, detailed descriptions of the various successfully developed existing strategic tools are described below, along with the level (**ecological/ecosystem, fisheries, management**) each strategic tool is most appropriate for assessing climate impacts and vulnerabilities of. A similar exercise will be covered in the near future for tactical tools (management-oriented instruments) be a dedicated workshop and associated material.

3. STRATEGIC TOOLS

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 assimilate information and 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 information in the ocean. Areas where data are collected, assimilated, and modeled at a higher spatial and temporal resolution can often produce a environmental predictions at finer spatial and temporal scales. These types of data are tools that can be used to understand how climate and environmental change impacts various entities at the **ecosystem/ecological** and **fisheries levels**.

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 gradients, 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 less readily available and often require additional data processing. Lastly, where biogeochemical models are developed, variables such as dissolved oxygen and nitrate are available for specific regions, 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)). Each of these variables have been considered when discussing environmental and 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 (including fishing vessels), ultimately affecting their distributions (Hazen et al. 2013, Dell'Apa et al. 2023). Many of the variables listed above 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. Projections could be near-term such as days, weeks, or months into the future (often called near-term or seasonal forecasts), or long-term, such as multiple decades into the future to end-of-century (i.e., 2050, 2100). The temporal period of the forecasted data is often based on the goal and scope of its specific application.

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 consists of in-situ measurements and remote sensing informed, data-assimilating global 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 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). These types of coupled Earth System Models (ESM) integrate different components of Earth’s climate system, like the atmosphere, oceans, and biogeochemical cycles. **To date, IATTC staff have downloaded, processed and used many of the variables mentioned above for the EPO from 1995 to 2023 mostly at daily temporal resolution and either 1/4° or 1/12° spatial resolution.**

Oceanographic data products are often the basis for many climate-resilient fisheries tools. As such, in the various tools sections below, applications of oceanographic data will be highlighted as these data arekey to determe 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. To predict a species distribution over a given area (e.g., EPO) and time period (e.g., July 2023), the oceanographic data need to be extracted for the same area and time period from available ocean products. In the climate change context, SDMs are often used to examine how distributions may change in response to various ocean conditions, making them an ideal tool to understand climate impacts on the **ecosystem/ecological** or **species level**. Vessels SDMs have also been used to predict where fishers may set based on given various ocean conditions (e.g., marine heatwaves) (Farchadi et al. 2024, Welch et al. 2025).

There are many types of SDMs that have been used to understand the impacts of the environment and 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. 2020c).

SDM development has been a priority for the IATTC staff because of their broad application use. For example, in addition to being used to predict environmental, and and climate impacts, SDMs can assist in spatial management decisions (Crear et al. 2021), vulnerability assessments (Griffiths et al. 2024), and bycatch avoidance tools (Hazen et al. 2018). IATTC is in the process of developing an SDM library where individual species SDMs are generated and can be applied to various applications mentioned above. To date, SDMs have been initially developed by staff for tropical tunas (SAC-10 INF-D) as well as bycatch species like leatherback sea turtles to understand species' habitat suitability and how it may shift with environmental changes like during El Nino Southern Oscillation (ENSO) (Figure 2; Lopez et al. 2024). SDMs are currently being developed for silky and oceanic whitetip sharks, as well as mahi mahi and various billfish species by IATTC staff and multiple collaborators to expand IATTC's SDM library.

As SDMs build on oceanographic data, many other climate-resilient fisheries tools build on SDM outputs. The integration of SDMs in other tools are described below.

3.3 PHYSIOLOGY/LABORATORY EXPERIMENTS

A downside to SDMs based on fisheries or tagging data is that the relationships determined between the species and the environment are limited to the conditions the animal experienced. This makes it difficult to identify a species response to more extreme or novel conditions. Further, there are life stages of many species that are not captured in fisheries or are tagged, making it difficult to understand and predict certain environmental effects. Conducting physiology experiments in the laboratory is therefore a tool that could help address both gaps when identifying climate impacts on the **ecological level**.

Several physiological metrics can be used to determine the effect of the environment on marine species, such as the species' metabolic rate, activity rate/swimming speeds, feeding rate, and mortality rate. For example, through respirometry, juvenile sandbar shark metabolic measured at different temperature and oxygen conditions identified the maximum temperature threshold and minimum oxygen threshold, which were conditions the species either avoid or do not experience in the wild (Crear et al. 2019). These types of relationships have been translated into physiology-based SDMs (Slesinger et al. 2024) or hybrid SDMs that combines field and laboratory relationships (Crear et al. 2020b). Slesinger et al. (2024) calculated a metabolic index (i.e., physiology-based SDM) based on species-specific physiological parameters from laboratory studies, mapped the areas that are unsuitable for species throughout different seasons, and estimated habitat loss under increasing atmospheric CO_2. Physiological and behavioral metrics measured in the lab have also been used to determine species response to fisheries capture (Bouyoucos et al. 2017) and how responses change under different environmental conditions (Crear et al. 2020a).

Younger life stages are often more influenced by the environment compared to older life stages. Changes during early life can lead to strong recruitment variability and, ultimately, to shifts in population dynamics, distribution, and reproduction. Understanding these processes is critical to interpreting and predicting changes at a population level. Fortunately, the IATTC has already begun to prioritize these relationships as a result of the extensive work that the Early Life History Group has been developing at IATTC's Achotines Laboratory over three decades. Among the research developed at the Achotines Laboratory (SAC-16 INF-L; Buchalla et al. 2024) the group has investigated the effects of climate and environmental change (temperature, oxygen, CO2) on the organ development, otolith morphology, metabolism, feeding behavior, growth and survival of yellowfin tuna eggs and larvae, with the goal of understanding the drivers that cause variability in tuna populations and thus, supporting management decisions (Wexler et al. 2011, Bromhead et al. 2015, Frommel et al. 2016, Margulies et al. 2016, Heuer et al. 2020). Some of this work has already informed a tuna biomass model in the Pacific (SEAPODYM, Nicol et al. 2022, see section 3.8.2). This work is planned to expand to juvenile life stages and to more species (e.g., other tuna species and bycatch species, pending funding opportunities). The results of these studies will be used to develop a recruitment forecasting tool, physiology-based SDMs, and other strategic and tactical tools.

3.4 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. Several 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 (**ecosystem/ecological level**) can be output from ecosystem models (e.g., Ecopath with Ecosim), 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 (**fisheries level**) like price or commercial fishing revenue may also be considered and help determine targeting of a specific species, provided data, often confidential and challenging to obtain regularly, are available. 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 -02-02￼. Changes in many of these indicators could be associated to and their impacts, which can help monitor and promote climate-ready fisheries. 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 that the gap between countries that have resources and inputs available versus countries that do not have the resources 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 indicators are prepared in collaboration with the managers and other relevant stakeholders that coordinate the response or action to change. IATTC staff have acknowledged the potential usefulness of indicators in depicting ecosystem status. Consequently, a workplan was created to develop 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 (EB-02-02). Discussions on indicators specifics are expected to be held in a regular manner with the EBWG and the SAC, as the *Ecocard* workplan advances.

3.5 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 inherent biological 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 and efforts. 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 qualitative and/or semi-quantitative framework of exposure, sensitivity, and adaptive capacity. Examples of CVAs at the **ecosystem/ecological** and **fisheries levels** are provided below.

3.5.1 Ecosystems/ecological

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 of the process 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) (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) (Figure 3; Loughran et al. 2025), 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 coastal-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 weight those 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 known, 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 4a). The species hazard scores were used to ultimately estimate fisheries risk; however, the remainder of the steps will be discussed in section 3.5.2 CVAs specific for fisheries and socioeconomics.

The last ecological 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 spatially. The global analysis was conducted on a 1° x 1° global grid, while this approach is being adapted for Atlantic Canadian waters, on ~2,000 species, at a 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 3.5.2.

3.5.2 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 4b). 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 4c). The scores for fisheries hazard, exposure, and vulnerability were combined to get an overall fisheries risk value for each country (Figure 4d). While using multiple tools, like indicators and risk assessments, 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 3.5.1), infrastructure (fisheries) , 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 provided 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 called the Climate Adaptation Framework for Fisheries (CAFF) (Boyce et al. 2023).

Environmental Defense Fund (EDF) have developed their own stepwise CVA process and has applied it to fisheries in the Bahamas and Belize. Like the previous examples in section 3.5.1, an initial ecological 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. This process was repeated at the fishery and fishing community levels, with stage-specific sensitivity attributes and exposure scores feeding forward from each prior level..

3.6 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 and other relevant stakeholders prepare, in a participatory approach, for the range of ways climate change could impact fisheries, both positive and negative. This process usually includes the following steps: i) identify key drivers of change, 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 that not only assesses impacts and vulnerabilities at all three levels (**ecosystem/ecological, fisheries,** and **management**), but also provides potential management adaptation ideas and actions (Step 4: identify possible adaptation actions, Figure 1).

3.6.1 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 distributions, potential jurisdictional and governance issues can 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 or viceversa? 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 scenario building workshop to develop plausible scenarios within the following uncertainty axes: health of stock productivity, predictability of change in ocean conditions and species distribution, and adaptability of the industry (see Figure 5). These scenarios were refined and reduced to four main 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.

3.6.2 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 can be important when informing policy makers.

3.6.3 US Atlantic salmon case study

To improve Atlantic salmon populations resilience to climate change NOAA Fisheries applied scenario planning (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 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 used to highlight the high priority research and management actions required for recovery and mitigation of the effects of the plausible future scenarios.

3.7 ECOSYSTEM MODELS

Ecosystem models are a powerful tool designed to disentangle the complex multidimensional trophic relationships between individual species and the environment, allow researchers to better understand the functioning of marine ecosystems, their integrity, and can facilitate a better understanding of the impacts by specific perturbations such as fishing and climate change. There are now several examples of ecosystem models being used to demonstrate how industrialized tuna fisheries have contributed to alterations of the structure and dynamics of marine ecosystems (Cox et al. 2002, Polovina et al. 2009, Griffiths et al. 2019), mainly a result of tuna fisheries impacting target and non-target species (e.g., tunas, billfishes, sharks) that occupy high trophic levels (TL > 4.0) and can exert strong predatory regulation of species populations at lower trophic levels (Baum and Worm 2009, Griffiths et al. 2013).

Ecosystem models provide an opportunity to explore the impacts of climate change on the **ecosystem/ecological**, **fisheries**, and **management level**. For example, Woodworth-Jefcoats et al. (2015) developed an Ecopath with Ecosim (EwE) model and size-based food web (SBFW) model for the central North Pacific which were driven by ESM outputs that specifically took into account the impacts of vertical stratification on phytoplankton density. They found by the end of the 21st century, as a result of climate change, large fish biomass could decline by 15% and 30% for the EwE and SBFW models, respectively. In another ecosystem model simulation, it was found that incorporating productivity regimes as a result of climate change and creating regime-specific fishing mortality, produced higher yields and fewer fishery closures compared to the traditional constant *F* approach (Fu et al. 2013). In the whole-ecosystem model, Atlantis, for the Gulf of Alaska, temperature is linked to biological processes of all functional groups including temperature-dependent abundance scalars based on species-specific thermal tolerance ranges, the effect of temperature on reproductive success, and the influence of temperature on metabolic rates which influence growth and biogeochemical processes. Multiple climate scenarios of increased temperature led to projected increases in weight-at-age and higher natural mortality in forage fish and groundfish (Rovellini et al. 2025).

The IATTC currently has an ecosystem model developed for the EPO (SAC-10-15; Olson & Watters 2003), which incorporate some environmental forcings. Under the assumption that ENSO likely affects middle and upper trophic levels in the EPO, the relationship between sea surface temperature anomalies and chlorophyll concentrations was incorporated to simulate the bottom-up effects of temperature on large phytoplankton biomass. The model also attempted to incorporate the effects of temperature on egg production by predators and how those interactions might impact the vulnerability of recruiting predators to predation.

3.8 CLIMATE-INFORMED STOCK ASSESSMENTS

3.8.1 Integrating stock assessments and the environment

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.

Multiple approaches have been developed that try to incorporate the environment and ecosystem into the stock assessment process to account for the impacts of and interactions between environmental and climate change and the stocks/species (**ecosystem/ecological level**). Climate tools mentioned above like CVAs and indicators can also 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. The stock assessment software 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). If the relationship between the environment and a stock's dynamics is tightly coupled, data is available, there is a way to incorporate that relationship into the stock assessment process, and 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 variables (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 necessarily 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 (e.g., the steepness of the stock-recruitment curve is relayed to an environmental variable) 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 should ideally 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. This is particularly relevant since the longline fisheries, that have been traditionally used to create indices of abundance, have been contracting their spatial range.

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

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. However, a recent approach that uses fine scale 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 far 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 by the IATTC to estimate absolute abundance for use in the EPO skipjack tuna stock assessment (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 implies significant advances 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.

Close Kin Mark-recapture can overcome many of the problems with traditional tagging but has had limited application and provides the most information on the absolute abundance of the adult population. While an appropriately designed CKMR model will provide estimates of juvenile abundance as well, additional data on juvenile abundance may be useful to refine estimates, particularly since many tuna fishing methods (e.g., purse seine) primarily capture juveniles.

3.8.2 Multiple 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 was 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).

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 for all tropical tuna, and projections can be made Pacific-wide.

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. The approach was applied 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. Although previous IATTC stock assessments provided projections, current IATTC stock assessments do not provide future projections.

3.9 MANAGEMENT STRATEGY EVALUATION

3.9.1 Integrating management strategy evaluation and climate change

Management strategy evaluation (MSE) is a strategic tool that consists of using simulations to evaluate the effectiveness and robustness of alternative management procedures (i.e., strategic and/or tactical tools) 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. Therefore, MSE is a tool that has the potential to identify and account for the impacts of climate and environmental change at the **ecosystem/ecological, fisheries,** and **management** levels and also provide potential management adaptation actions (Step 4: identify possible adaptation actions, Figure 1). 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 accurately environmental variables may predict the parameters in population dynamics and how accurate the actual forecasted climate model may be into in 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 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 then based on the set of years from the most recent regime.

3.9.2 Multiple 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 the current management strategy to a dynamic B_0 strategy when age-1 recruitment was driven by climate for Gulf of Alaska walleye pollock. The relationships between age-1 abundance and climate indices (e.g., SST and precipitation) and their associated uncertainty were characterized within an age-structured operating model (A'mar et al. 2009). They found the results were sensitive to the specific climate model selected and that management performance deteriorated when recruitment was forced by climate. 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 (inherently incorporates environmental change) 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 (Figure 7). 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.

3.10 FISHERIES SURVEYSQUESTIONAIRES

An important tool to identify climate impacts and vulnerabilities to **fisheries** is by surveying the fishing industry. Three case studies below highlight the various types of fisheries surveys and how they provide insight on the perception the fishing industry has on climate change.

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). Part of the handbook 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. Based on stakeholder responses, a fishery risk score is calculated. The different survey implementation method can vary from an online survey-questionnaire to phone or face-to-face interviews to expert elicitation, or workshops. Figure 6 (taken from Table 4-5 in Fulton et al. 2020) outline those different methods and provides advantages and disadvantages of each method. Surveys could be used to discuss several potential adaptation responses related to shifts in target species abundance, distribution, quality, and phenology (i.e., fishing season), such as changes in effort, moving fishing location, changing target species, investing in new technology, etc. Fulton et al. (2020) describe that from the participant responses, fishery risk can be derived from three risk variables: the number of responses available to fishers to adapted to an ecological change, the likelihood those responses can be implemented by the fishers, and economic and social impact of that ecological change.

In Puerto Rico, to understand the perceptions of fishers and their ability to adapt to environmental and climate change, researchers surveyed fishers at different fishing associations and landing sites (Seara et al. 2020). Survey results indicated that just under half of respondents said they have observed changes to their marine resource they felt were related to climate change, with the most common changes being resource stock decline, habitat shifts, and species composition. They also found that the majority of respondents have changed some aspect of fishing activity in response to environmental change, such as changing fishing grounds, gear changes, fishing in deeper water, and fishing farther from shore (Seara et al. 2020).

A final example used an online survey to understand Canada's Pacific commercial fishers' perception on climate impacts as well as their responses to those impacts (Harper et al. 2023). Survey results indicated that 77% agree that climate change is occurring, 72% think climate change will harm future generations, and 56% think climate change will harm them personally. Further, 72% of fishers did not feel fisheries management can adapt and respond quickly to changing environmental conditions, 71% could not easily move into a new fishery, and 51% believe climate change should be considered in fisheries management (Harper et al. 2023). Discussions also revealed that by incorporating diverse voices in fisheries management along with improved communication, climate adaptation would advance.

3.11 MANAGEMENT SURVEYS

Similar to fisheries-based surveys targeting fishers, management-based surveys targeting fisheries managers is a common way to understand how robust and adaptive current management measures are to environmental and climate change.

The Climate Adaptation Handbook described in 3.10 also has a management risk assessment (Fulton et al. 2020). The handbook identifies numerous management responses (tactical tools) fisheries managers have to respond to various socio-ecological changes, including catch-based tools (e.g., landing restrictions, adjust trigger limits for target or bycatch), effort-based tools (e.g., limit or encourage new entrants), gear-based tools (e.g., adjust gear or vessel restrictions or limitation), and spatiotemporal tools (e.g., adjust/opening/closing fishing area, shift timing or length of fishing season). Because this workshop is primarily focused on strategic tools, extensive discussions on the many tactical tools available to managers will occur in a future workshop. Despite this, we still discuss how management risk can be assessed through many attributes, such as the number of available management instruments (more available instruments lowers the risk), time to implementation (greater time increases risk), the complexity to the management process for a given regulatory change (more complex increases risk), and the management implementation cost of on going or new management measures (higher cost increases risk) (Fulton et al. 2020). Managers taking this risk assessment would provide a risk score for each of these attributes to calculate the overall management risk.

More simplified approaches are also possible when surveying managers. Initial education on climate impacts on the ecology and socioeconomics for practitioners is an important first step. Then, a survey could be distributed to key decision makers asking them to identify and rank how vulnerable current and potential management instruments (i.e., tactical tools) and conservation and management measures are to the environment and climate change. For example, the timing of a fishery closure may be appropriate for an El Niño year but could actually be inappropriate (e.g., decrease access to target species or increase access to bycatch species) during a La Niña. These approaches provide unique opportunities to detect climate vulnerabilities at the **management level**.

4. PRELIMINARY STAFF RECOMMENDATIONS

After a thorough review of the available strategic tools, and the current progress that staff has already made on several tools, the staff has provided a preliminary list of recommended climate related tools that IATTC could focus on over the next three years or so to accomplish Step 2 of the IATTC Climate Resilient Fisheries Framework (i.e. assess climate impacts and vulnerabilities). Table 1 below lists the various strategic tools discussed in section 3 and provides pros and cons of using or developing each tool in the context of IATTC. Given the relatively short timeframe (three-year for a first iteration, the staff has developed or is considering a comprehensive set of tools, or versions of them, it hopes to produce that can help improve IATTC's climate resilience. Fortunately, some of the tools are in the process of being developed, making them easy to recommend continued work on (e.g., oceanographic data, SDMs, physiological/laboratory experiments, indicators). Further, many of these tools can be worked on simultaneously. Other tools such as ecosystem models, fisheries surveys, stock assessments, and MSE have already been developed (stock assessments), are underway (MSE) or will be updated (ecosystem model, fisheries surveys), which creates an opportunity to integrate the environment into them. Given this context, the two most ambitious tools the staff recommends be developed are a CVA and climate change scenario planning because they may require additional funding and coordination to engage with stakeholders via in person workshops. Fortunately, the climate change scenario planning exercise has already received external funding by the Blue Convergence Fund. The staff has also identified the anticipated timeline for the development and implementation of each tool, ensuring alignment with the framework and schedule of the workplan (SAC-15-12). IATTC staff look forward to reviewing this preliminary recommendation and correspnding list of tools with CPCs and stakeholders during the process of future workshops and discussoins.

Therefore, regarding strategic tools, the IATTC staff recommends that:

As a priority for the next three years, the Commission focus on developing a Climate Vulnerability Assessment (CVA) and a climate change scenario planning exercise, while concurrently advancing and integrating climate-related tools already underway — including species distribution models, collaborative physiological and laboratory studies (e.g. Achotines Laboratory), oceanographic indicators, ecosystem models, fishery surveys, and stock assessments/management strategy evaluation — to fulfil Step 2 (assess climate impacts and vulnerabilities) of the IATTC Climate Resilient Fisheries Framework.

5. TABLES

Table 1. Strategic tools described in section 3 with the assessment level that tool could measure the impacts of (ecosystem/ecological, fishery, management). The pros and cons of developing each tool from an IATTC context is provided, along with whether the staff recommends the IATTC pursue each tool and the year(s) the staff plans to work on the tool.

Tool	Assessment level	Pros	Cons	Recommended (Years)
Oceanographic data (historical and future conditions)	-Ecosystem/ ecological -Fisheries	- basis for many other climate and non-climate related tools -accessing data is free -historical data (i.e. 1993) has updated to 2023 -no funding needed	-takes up significant digital storage	YES, continue doing (2024-2028)
Species distribution models (SDMs)	-Ecosystem/ ecological	- basis for many other climate and non-climate related tools	-many target and bycatch species -requires computing power	YES, continue doing (2024-2028)

		-developed for several species already, including tuna -expertise in house -can be done through academic collaborations to expand species list, libraries -no funding needed		
Physiological/ laboratory experiments	- Ecosystem/ ecological	-have infrastructure in place (Achotines Lab) that is used for climate and non-climate related tools -access to live animals -expertise in house -can be done through academic collaborations, especially via external funding	-time consuming -will require funds -some species hard to obtain	YES, continue doing (2024-2028)
Indicators	-Ecosystem/ ecological -Fisheries	-already undergoing EcoCard workplan -ecosystem model already developed -collaborating with other tRMFOs and global experts -no funding needed	-a lot of potential indicators to choose from (surveillance vs operational) -IATTC lost senior ecosystem scientist, training needed - Ecosystem model needs update	YES, continue doing (2024-2028)
Climate vulnerability assessments (CVAs)	-Ecosystem/ ecological -Fisheries	-provide overall/qualitative vulnerability rank for specific species, habitat, or fishery that is comparable -conducted on all species or fisheries at once -CVAs are already developed by many groups that can be adapted (e.g., WCPFC is planning CVA) -direct participation of stakeholders. Best if done in person workshop	-time needed to adapt a CVA for IATTC -requires a lot of planning for in person workshop -potentially separate CVAs for ecological and fishery levels -could require additional funds	YES, ecosystem/ecological CVA to start (2027-2028)
Climate change scenario planning	-Ecosystem/ ecological -Fisheries -Management	-can assess risk at all three levels -model/adapt to already successful scenario planning exercises -participation of stakeholders at in person workshop -external funds already acquired	-time needed to adapt a CVA for IATTC -requires significant planning for in person workshops	YES, (2026-2027)
Ecosystem models	-Ecosystem/ ecological -Fisheries -Management	-can assess risk at all three levels -ecosystem model already developed -collaborating with other tRFMOs and global experts	-complex and requires a lot of data -IATTC lost senior ecosystem scientist, training needed -Ecosystem model may need updates	YES, >2026
Climate-informed stock assessments	-Ecosystem/ ecological	-already have stock assessments developed for tuna -novel approaches are being developed to incorporate environmental variables -there are many ways stock assessments can be climate-informed	-some attempts have been made to incorporate -attempts to integrate environmental variables has occurred with minimal success	TBD

		-funds have been acquired to improve stock assessments		
Management strategy evaluation (MSE)	-Ecosystem/ ecological -Fisheries -Management	-can assess risk at all three levels -bigeye MSE is almost complete -variety of ways to incorporate the environment into MSEs	-requires a lot of time and resources	YES, (>2027)
Fisheries surveys	-Fisheries	-engages with stakeholders -fairly simple to initiate -could be paired with scenario planning or use ongoing skippers seminars and forms to collect data from fishers directly - potentially done at no cost	-requires large number of responses from fishers	YES, (>2026)
Management surveys	-Management	-engages with stakeholders -one of only a few opportunities to assess management vulnerabilities -could be paired with scenario planning	-requires large number of responses from managers	YES, (2027-2028)

6. FIGURES

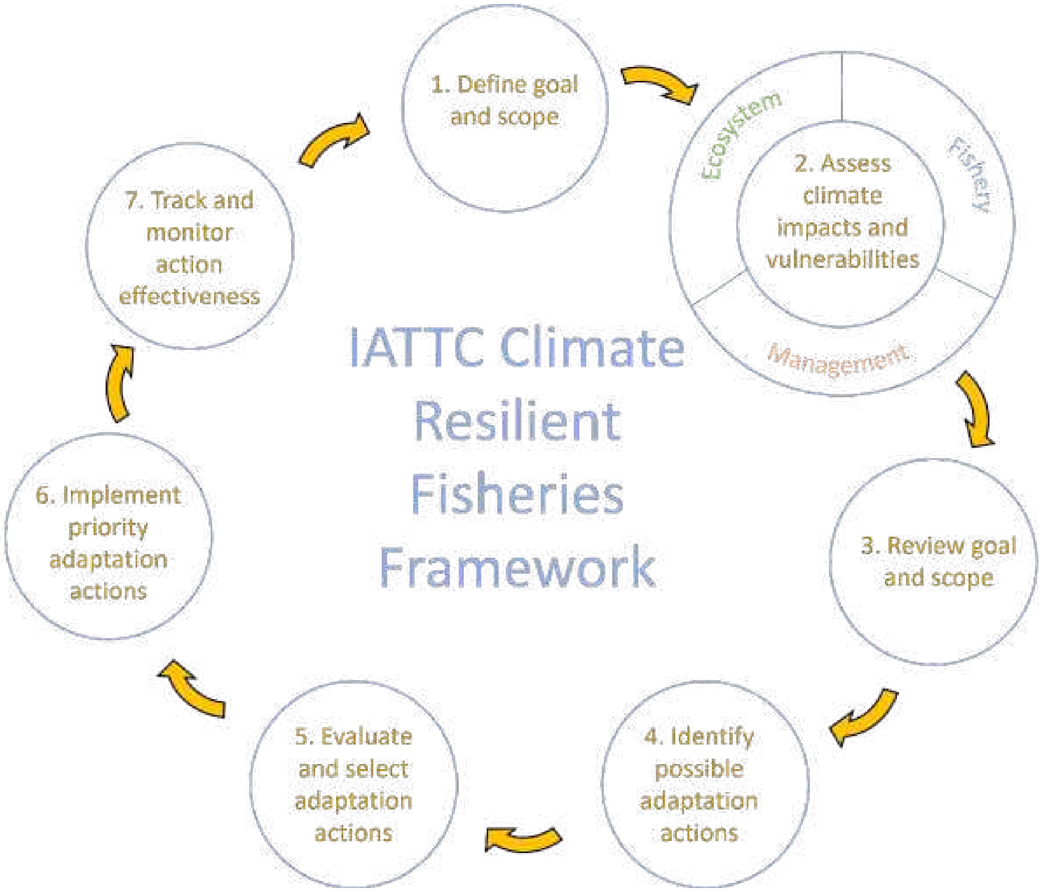


Figure 1. The IATTC Climate Resilient Fisheries Framework, the structure for adaptation and fishery management implementation under a changing climate.

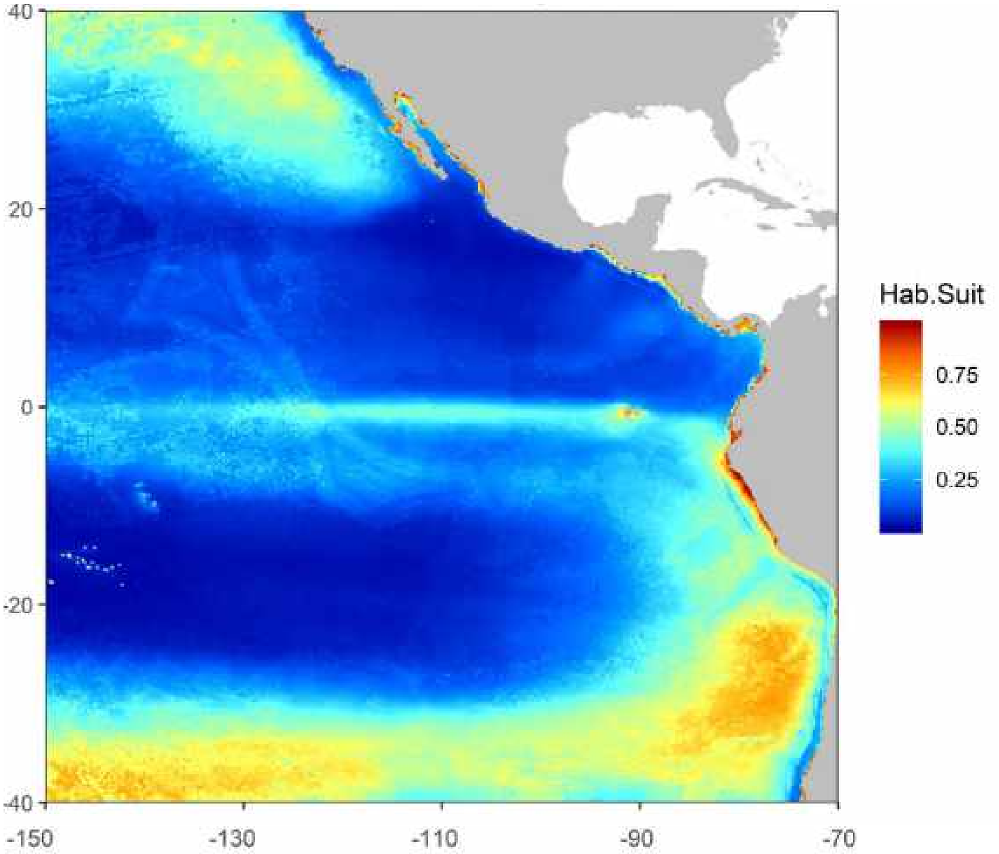


Figure 2. Average habitat suitability predictions from the leatherback species distribution models (SDMs) across the Eastern Pacific Ocean (EPO) from Lopez et al. (2024). Areas in red, orange, and yellow are most suitable, whereas areas in dark blue are least suitable.

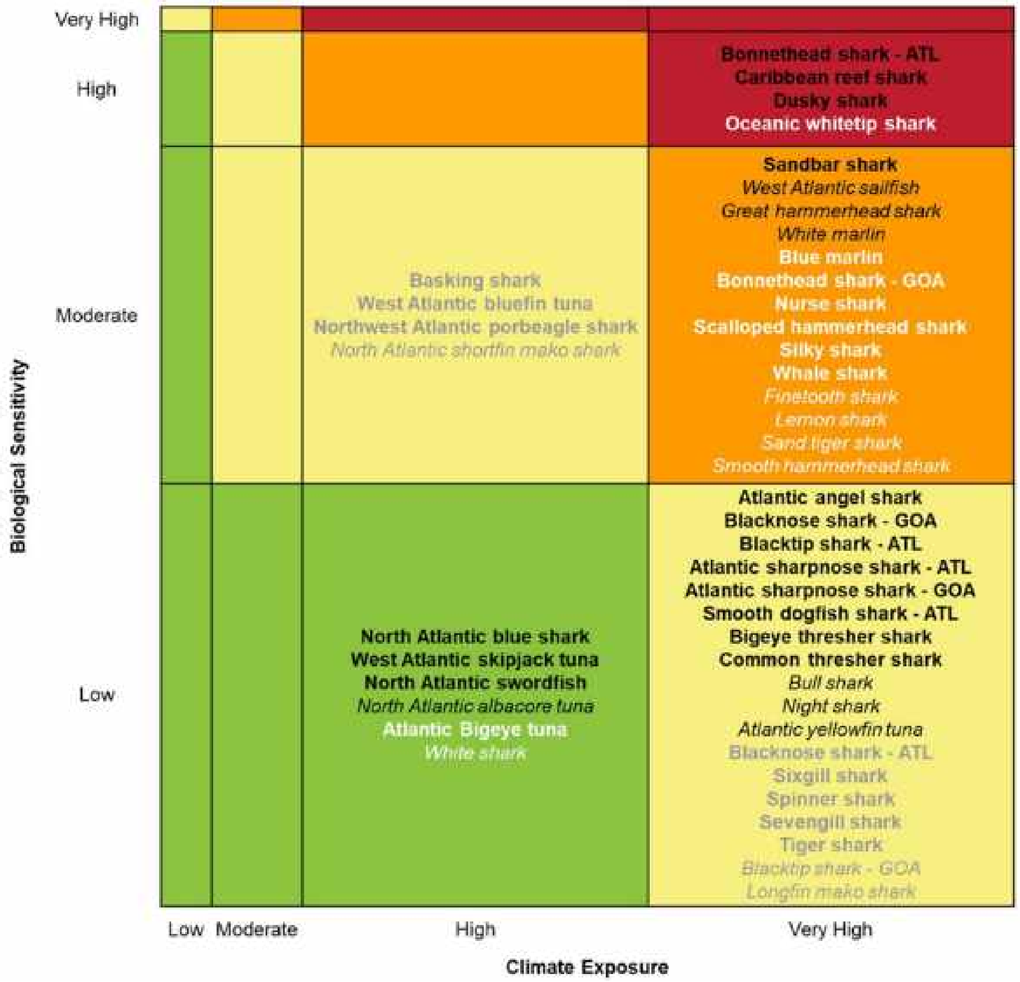


Figure 3. Vulnerability categorization for Atlantic highly migratory species. Vulnerability categories are colored from green (Low) to red (Very High). Species or stocks in **bold** had a >25% chance of being placed in the next highest vulnerability category in the bootstrap analysis; those in *italics* had a >25% chance of being placed in the next lowest vulnerability category in that analysis. From Loughran et al. (2025).

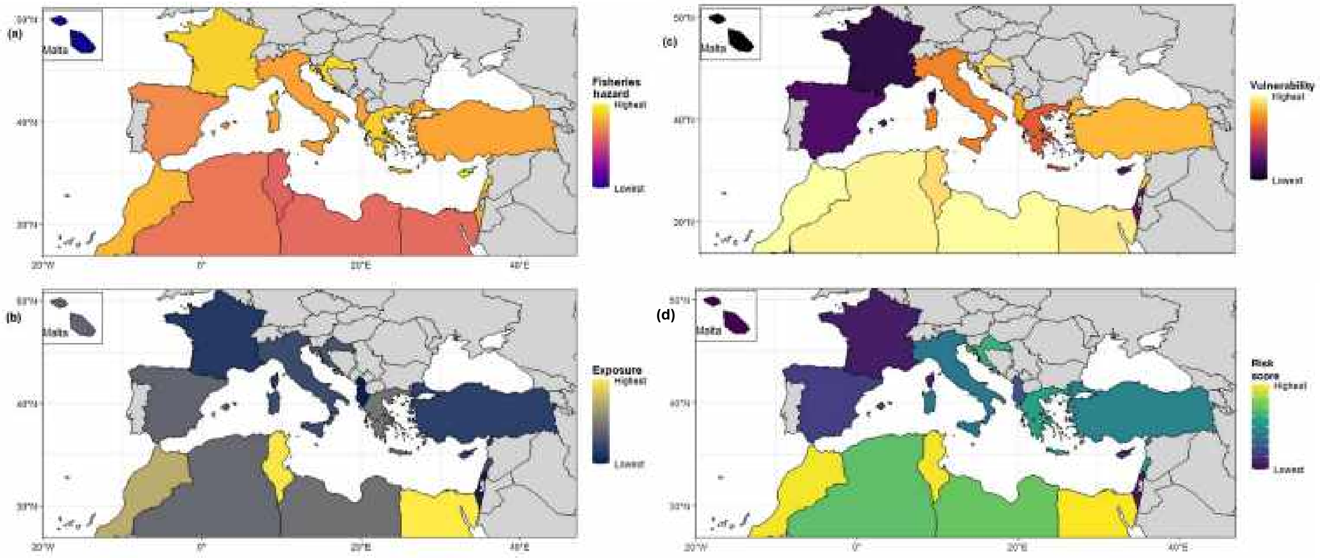


Figure 4. Adapted from Pita et al. (2021). Geographical distribution of the 16 studied Mediterranean countries for the three components of fisheries risk: (a) fisheries hazard, (b) exposure, and (c) vulnerability. Combining the three components resulted in the (d) fisheries risk scores amongst the 16 studied countries under the RCP8.5 climate change scenario by 2050.

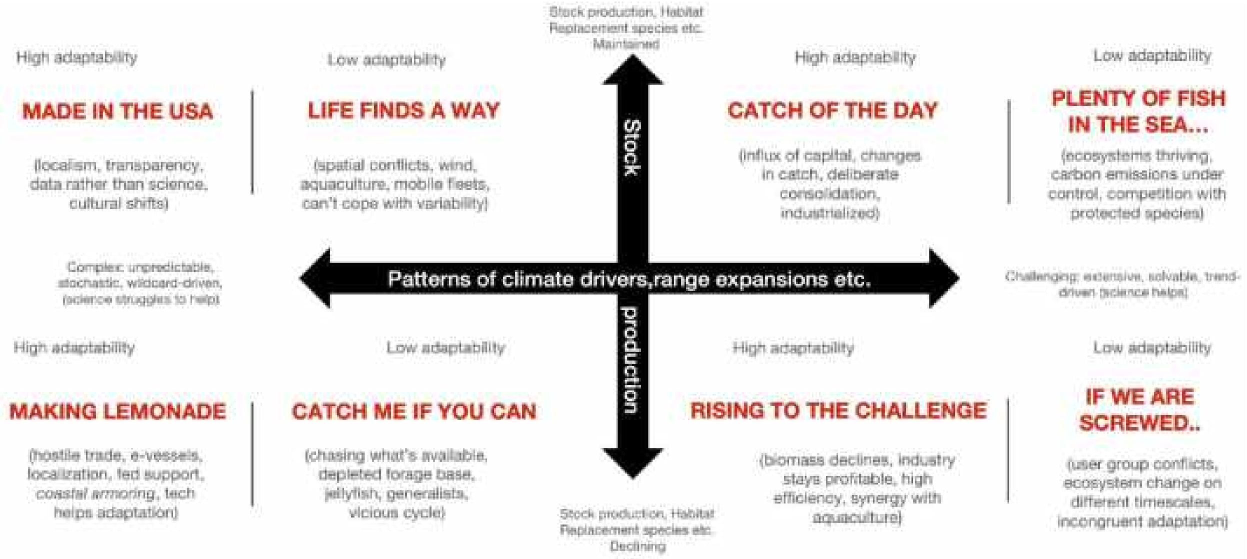
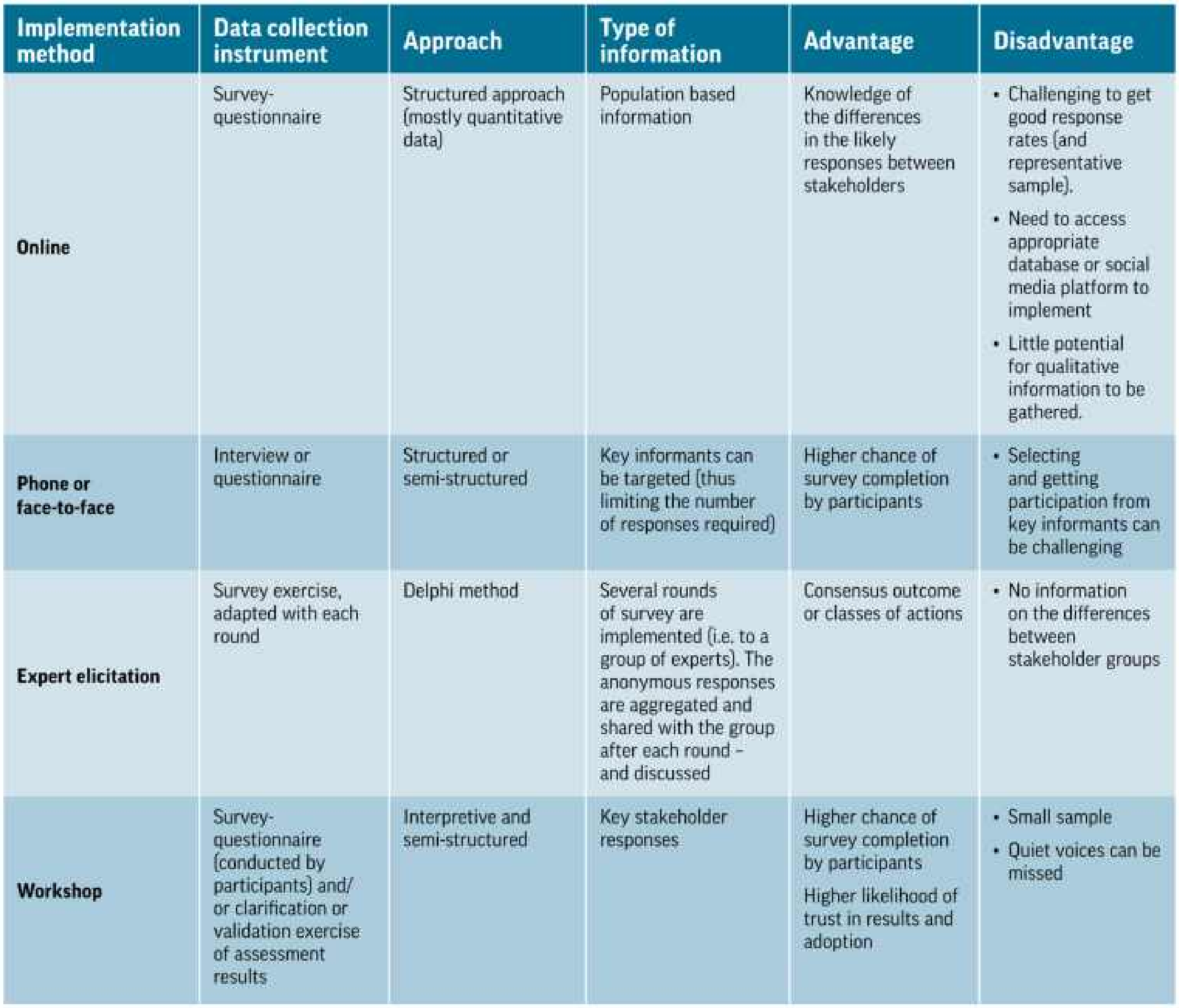


Figure 5. The scenarios created during the scenario building workshop from three uncertainty axes: health of stock productivity, predictability of change in ocean conditions and species distribution, and adaptability of the industry, from MAFMC (2023).



Implementation method	Data collection instrument	Approach	Type of information	Advantage	Disadvantage
Online	Survey-questionnaire	Structured approach (mostly quantitative data)	Population based information	Knowledge of the differences in the likely responses between stakeholders	• Challenging to get good response rates (and representative sample). • Need to access appropriate database or social media platform to implement • Little potential for qualitative information to be gathered.
Phone or face-to-face	Interview or questionnaire	Structured or semi-structured	Key informants can be targeted (thus limiting the number of responses required)	Higher chance of survey completion by participants	• Selecting and getting participation from key informants can be challenging
Expert elicitation	Survey exercise, adapted with each round	Delphi method	Several rounds of survey are implemented (i.e. to a group of experts). The anonymous responses are aggregated and shared with the group after each round – and discussed	Consensus outcome or classes of actions	• No information on the differences between stakeholder groups
Workshop	Survey-questionnaire (conducted by participants) and/or clarification or validation exercise of assessment results	Interpretive and semi-structured	Key stakeholder responses	Higher chance of survey completion by participants Higher likelihood of trust in results and adoption	• Small sample • Quiet voices can be missed

Figure 6. Taken from Table 4-5 in Fulton et al. 2020, this table shows the different implementation methods to assess fishery risk.

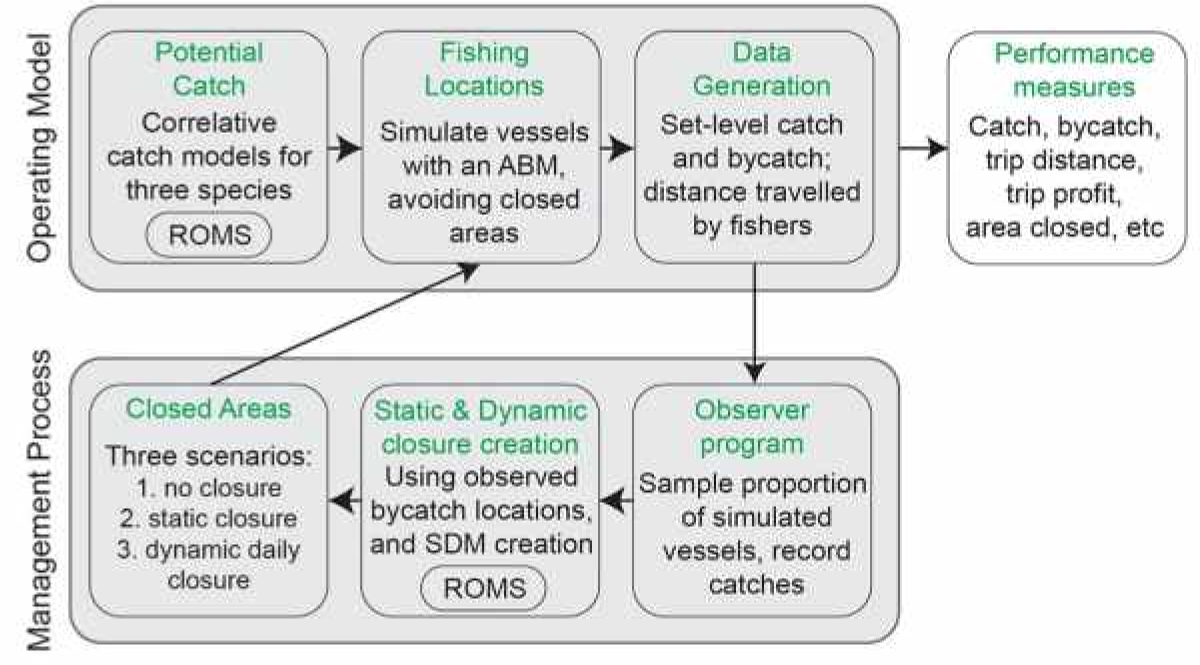


Figure 7. Taken from Figure 3 in Kaplan et al. (2021) that shows the structure of the swordfish MSE which evaluates spatial closure strategies using agent-based models (ABMs), species distribution models (SDMs), and regional ocean modeling system (ROMS).

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