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Adaptive management of fisheries in response to climate change

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Preparation of this document

The preparation of this document was initiated in response to a request from the government of Canada at the 33rd session of the FAO Committee for Fisheries (COFI) to host an expert workshop on fisheries management in the context of climate change. The Technical Paper is aimed primarily at policymakers, fisheries managers and practitioners, with a view to provide preliminary guidance on responses to climate change impacts.

A joint task team between FAO (Tarûb Bahri, Xuechan Ma, Marcelo Vasconcellos) and Department of Fisheries and Oceans (DFO Canada) (Max Kaplan) designed the draft contents of the Technical Paper and took responsibility for selecting and commissioning case studies. David Welch and Johanna Johnson (C_2O Fisheries, Vanuatu) joined the task team and provided assistance for the organization and facilitation of an expert workshop that took place in Rome, Italy on 12–14 November 2019, bringing together 26 participants and chaired by Ian Perry (DFO Canada). The objectives of the workshop were to present the selected case studies of fisheries management adaptation, discuss guidance on effective fisheries management responses to climate change based on the lessons learned from the examples presented, and design the draft content of the Technical Paper. The case studies were commissioned from experts from all over the world who submitted their first drafts prior to the workshop and updated them based on the workshop outcomes.

Chapters 2 and 3 were prepared based on the inputs provided by the participants in the workshop (see the list of participants in the Appendix). They were drafted by David Welch and Johanna Johnson, and finalized by Ian Perry with contributions from Tarûb Bahri, Xuechan Ma, Marcelo Vasconcellos and Rishi Sharma. All case studies (Chapters 4 to 16) were reviewed by the editors. Chapters 2 and 3 were reviewed by Manuel Barange, Johann Bell, Kevern Cochrane, Diana Fernandez Reguera, Ernesto Peñas Lado and Raymon Van Anrooy. Copy-editing, formatting and layout were provided by Evan Jeffries and Cath Perry (Swim2Birds Ltd., UK). The cover was designed by Pietro Bartoleschi.

Abstract

This report aims to improve understanding of how flexibility can be introduced into the fisheries management cycle in order to foster adaptation to climate change. This work contributes to the overall scope of improving the resilience of fisheries, reducing their vulnerability to climate change, and enabling managers to respond in a timely manner to the projected changes in the dynamics of marine resources and ecosystems. The findings build on the conclusions of previous FAO publications that highlighted the lack of evaluations of adaptation success. Thirteen case studies from different locations across the globe are analysed: Myanmar, the Northeast Atlantic, South Africa, Uruguay, south-eastern Australia, Belize, the Western and Central Pacific Ocean, the Philippines, the Mediterranean, Canada (east and west coasts) and Peru. They provide details on the challenges presented by climate-driven impacts to fisheries with a widely varied range of socio-ecological contexts, governance systems, data availability (data-poor to data-rich), geographical locations and scales, fishery types and species, and adaptation responses.

Understanding the general impacts of climate change on marine ecosystems and fisheries is a first step towards developing climate-adaptive fisheries management measures. Indeed, understanding the potential impacts on any specific system provides the background information necessary for selecting adaptation measures for that system. Based on the case studies presented, the most common impacts of climate change are shifts in species distributions, changes to productivity, and changes to species composition.

A ‘good practice’ chapter pulls out the lessons learned from the case studies on how to adaptively manage fisheries in the face of climate change; it highlights the importance of adaptive and participatory management along with foundational principles of fisheries management. An effective fisheries management system is the first foundation of climate-resilient fisheries. The second foundation is stakeholder participation, whether it entails one-way flows of information (passive participation) or self-mobilization of stakeholders with independent community control of management. The third foundation relates to uncertainty and risk; a set of precautionary actions that can be taken in the planning and implementation phases of the fisheries management cycle are identified to assist decision-makers in addressing uncertainty and risk arising from climate impacts. Finally, the fourth foundation of climate-resilient fisheries is adaptive management: this recognizes the impossibility of determining the perfect management strategy and calls for management strategy evaluation, with periodic monitoring of status indicators and revision of management measures.

Criteria are included to assist with selecting good practice adaptation measures, to ensure they meet minimum standards. There are three mandatory good practice criteria and two additional criteria that are considered beneficial. The mandatory criteria are: (i) the adaptation measure explicitly addresses climate-related risk(s) (with a clear objective); (ii) there is sufficient evidence to infer/assess effectiveness or robustness; and (iii) the adaptation measure must be a win-win or lose-win option. The two beneficial criteria are that the measure is: (iv) flexible or responsive; and

(v) socially acceptable. For wider use, it is acknowledged that these criteria identify adaptation measures likely to be effective generally and do not assess their suitability for all specific local contexts. Moreover, good practice measures will only be effective when implemented rigorously and appropriately to the local context.

When screened against the good practice criteria, the 13 fisheries case studies demonstrate 15 good practice adaptation measures in response to climate change. These are each linked to one or more of the three common climate-related impacts on fisheries resources (distributional change; productivity change; and species composition change) that can serve as practical entry points to guide decision-makers in identifying adaptation measures suitable for their local context. This information provides the basis for a framework that applies the good practice criteria to assist fishery practitioners in identifying suitable climate adaptation measures. The framework provides a means to track how the good practices are identified, and assess the likely effectiveness and suitability of the adaptation measures. To help ensure that good practice adaptation measures are relevant to each local context, local management capacity requirements are indicated: low (L), medium (M) or high (H).

A number of challenges remain for the effective implementation of climate adaptation measures in fisheries management; they relate to political will, governance capacity and structures, uncertainty, rights disputes, and inflexible legal frameworks. The report identifies potential solutions for these challenges. It also recommends ways in which it may in future be possible to move from ‘good practices’ to ‘(normative) guidelines’ in climate-adaptive fisheries management. These include the development of a catalogue of examples of successful adaptation, using a common template to facilitate their analysis. Another recommended area of work is the downscaling of climate projections – including social and economic scenarios – to match scales at which fisheries management occurs, with special attention on low-capacity regions, countries and areas. In addition to the need for more detailed information on localized climate impacts, identifying the (local) enabling conditions that help foster and accelerate the development and uptake of climate-adaptive measures is essential. Finally, future research could include the assessment of good practices for climate-adaptive management of inland fisheries.

Contents

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Evan Jeffries and Catherine Perry (Swim2Birds) handled the editing and layout of the entire document. Their diligence and patience are gratefully acknowledged. Many thanks to Pietro Bartoleschi (Studio Bartoleschi) for the design of the cover. Safa Gritli (FAO Fisheries Division) provided administrative support for the expert workshop and for the development of the publication. Marianne Guyonnet and Chorouk Benkabbour (FAO Fisheries Division) are gratefully acknowledged for their assistance in the publication process.

Abbreviations and acronyms

ABS	Australian Bureau of Statistics
AFMA	Australian Fisheries Management Authority
AIRF	Abalone Industry Reinvestment Fund
AMF	Adaptive Management Framework
AMO	Atlantic Multidecadal Oscillation
AUD	Australian dollar
BAS	Bureau of Agricultural Statistics
BFAR	Bureau of Fisheries and Agricultural Resources
BFD	Belize Fisheries Department
BMSY	Biomass corresponding to maximum sustainable yield
BOBLME	Bay of Bengal Large Marine Ecosystem
CalCOFI	California Cooperative Oceanic Fisheries Investigations
CBD	Convention on Biodiversity
CBDC	Community-based data collection
CCRIF	Caribbean Catastrophe Risk Insurance Facility
CCSBT	Commission for the Conservation of Southern Bluefin Tuna
CIL	Cold intermediate layer
CITES	Convention on International Trade in Endangered Species of Wild Fauna and Flora
CMIP5	Coupled Model Intercomparison Project Phase 5
CMM	Conservation and management measures
CO_2	Carbon dioxide
COFI	FAO Committee for Fisheries
COFI-33	33rd session of the FAO Committee for Fisheries
CPUE	Catch per unit effort
CU	Conservation unit
DA-BFAR	Department of Agriculture - Bureau of Fisheries and Aquatic Resources (the Philippines)
DAFF	Department of Agriculture, Forestry and Fisheries (South Africa)
DEFF	Department of Environment, Forestry and Fisheries (South Africa)
DFO	Department of Fisheries and Oceans (Canada)
DG-Fish	Directorate General of Fisheries and Aquaculture (European Community)
DINARA	Dirección Nacional de Recursos Acuáticos (Uruguay)
DoF	Department of Fisheries (Myanmar)
DPIPWE	Tasmanian Department of Primary Industries, Parks, Water and Environment
EAC	East Australian Current
EAF	Ecosystem approach to fisheries

EC	European Community
EDF	Environmental Defense Fund
EEZ	Exclusive economic zone
ENSO	El Niño Southern Oscillation
EoCA	East of Cape Agulhas
ESA	Endangered Species Act
FAC	Fishery Advisory Committee
FAO	Food and Agriculture Organization of the United Nations
FARMC	Fisheries and Aquatic Management Council
FFA	Pacific Islands Forum Fisheries Agency
FMA	Fisheries Management Area
FMSY	Fishing mortality at maximum sustainable yield
FRAG	Fishery Resource Advisory Group
FRDC	Fisheries Research and Development Corporation
FRSSI	Fraser River Sockeye Spawning Initiative
FTE	Full-time equivalent
GAM	Generalized additive modelling
GFCM	General Fisheries Commission for the Mediterranean
GHG	Greenhouse gas
GSA	Geographical sub-areas
GSL	Gulf of Saint Lawrence
GT	Gross tonnage
HAB	Harmful algal bloom
HCR	Harvest control rule
ICCAT	International Commission for the Conservation of Atlantic Tunas
ICES	International Council for the Exploration of the Sea
IFARMCs	Integrated Fisheries and Aquatic Management Councils
IMAP	Integrated monitoring and assessment programme
IMARPE	Peruvian Marine Research Institute
IMOS	Integrated Marine Observing System
IPCC	Intergovernmental Panel on Climate Change
IPCC-AR5	5th assessment report of the Intergovernmental Panel on Climate Change
ISSG	Invasive Species Specialist Group
ITQ	Individual transferable quota
IUCN	International Union for Conservation of Nature
IUU fishing	Illegal, unreported and unregulated fishing
LFC	Local Fishery Council
LGU	Local government unit
LMMA	Locally Managed Marine Area
MA	Management adjustment
MAR	Mesoamerican Reef
MCS	Monitoring, control and surveillance
MERF	Marine Environment and Resources Foundation

MoU	Memorandum of understanding
MPA	Marine protected area
MSC	Marine Stewardship Council
MSE	Management strategy evaluation
MSY	Maximum sustainable yield
MU	Management unit
NAPA	National Adaptation Programme of Action
NEA	Northeast Arctic
NEAFC	North East Atlantic Fisheries Commission
NFARMC	National Fisheries and Aquatic Resource Management Council
NFSCC	National Framework Strategy on Climate Change
NGO	Non-governmental organization
NIS	Nonindigenous species
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NORAD	Norwegian Agency for Development Cooperation
NPAFC	North Pacific Anadromous Fish Commission
NSAP	National Stock Assessment Programme
OCN	Oregon Coast northern coho
OECD	Organization for Economic Co-operation and Development
OMP	Operational management procedure
OSMOSE	Object Oriented Simulator of Marine Ecosystems
PAE	Party allowable effort
PCIC	Pacific Climate Impacts Consortium
PDO	Pacific Decadal Oscillation
PNA	Parties to the Nauru Agreement
PRODUCE	Peru Ministry of Production
PSA	Philippine Statistics Authority
PSC	Pacific Salmon Commission
PST	Pacific Salmon Treaty
PUCL	Precautionary upper catch limit
R/V	Research vessel
RAP	Regional Advisory Process
RCP	Representative Concentration Pathway
RFMO	Regional Fisheries Management Organization
SAG	Science Advisory Group
SBMSY	Spawning biomass at maximum sustainable yield
SEAFDEC	Southeast Asian Fisheries Development Center
SEAPODYM	Spatial Ecosystem and Population Dynamics Model
SEFSC	Southeast Fisheries Science Center
SMSY	Spawners at maximum sustainable yield
SOI	Southern Oscillation Index
SPC	Pacific Community
SP-SWG	Small Pelagic Scientific Working Group

SRZ	Stock Rebuilding Zone
SST	Sea surface temperature
STECF	Scientific, Technical and Economic Committee for Fisheries
TAB	Total allowable bycatch
TAC	Total allowable catch
TAE	Total allowable effort
TIDE	Toledo Institute for Development and the Environment
TL	Turkish Lira
TRP	Target reference point
TSIC	Tasmanian Seafood Industry Council
TT CMM	Conservation and management measures for tropical tuna
TTX	Tetradotoxin
TURF	Territorial Use Rights for Fisheries
UNCLOS	United Nations Convention on the Law of the Sea
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
USAID	United States Agency for International Development
USD	United States dollar
VAT	Value-added tax
VA-TURF	Vulnerability Assessment Tool for Understanding Resilience of Fisheries
VDS	Vessel Day Scheme
VMS	Vessel monitoring system
WCPFC	Western and Central Pacific Fisheries Commission
WCPO	Western and central Pacific Ocean
WG	Working group
WoCA	West of Cape Agulhas

Chapter 1: Introduction

There is considerable evidence that climate change is affecting the fisheries sector worldwide. It is expected to disrupt current practices and approaches throughout the value chain, from resource distribution and abundance, to timing and locations of fishing, landing sites, fish preservation, marketing and consumption. FAO Technical Paper No. 627 (Barange *et al.*, 2018) was a milestone which consolidated knowledge of climate change impacts on marine fisheries sectors, and described potential adaptation and mitigation solutions. The publication was welcomed by the 33rd session of the FAO Committee for Fisheries (COFI-33), which requested further exploration of how to mainstream climate change into fisheries management, and practical guidance on the matter. The present Technical Paper was developed in response to COFI-33's request and proposes good practices for developing climate-adaptive fisheries management, based on practical examples in which climate change implications have been included into current fisheries management regimes.

The importance of improving fisheries management practices to build sustainability into the fisheries sector as a response to climate change was underscored during the Fisheries Sustainability Symposium (18-21 November 2019, Rome, Italy) (FAO, 2020). Climate change is a major challenge, which requires flexible and adaptive responses. Adaptability in fisheries management is not a new concept, and has been examined by several authors, either in relation to or independently from climate change. The application of adaptive management to natural resources was pioneered in the 1970s (Holling, 1978; Walters and Hilborn, 1978) and has been discussed for several decades (Walters, 1986; Hilborn and Sibert, 1988; Failing, Horn and Higgens, 2004; Nevill, 2008; Grafton, 2010; Williams, 2011; McDonald *et al.*, 2018). In particular, Grafton (2010) explicitly described adaptation of fisheries management to climate change, including fundamental principles such as precaution, flexibility and stakeholder engagement. Subsequent literature has either narrowed the scope of fisheries management adaptation to focus on models (e.g. Melnychuk, Banobi and Hilborn, 2014) or broadened the scope to include socio-economic considerations (e.g. Ojea *et al.*, 2017).

However, the implementation of climate-adaptive fisheries management and the evaluation of its success in real-world situations are generally lacking (Bell *et al.*, 2020). In fact, most fisheries management strategies remain reliant on static population dynamics without accounting for climate-related impacts such as altered productivity and distribution of aquatic species, which will likely impede the achievement of fisheries sustainability (Szuwalski and Punt, 2013; Pinsky *et al.*, 2018; Bell *et al.*, 2020). Hence, there is a need to understand how flexibility can be introduced into the fisheries management cycle in order to foster adaptation, strengthen fisheries resilience, and enable managers to respond in a timely manner to changes in the dynamics of marine resources and ecosystems (Barange *et al.*, 2018). A robust, adaptive management framework that allows fishery managers and stakeholders to test, evaluate, review and adjust decisions based upon monitoring or observations of changing fishery, climatic and environmental conditions is essential to improving climate readiness in the fishery management cycle (Plagányi *et al.*, 2011; Ojea *et al.*, 2017; Wilson *et al.*, 2018). This also includes learning from successful (and unsuccessful) outcomes of previous management decisions.

Combining the principles and considerations found in the literature on climate-adaptive fisheries management and the latest review of available knowledge, the objective of this Technical Paper is to review existing solutions and to propose good practices for developing climate-adaptive fisheries management in a variety of practical contexts. This is accomplished through two sub-objectives: (1) to identify adaptation measures in fisheries management that have been used successfully to strengthen the resilience of fisheries to climate change; and (2) to highlight lessons learned from specific case studies to adaptively manage fisheries in the face of climate change.

What is often missing in reviews of this kind is discussion of the practical actions that promote the implementation of these adaptation measures, in particular those actions which go beyond fisheries management, including scientific and communications capacities, governance arrangements, etc. In this Technical Paper we rely on several case studies to document and identify existing examples of practical management measures and actions that have been taken to adapt the fisheries sector to the impacts of climate change. These case studies represent a range of regions, species, environments and governance systems, involve both small-scale and industrial fisheries, and provide practical examples of fisheries management responses to a diverse range of climate impacts. The case studies were presented and lessons learned about good practices were synthesized during an expert workshop organized by FAO and Fisheries and Oceans Canada (12-14 November 2019, Rome, Italy) (Appendix lists participants at the workshop and others who contributed to this report).

Building on the workshop outcomes, this Technical Paper presents a set of good practices for developing climate-adaptive fisheries management. It also provides practical guidance to assist decision-makers in identifying 'good practice' adaptation measures suitable for local contexts. The publication is divided into two parts. **Part 1** includes the first two chapters; it synthesizes the lessons learned and the good practices identified through the analysis of case studies and literature. **Chapter 2** summarizes good practices and the foundational principles of fisheries management needed to cope with climate change. It identifies 15 climate adaptation measures for fisheries management, and concludes with a discussion of the challenges to effective implementation of these good practices, along with recommendations for future directions. While these principles are not new, it is important to highlight their relevance when dealing with any disruptions to natural systems; climate change is no different. **Chapter 3** describes the details of the adaptation measures presented in the case studies; it provides a selection of good practice adaptation measures, outlines the criteria used to identify such measures, details the circumstances for their use, and offers tips for effective implementation.

Part 2 contains the 13 case studies presented at the workshop and used as a basis for the identification of the good practices described in Part 1. The case studies are described in Chapters 4 to 16.

Chapter 4 develops a simulation framework to assess limit reference points under different climate scenarios as well as to examine how they may affect the species being managed. It also provides examples of fisheries that attempted to take into account the uncertainties in productivity in a changing environment to make management systems more robust to climate change.

Chapter 5 provides an overview of the current condition of Myanmar's marine fisheries management. Overall, the management system is not resilient and struggles to appropriately respond to large-scale change, such as climate change, despite several developments including measures spelt out in Myanmar's National Adaptation Programme of Action (NAPA) to Climate Change and the efforts of local groups to build primary fishery management capacity.

Chapter 6 analyses the role of Belize's 'Managed Access' programme, which links expanded marine protected area (MPA) networks to nationwide rights-based fisheries management, in countering the negative effects of climate-induced warming on complex finfish assemblages.

Chapter 7 discusses the sardine fisheries in the Philippines, where measures that take account of environmental variability are generally lacking. It describes how the country's current priority is addressing overexploitation to help improve resource sustainability and build resilience to future climate-related changes.

Chapter 8 details adaptive management measures implemented in the Uruguay small-scale yellow clam (*Mesodesma mactroides*) fisheries management cycle to cope with negative climate impacts. These measures include conservative catch quotas, co-management, shifting marketing strategies, and weekly phytoplankton toxin monitoring.

Chapter 9 discusses the management responses to two very different invasive non-indigenous species (NIS), namely Rapa whelk (*Rapana venosa*) in the Black Sea and pufferfish (*Lagocephalus sceleratus*) in the Mediterranean basin, both of which have increasing survival rates owing to climate change and its associated warming of the seas.

Chapter 10 analyses adaptation measures that have been implemented in the small pelagic fisheries in South Africa as a response to declining population size of sardine (*Sardinops sagax*) driven by climate change (e.g. importing frozen sardine to keep factories operational and meet local demand). It also explores other potential adaptation measures including, for example, rebuilding of the sardine population, and increasing exploitation or development of other small pelagic fish – e.g. anchovy (*Engraulis encrasicolus*) and round herring (*Etrumeus whiteheadi*) – for human consumption.

Chapter 11 uses Northeast Arctic cod (*Gadus morhua*), North Sea cod (*Gadus morhua*), Norwegian spring-spawning herring (*Clupea harengus*) and Northeast Atlantic mackerel (*Scombrus scombrus*) as examples to study the influence of climate-induced shifts in stock distributions on existing management and the allocation of quotas of straddling and transboundary stocks in the Northeast Atlantic.

Chapter 12 analyses the Vessel Day Scheme (VDS), which is used by eight Pacific Island countries that are the Parties to the Nauru Agreement (PNA) and Tokelau (and which sustain the world's largest tuna fisheries) as a non-confrontational and effective adaptation in response to climate impacts (e.g. changes in distribution and abundance of tuna) within their exclusive economic zones (EEZs).

Chapter 13 describes the decrease in catches of Greenland halibut (*Reinhardtius hippoglossoides*) in the Gulf of St Lawrence, Canada, due to declining productivity as a result of rapid warming of water in their preferred deep bottom habitat. Potential management responses to address these climate impacts include developing fisheries for other species whose productivities are increasing due to the changing climate.

Chapter 14 recommends the incorporation of near-real-time observational data of the marine environment and the anchoveta population (*Engraulis ringens*) into decision-making in Peru. This is making the fisheries management system more flexible and adaptive in responding to negative climate impacts on anchoveta fisheries in this country.

Chapter 15 summarizes the fishery responses in Tasmania, a global temperature hotspot in the southeast Australian marine region, to amplified effects of climate change in the form of more frequent marine heatwaves and the intensification of poleward transport of warmer waters. It also proposes key recommendations to improve the climate adaptation of Tasmanian commercial fisheries of wild-catch rock lobster (*Jasus edwardsii*) and abalone, including blacklip abalone (*Haliotis rubra*) and greenlip abalone (*H. laevigata*).

Chapter 16 discusses concerning declines in the survival and number of sockeye salmon (*Oncorhynchus nerka*) in the Fraser River in western Canada in recent decades, due to climate change and habitat deterioration. These changes add uncertainty to in-season management; addressing these concerns will require greater adaptability in the allocation of science and management resources, more precautionary approaches to management, and actions concerning restoration or conservation of freshwater habitats.

This report is not intended to be a generalized and comprehensive framework applicable to all fisheries management contexts. Rather, it is intended to foster greater uptake and implementation of good practice adaptation measures to enhance fisheries management responsiveness to climate change, based on transferable experiences and lessons learned from selected examples around the world. It should be considered as a step towards more complete guidance on this topic.

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Chapter 2: Good practices in adaptive management of fisheries in response to climate change

1. INTRODUCTION

The world's marine fisheries face significant challenges from global climate change driven by rising anthropogenic greenhouse gas emissions. The most recent Intergovernmental Panel on Climate Change (IPCC) Assessment Report (IPCC-AR5 2013) and the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC, 2019) provide strong evidence that the global ocean surface and subsurface environments are changing, particularly ocean temperatures and acidification (IPCC, 2019; Rhein *et al.*, 2013). These, and other changes to ocean conditions, are altering the timing, location and extent of the upwelling and mixing processes on which most oceanic productivity depends.

Global models indicate that there is likely to be a net decline in the productive potential of the world's oceans due to climate change, although regional and local effects are less clear. For example, upwelling may intensify in some eastern boundary systems, resulting in a positive impact on nutrient inputs and primary production while simultaneously increasing the prospect of low-oxygen waters in shelf habitats (Barange *et al.*, 2018). Such changes to the physical and chemical characteristics of marine ecosystems are driving major shifts in the productivity and distributions of fish and invertebrate populations (Barange *et al*., 2018). In addition, coastal habitat degradation, marine heatwaves (Hobday *et al*., 2016) and other extreme events are accelerating the impacts of climate change on ecosystems (Smale *et al*., 2019) and having large effects on fisheries around the world. These impacts are occurring cumulatively and synergistically with the existing pressures of fishing on stocks (Perry *et al*., 2010). Overall, global oceans are experiencing an era of profound change, affecting marine life and the fisheries they support, and will be increasingly subject to extreme and more destructive events (Barange *et al*., 2018; Johnson and Lyman, 2020) and increased interannual variability (e.g. Pinsky and Mantua, 2014).

The total maximum fish catch potential that can be sustained by marine ecosystems is expected to decrease in the world's exclusive economic zones (EEZs) due to climate change (Barange *et al.*, 2018). This decline is expected to range from 7.0–12.1% under a 'business-as-usual' high greenhouse gas (GHG) emissions scenario, and 2.8–5.2% under a low GHG emissions scenario. These changes will be unevenly distributed across the planet. The greatest impacts are expected in the tropics (Lam *et al*., 2020), whereas in northern latitude regions catch potential is projected to show a smaller decrease or even an increase. Shifts in fish abundance and distribution in higher-latitude waters are also expected to be profound, particularly for historically important cold-water species (e.g. salmon, northern shrimp, Atlantic cod). This will have significant impacts on the global distribution of fisheries, and will require large-scale human adaptations that cross geopolitical boundaries.

Despite these relatively dire predictions, it should be possible for many fisheries around the world to mitigate these expected impacts and to continue to rebuild and improve compared to the status quo (Gaines *et al.*, 2018), as well as take advantage of opportunities related to expected changes in fish distribution and productivity. As a result, even as the productive potential of the world's oceans declines, many fisheries still have opportunities for regeneration compared to their present status. For example, modelling studies suggest that adopting fisheries management measures which take account of climate-induced changes in fish productivity and distribution would yield higher cumulative catches and profits than business-as-usual management for a majority of countries under all but the most severe climate scenarios (Barange, 2019; Free *et al.*, 2020). Therefore, the food security, livelihood, and biodiversity outcomes of most concern as a result of climate change can be mitigated to a great degree through the implementation of climate-adaptive fisheries management.

While fisheries have traditionally coped with climate variability, and fisheries management regimes have reacted to shifts in fish stock abundance and distribution, observed and projected changes are accelerating and becoming more extreme and frequent as a result of climate change. In addition, climate change will cause directional changes to marine ecosystems, and not simply increased variability about the same mean levels for which management systems have been developed. For example, directional changes (often poleward) in the distributions of marine species will cause 'traditional' species to disappear from some areas. In contrast, 'non-traditional' species are likely to become more abundant in other areas. Such changes will make many fisheries management plans obsolete. Maintaining the health and resilience of industries and communities that depend on fishery resources will require greater adoption of adaptive management measures (i.e. feedback control systems governed by some set of rules), and may also include the use of relatively new approaches and innovations (collectively referred to as climate-adaptive management). These new approaches may differ in scale, for example, between wide-ranging industrial high-seas fisheries (such as for Peruvian anchovy, e.g. Oliveros-Ramos *et al.*, this volume) and community-based local fisheries (such as Uruguayan yellow clam, Defeo *et al.*, this volume).

Globally, the implementation of climate-adaptive measures in fisheries management has been slow, and there are many challenges in documenting their effectiveness and benefits. In particular, many climate adaptations have been implemented in response to extreme (often weather-related) events rather than slow onset changes, which limits their utility to being reactive (autonomous) rather than proactive (planned). Other adaptations have not focused specifically on climate change, making it difficult to untangle their effectiveness in coping with non-climate stressors such as intensive fishing (Poulain, Himes-Cornell and Shelton, 2018).

This chapter proposes good practices for developing climate-adaptive fisheries management, under a variety of species, environmental and governance contexts. It begins by describing good practices and the foundational principles of fisheries management in general, which are also central to coping with climate change. The chapter then identifies 15 climate adaptation measures for fisheries management. It concludes with discussion of the challenges for effective implementation of these good practices and recommendations for future directions. Chapter 3 presents details of the 15 good practice climate adaptation measures, including examples, advantages, tips and challenges. These good practices for climate-adaptive fisheries management are based on the experiences and learnings from 13 case studies, which are described using a common template in Part 2 of this report, plus selected studies from the literature. All these studies involve marine species, with the exception of one study of anadromous Pacific salmon. The extension of these good practices to inland fishery systems is discussed in the section on future directions. Ultimately, this chapter aims to accelerate implementation of climate change adaptation in fisheries management throughout the world and to provide a range of options for the fishing industry, fishery managers, policymakers and other stakeholders to select specific adaptations suitable for their individual contexts.

2. FUNDAMENTAL PRINCIPLES OF CLIMATE-ADAPTIVE FISHERIES MANAGEMENT

2.0. Fisheries management as a foundation to cope with climate change

Predicting marine ecosystems' and fisheries' responses to climate change will always be highly uncertain. The directional nature of many climate-related changes, however, introduces fundamentally new elements for which traditional fisheries management approaches may be insufficient. The four foundations of climate-resilient fisheries are (1) establishing effective fisheries management systems, (2) setting participatory fisheries management systems, (3) precautionary systems dealing with uncertainty and risks, and (4) adaptive fisheries management systems. These are also key features of the good practices (Box 1) identified in the climate adaptation literature (e.g. Willows *et al*., 2003, Bell *et al*., 2020), and are core components of sustainable fisheries management.

2.1. Effective fisheries management systems

An effective fisheries management system is the first foundation of climate-resilient fisheries (e.g. Hilborn *et al*., 2020). It involves a number of tasks that collectively aim to ensure the sustainable use of fisheries resources for diverse societal goals. The tasks can be broadly grouped in two inter-dependent phases: a planning phase, when objectives, rules and management measures are defined; and an implementation phase, when mechanisms are put in place to implement the agreed rules, ensure compliance, and monitor outcomes (Figure 1; FAO, 2012).

The planning phase involves the steps of scoping, gathering background information and analysis, setting of objectives (including agreed criteria or indicators for measuring progress towards these objectives and specific targets or standards to aim for in a specified time frame), and formulation of rules. In the implementation phase, these rules are put into practice and fisheries are monitored through collection of relevant data which are used in short-term (often annual) assessments to guide implementation arrangements and enforcement. The long-term (5-10 year) outcomes of the implementation phase can be used to review the management plan.

Box 1

What is a good practice?

A good practice is a practice that has been proved to work well and to produce effective results, and can therefore be recommended as a model. It is a successful experience that has been tested, validated and repeated, and hence deserves to be shared so that a greater number of people can adopt it.

Source: FAO, 2013

However, climate change will require modifications to this two-stage process, specifically to address continual directional changes (for example to species distributions). This means that decision-makers will frequently need to review their objectives and indicators and, based on information from monitoring and short-term assessment, be prepared to alter traditional plans (Figure 1). The entire process should be guided by stakeholder consultation and the use of best available knowledge. In an ideal participatory system (see Section 2.2, below), such modifications could be discussed and approved prior to the observation of significant changes so that revisions to objectives and indicators would be almost automatic. Such a fisheries management cycle of planning, implementation, monitoring and review is fundamental to sustainable resource use and is also the starting point for supporting climate change adaptation measures. When combined with management strategy evaluation (MSE; see for example Holland, 2010; Goethel *et al.*, 2019; Sharma *et al.*, this volume; Box 2) to examine potential climate impacts, risks and adaptation options in the management planning phase, this approach empowers decision-makers, industries and local communities to react and adapt to changes as they occur.

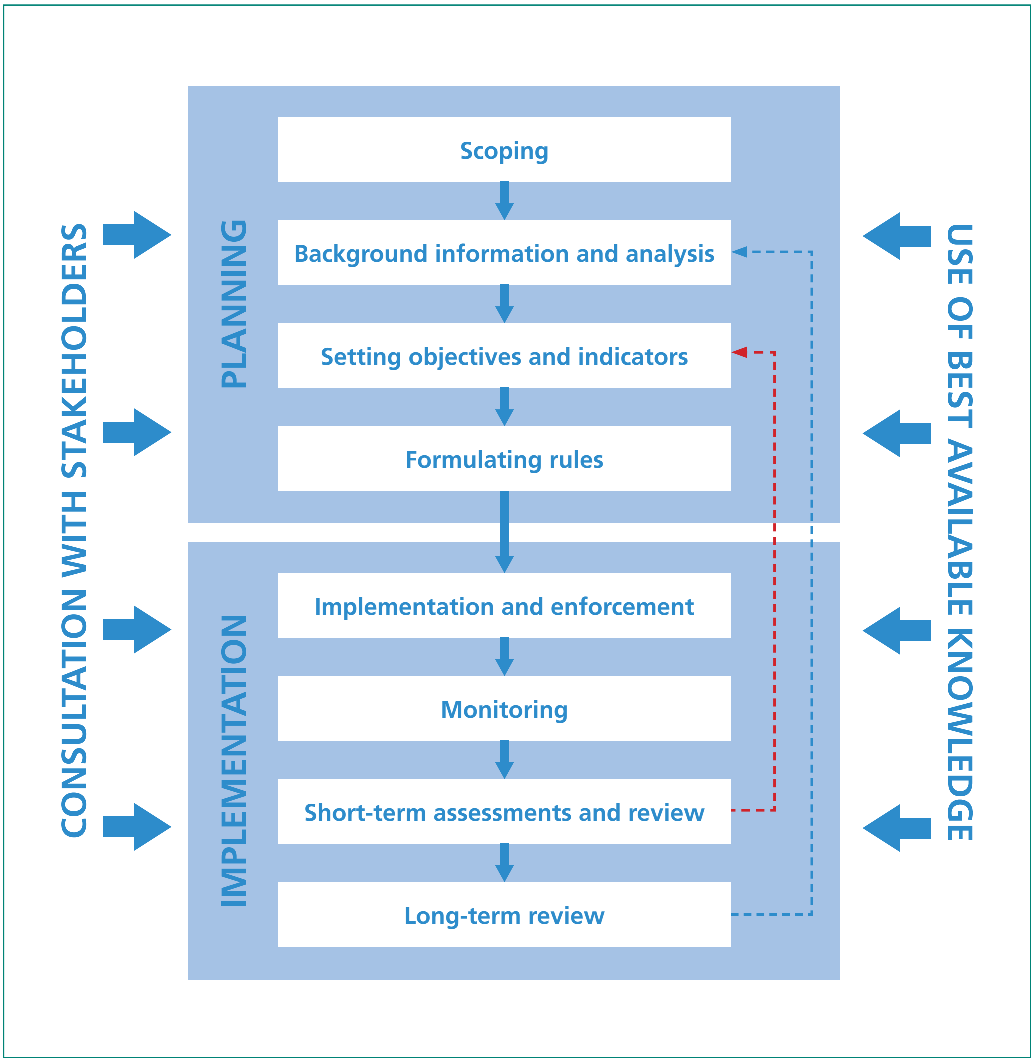


Figure 1. Generic steps in fisheries management (adapted from FAO, 2003). Dashed red line represents additional loops that will be required to address the dynamic nature of climate change.

Box 2

Management strategy evaluation

Management strategy evaluation (MSE) is a framework to simulate a fisheries system, potentially including environmental and biological variability, data collection systems, assessment of stock status, and social and economic objectives – i.e. management procedures. Its goal is to test, in a simulated environment, a number of alternative management actions and to identify those which perform best against the desired objectives. 'Best' in this sense means the strategies perform well and are robust to uncertainty and natural variability, while balancing biological and socioeconomic objectives. Key challenges for effective use of MSE include identifying the objectives and uncertainties, determining plausible scenarios, and working with decision-makers and stakeholders to interpret and implement the results.

Sources: Holland, 2010; Punt *et al*., 2016; Pew Charitable Trusts, 2016

2.2. Participatory processes are essential

Stakeholder participation is vital for an effective fisheries management system, and for adapting management plans to climate change. This is the second foundation of climate-resilient fisheries and can take various forms (e.g. Jentoft and McCay, 1995). For example, Leite and Pita (2016) identified five types of participation by fishing communities in fisheries management within the European Union (Table 1). These ranged from passive participation, involving one-way flows of information; to self-mobilization, in which community control of management was fairly independent of other institutions. The majority of partnerships they identified were of the 'functional partnership' type, which they defined as largely driven by governments as a means to achieve predetermined goals. In many cases barriers need to be overcome; for example, the predominant knowledge system may differ between users and governing institutions, hindering assessment of climate change impacts and uptake of adaptive measures. Consultative scoping of issues that incorporates different knowledge systems and objectives, particularly those of indigenous peoples, should be done before solutions are proposed to maximize effectiveness and distribution of costs and benefits.

Co-management (Box 3) is one participatory approach to fisheries management that involves shared responsibility for the management and utilization of fisheries resources between regulatory authorities (often, but not necessarily, governments) and user groups (Pomeroy and Rivera-Guieb, 2006). In this definition, 'co-management' is similar to the 'interactive participation' identified by Leite and Pita (2016). It has been demonstrated in many instances that fishers and the fishing industry are capable of reacting and adapting more quickly to changes in environmental conditions (whether or not associated with climate change) compared to reactions that rely on a centralized management decision-making process (e.g. see Nursey-Brey *et al.*, 2018; Defeo *et al.*, this volume; Fogarty and Pecl, this volume).

It is possible to implement decentralized co-management structures, along with closer relationships between fishers, industry and management, to capitalize on the adaptive capacity of fishers and industry and to take advantage of knowledge, skills, technology and funding that may not be fully utilized under existing management systems (Wilson *et al*., 2018). This can be done while simultaneously ensuring that adjustments in fishing practices made in this decentralized manner are able to cope with changing conditions, are timely, and can be assessed by scientists and managers to avoid maladaptations.

However, the effectiveness of co-management arrangements depends on existing policy and legal environments, local and national support for stakeholder-based initiatives, ongoing communication and the capacities of the various partners involved. Building and maintaining this capacity, developing trust, and instilling the right structures and expectations, is necessarily an evolving process that will take time, and should not be seen as a 'quick fix' (Jentoft, 2005).

Several of the case studies in this Technical Paper present examples of how various co-management arrangements (mostly of the 'Participation by consultation' to 'Interactive participation' types of Table 1) have been developed to resolve resource problems arising, at least in part, due to climate change. In Belize, an approach that connects place-based co-management systems, known as 'Managed Access', to large marine protected area (MPA) networks was applied to the management of reef fisheries. The system provides secure fishing rights within designated local areas to eligible fishers to enhance resource stewardship, reduce illegal fishing, improve catch reporting and incentivize higher compliance with regulations. Implementation of the approach at pilot sites resulted in a drop in illegal fishing, increases in catch rates and stabilization of seagrass, mangrove and coral cover. These positive results led the government to scale up the implementation of the approach (Rader *et al*., this volume).

In Myanmar, the recently established co-management arrangement facilitates joint enforcement efforts between local fishery associations and government to address illegal fishing activities. The resulting decline of illegal fishing activity has led to social benefits through larger catches going to local communities, thus building their resilience (Burden *et al*., this volume).

The yellow clam fishery of Uruguay (Defeo *et al*., this volume) provides an example in which co-management favoured the use of local traditions and knowledge in the design of flexible management measures to cope with climate stressors. The participation of fishers in monitoring and decision-making generated a sense of ownership that was key to promoting sustainable fishing practices and livelihood options that enhanced community well-being.

The management of salmon in the Northeast Pacific provides examples of an 'interactive participatory' approach involving multiple stakeholders. Management of these stocks is complex and not always entirely effective, especially as the poleward migration of stocks benefits some stakeholders more than others. This is demonstrated in the Fraser River sockeye (Grant *et al*., this volume) and Oregon coast coho (Sharma *et al*., this volume) case studies. Having a forum to exchange ideas and perspectives is important for effective management outcomes.

Table 1. Typology of fishing community participation in fisheries management, within the European Union. Adapted from Leite and Pita, 2016.

Passive participation	One-way flow of information, often involving unilateral announcements by an administration or project manager without consulting fishers.
Participation by consultation	Two-way flow of information, in which fishers participate by being consulted or by answering questions, usually pre-defined by external agents.
Functional participation	Government-driven partnership, in which participation is often seen by external agencies as a means to achieve predetermined goals.
Interactive participation	Industry-driven partnership, often a formal partnership with administration to share planning and decision-making responsibilities.
Self-mobilization	Community control of management, which is fairly independent from other institutions, including funding.

Box 3

The role of co-management in climate-resilient fisheries

Co-management can strengthen relationships and trust among fisheries stakeholders, empower fishers, and foster greater collective actions for sustainable fisheries and effective adaptation options to climate change (Jentoft, 2005; Pittman *et al.*, 2019). It can confer relatively rapid adaptive capacities in fisheries management by leaning on the skills, knowledge and observations of local stakeholders to make management rules tailored to a given area, while the government ensures certain over-arching standards and support in the form of governance, enforcement and scientific capacity. Co-management involves a decentralization of fisheries management responsibility that has the potential to increase resilience in different ways, including by: i) being more responsive and adaptive than centralized structures, ii) providing greater levels of stakeholder participation and input into decision-making, iii) tailoring rules to the local context, and iv) making enforcement more effective when founded on a cooperative community-based framework.

Another benefit of co-management is the internalization of the rewards and penalties, i.e. stakeholders are rewarded for good management and penalized for poor management, and they are empowered to do either. Therefore, fishers are more likely to take anticipatory action due to climate change because of this internalization.

2.3. Precautionary systems to deal with uncertainties and risks

Information on forecasted impacts of climate change on specific marine ecosystems and fisheries is still limited and subject to high levels of uncertainty. Fishery stakeholders and managers (under the range from centralized to co-management systems) need to be prepared to cope with these impacts and to deal with the significant degree of uncertainty associated with them. Managing fisheries in the face of climate change is therefore a special case of decision-making that must consider the additional uncertainty and risk arising from climate impacts. It requires additional emphasis on the broad uptake of established strategies for risk management, such as the precautionary approach and adaptive management.

Precaution to account for uncertainty and unknowns is the third foundation of climate-resilient fisheries. The precautionary approach is acknowledged as a key underlying basis for incorporating uncertainty into decision-making. The United Nations Convention on Biodiversity definition of the precautionary approach is: 'where there is a threat of significant reduction or loss of biological diversity, lack of full scientific certainty should not be used as a reason for postponing measures to avoid or minimize such a threat' (CBD, 1992; see also Richards and Maguire, 1998). This definition revolves around defining what might be a 'threat of significant reduction or loss', which may be difficult for developing or low-capacity fishery situations. The definition used by the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) in its listing criteria, '…the Parties shall act in the best interest of the conservation of the species concerned and… adopt measures that are proportionate to the anticipated risks to the species'[1] may be more helpful in a practical context. Precautionary approaches are recommended for each stage of the fisheries management process, from planning through to implementation, as presented in Table 2.

One particular precautionary activity to highlight is the use of risk assessment methodologies in the planning/scoping phase of the management cycle. Such practice is in line with the ecosystem approach to fisheries (FAO, 2003; 2012) and is consistent with the climate change risk management framework (Poulain, Himes-Cornell and Shelton, 2018). This approach aims to identify the priority issues affecting the sustainability of a fishery, including external stressors and vulnerabilities related to climate change. Watkiss, Ventura and Poulain (2019) identified five approaches to adapting to climate change-related risks in fisheries: reduce risks, reduce exposure, reduce vulnerability, spread risks, and live with the risks. Each of these requires evaluation of social and economic contexts. For example, how do the ecological relationships (and therefore the productivities) of fish populations change as some species move and others do not, resulting in new arrangements of fish communities? How do changes in temperature affect fish growth, and therefore biomass and assessments of maximum sustainable yields? How do changes in fish distributions affect fishing rights (plus see Section 5, below)? The case study by van der Lingen (this volume) provides an example of the use of a vulnerability assessment to identify priority issues concerning the impacts of climate, including changes in fish distributions, on the small pelagic fisheries in South Africa. Further examples of applications and methodologies for risk and vulnerability assessments in fisheries can be found in FAO (2012; 2015).

[1] CITES Conf. 9.24 (Rev. CoP17) Criteria for amendment of Appendices I and II, p. 2; https://cites.org/sites/default/files/document/E-Res-09-24-R17.pdf.

Table 2. Examples of precautionary actions that can be taken in the *planning and implementation* phases of the fisheries management cycle (Figure 1) to cope with climate change (adapted from FAO, 1996; Cochrane, 2002).

Planning phase	• Understand the overall exposure of the fishery to climate drivers and expected impacts, including the potential species composition and yield for a fishery as climate change progresses. • Assess risks to identify priority issues and vulnerability factors related to climate change. • Use best available information for setting objectives and management strategies, including scientific and local/traditional knowledge. • Identify the capacities of science, stakeholders and fisheries managers, and ensure goals and expectations of the fishery are aligned appropriately. • Define goals, objectives, indicators, targets, constraints, management measures and procedures that are appropriate to apply in the face of climate change, and allow for adjustment of management measures as necessary. • Explicitly consider precautionary actions that could be taken to avoid specific undesirable outcomes that may arise from climate change, with due consideration of their potential social and economic impacts. • Set precautionary targets commensurate with the level of uncertainty, i.e. the higher the uncertainty the more conservative should be the targets (e.g. target fishing mortality levels should be less than the estimated fishing mortality at the maximum sustainable yield). • Have an agreed harvest control rule for a fishery response when a reference point is breached. • Give priority to rebuilding overfished stocks, avoidance of overfishing, and avoidance of excessive harvesting capacity. • Ensure broad acceptance of precautionary actions through appropriate consultations with stakeholders.
Implementation phase	• Ensure the management programme can be implemented given the capacity of scientists, stakeholders and managers. • Collect all information necessary to ensure that the management plan is being executed and that it is achieving the desired results, including environmental and socio-economic data (e.g. community-based data collection programmes). • Use best available information to monitor the fishery, including scientific and local/traditional knowledge. • Implement fishery-dependent or -independent data-gathering systems (monitoring) that can track changes in the geographic range of species and potentially provide advanced warning of changes in fish distributions and species composition. • Set up procedures for assessing the state of stocks, rule setting, economic assessments, and communication of decisions and rationale for communities and the fishing industry. • Design and implement contingency rules to ensure compliance with targets in the face of major adverse events from climate- and non-climate-related stressors. • Ensure appropriate systems to incentivize compliance, and facilitate enforcement and penalties for non-compliance. • Periodically re-evaluate and revise management measures to assess potential impacts of climate change and other changes. • Use simple rules-based systems based on common-sense indicators for under-resourced systems or systems without established response-based fisheries management.

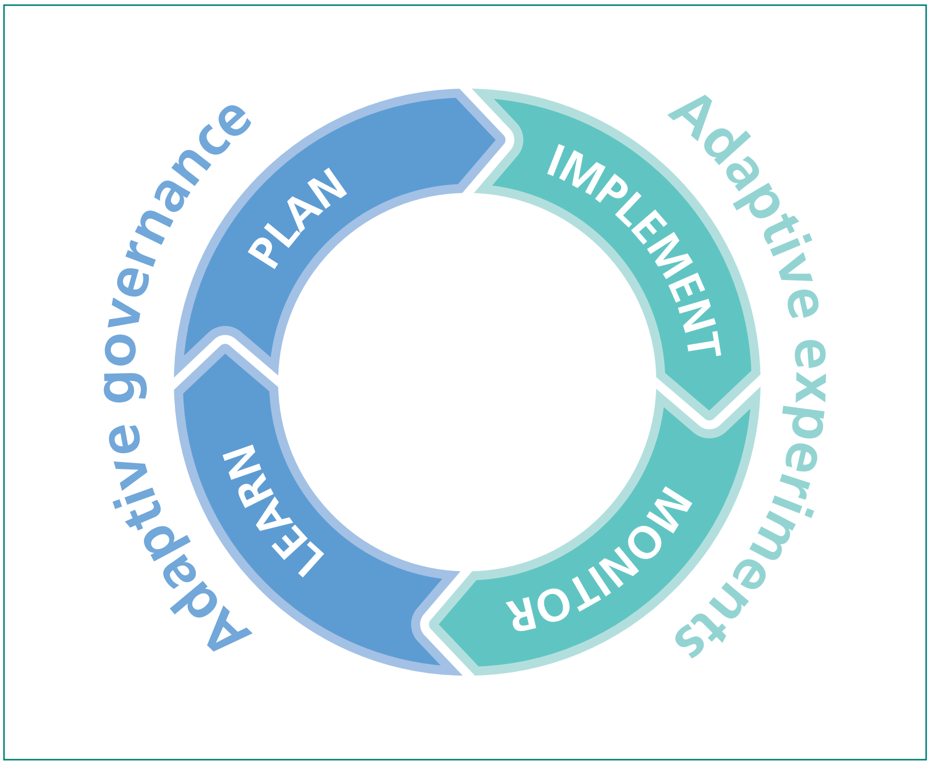


Figure 2. Simple conceptualization of an adaptive management cycle. Adaptive experiments involve a structured approach to trying different implementation activities and monitoring to distinguish what works and what does not; adaptive governance involves use of the outcomes of these adaptive experiments in subsequent planning phases (Allan, 2007).

2.4. Use adaptive management approaches to cope with climate change

Adaptive management is the fourth key foundation of climate-resilient fisheries. This is an approach that recognizes, in the face of uncertainty, that it is impossible to determine the perfect management strategy. There is a great deal of uncertainty in relation to climate change, therefore adaptive management is an essential tool. Adaptive management considers resource management strategies as experiments, from which managers can learn and then adapt or change such policies iteratively (Figure 2; Walters, 1986; FAO, 2009). Feedback from the fishery system can be collected through monitoring (e.g. by using status indicators and comparing stock status to pre-determined reference points, as noted in Table 2), and analysed for successes or failures to revise the planning and implementation decisions within the management system. Revisions in management measures are then followed by further implementation and experimentation, shaping subsequent policy and management actions. Such approaches are also commonly part of MSE.

Adaptive management approaches also need to be robust to uncertainty. Such approaches ideally have a high likelihood of producing outcomes that are reasonably acceptable despite information gaps about the fishery or ecosystem. In this context, a robust measure could be considered a type of 'no-regret' adaptation approach that is cost-effective under prevailing climate conditions and delivers the desired benefits regardless of future climate scenarios. One example is the use of ramped harvest control rules that raise and lower the fishing rate on a stock based on its biomass indicators. This type of approach, originally developed to help rebuild a declining stock, has been shown to foster adaptation to situations where climate change is affecting a stock's underlying productivity (see Kritzer *et al.*, 2019; Sharma *et al.*, this volume).

Developing flexible fisheries management systems is another example of an adaptive management approach. Chile has an effective management system with high stakeholder participation. However, when environmental conditions changed and traditional target species declined and were replaced by other species such as tuna, fishers were unable to catch these 'new' species because they were not on the list of authorized and licensed species (Reyes *et al*., 2019). Correcting this problem would be an example of 'plan, learn, and adapt' (adaptive governance) as illustrated in Figure 2.

The desired robustness of a management system often involves a 'redundancy' in the choice of management measures and tactics or a combination of management measures (Gutierrez, Hilborn and Defeo, 2011; Bell *et al*., 2020; Defeo *et al*., this volume). In this sense, 'redundancy' refers to back-up systems or processes such that, if one part fails, the system as a whole will still be able to function. Experiments with multiple adaptive management measures and tactics should increase the robustness of that management system to uncertainties due to climate change, for example by improving information flows and feedback on management actions. Stefansson and Rosenberg (2005), for instance, showed that combining more than one type of direct control on fishing provides a greater buffer to uncertainty than any single form of fishery control alone. Their study showed that combining closed areas with input (effort limits) and/or output (catch quotas) controls performed better in reducing the risk of stock collapse and maintaining both short- and long-term economic performance than single measures alone. This is particularly important, given the general lack of reliable information on the effects of climate change on many of the world's fisheries.

3. IDENTIFYING GOOD PRACTICE CLIMATE-RESILIENT ADAPTATIONS

Case studies across the globe

The 13 case studies from around the world presented in Part 2 of this publication provide examples of how fisheries management has dealt with the effects of climate variability and change, while sustaining fish catch. The case studies represent a range of regions, sectors, species, environments and governance systems. They also encompass responses to a diverse range of climate impacts by fisheries with different levels of complexity, from well-developed management systems to those undergoing improvement (Figure 3). This complexity spans data-poor fisheries such as those in Myanmar (Burden *et al.,* this volume) and the Philippines (Campos and Bagarinao, this volume), to fisheries with intermediate data availability such as in Uruguay (Defeo *et al*., this volume), to those with relatively rich data such as in North America (Duplisea *et al.*, this volume) and Europe (Gullestad and Bakke, this volume). The level of complexity also depends on the socio-economic context, the scale of the fishery (Clark *et al*., this volume), the amount of human and financial resources available (Grant *et al.*, this volume), and existing governance arrangements.

In general, it is expected that the greater information, measures and controls available in more complex management systems will enhance capacity to understand and adapt to the effects of climate change. In contrast, systems with few management measures and limited data will be more vulnerable to the impacts of climate change, and require more conservative management measures to cope with impacts (Figure 3). Ultimately, effective adaptation to climate change depends on knowledge, data, management controls and institutions working in concert to achieve desired outcomes. Management systems without these attributes are likely to produce maladapted measures or to fail in delivering meaningful action.

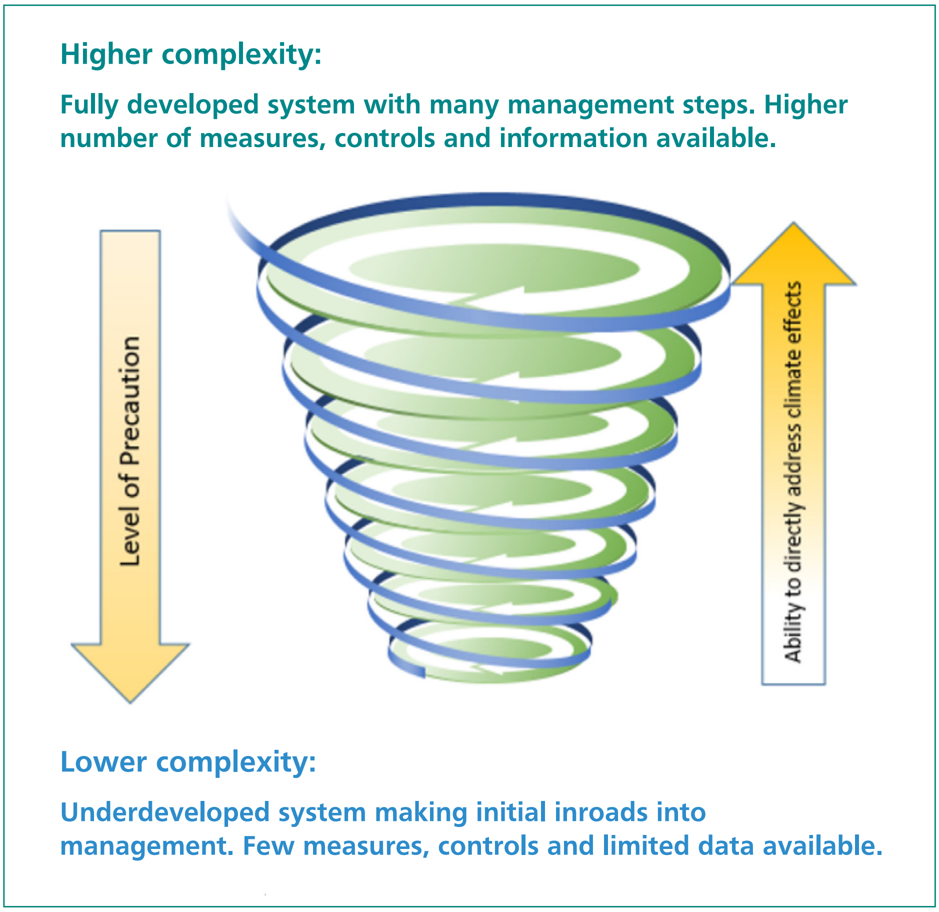


Figure 3. Schematic showing how the level of complexity of the fishery management system relates to the level of precaution required and the ability and tools available to address climate impacts (adapted from Burden, 2019; see also Cochrane *et al.*, 2011. The adaptive management cycle (Figure 2) can be applied at each level of this spiral, from lower to higher complexity systems.

The details of the adaptation measures selected from these case studies, as well as other examples from the literature, are presented in Chapter 3. Together, they provide a basis for learning about which fisheries management adaptations designed to deal with the impacts of climate change work well, and which practices to avoid to prevent the unintended or negative consequences of maladaptation. Examples of such maladaptation are changing gear types to compensate for declining catches without adjusting effort to ensure the fishing mortality is sustainable, and/or introducing gears that cause more habitat destruction.

Criteria for good practices in climate adaptation measures

The case studies compiled in this volume (Chapters 4 to 16), and other examples from the literature, were analysed to identify criteria for selecting climate adaptation measures likely to be effective or, at a minimum, effective under the circumstances in which they are applied. This analysis revealed that three mandatory criteria should be met, and two additional beneficial criteria should be considered, when designing and implementing climate adaptation measures in fisheries. An adaptation measure can be considered a good practice if it meets the three following criteria.

1. ***The adaptation measure explicitly addresses climate-related risk(s) (with a clear objective).*** All management systems have been designed, more or less, with the idea that ocean resources fluctuate around some average level (which differs among populations and locations). Climate change, however, will negate this assumption in many cases – determining when and for which cases this will occur is part of the challenge. The adaptation measure must have a clear climate-adaptation focus or connection. This explicit link to climate change is required to distinguish it from fisheries and habitat regulatory measures that have not considered climate change adaptation in the planning and implementation processes. For example, where coastal fish habitats have been heavily impacted and/or stocks of fish and invertebrates have been overfished, measures that reverse habitat degradation and restore stocks are considered to be integral to effective coastal zone management and sustainable fisheries management. While these measures may indirectly improve the resilience of the system to climate change, they are not specific measures to address climate change impacts although they may form part of the climate-adaptive strategies.
2. ***There is sufficient evidence to infer/assess effectiveness or robustness.*** Fisheries management outcomes produced by the adaptation measure must be measurable. There must be some ability to determine whether or not fisheries are more adaptable to changing environmental conditions after the application of the measure. Many adaptation measures have been proposed in the fisheries and climate literature, but their effectiveness is largely unknown. However, the case studies included in this report do showcase effective implementation of adaptation measures and monitoring of outcomes. The effectiveness of an adaptation measure can be demonstrated through monitoring of projected outcomes (indicators), qualitative expert opinion, modelling, or comparing results with published research where success can be reasonably inferred.
3. ***It must be a win-win or lose-win option.*** The measure must ultimately have a positive outcome (win), even though there may also be costs (loss). In the immediate or short term, an adaptation can be a ‘win’ (e.g. protection of fish habitat) or ‘loss’ (e.g. reducing catch limits) but it must result in a longer-term benefit or ‘win’ under climate change (e.g. increasing stocks). Bell *et al.* (2011, 2018) presented a range of win-win options for coastal fisheries supporting food security in small island developing states, where the costs of the adaptation measure are exceeded by the benefits to the fishery both in the short and long term, or lose-win options, where benefits are exceeded by costs (losses) in the short term but accrue to a benefit under longer-term climate change conditions. Thinking about trade-offs in this way is not without difficulties, however, because the currency and timeframe of wins and losses must be considered – and they may differ between ‘wins’ and ‘losses’. For example, in the human social context, the impacts on losers also need to be taken into account and, where necessary, alternatives sought to mitigate the losses. Measures to adapt fisheries to climate change should avoid focusing on short-term wins that result in long-term losses (win-loss), i.e. maladaptation. Note that well-designed win-win adaptation measures can also help to meet the core aims of fisheries management, as well as the impacts of climate change (i.e. there is a link between criteria 1 and 3).

Apart from these three criteria, there are two additional beneficial criteria that an adaptation measure may consider to improve its design and implementation.

4. ***It should be flexible or responsive.*** Given the uncertainty associated with how climate change affects fish populations and fisheries, it is important that adaptation measures be as flexible as possible. Management measures that will address a range of future climate change scenarios (e.g. Holsman *et al.*, 2019) are especially recommended.

5. ***Socially acceptable.*** Similar to any policy and/or management change, the success of an adaptation measure is likely to be closely linked to stakeholder perception and acceptance. For example, a measure may appear to be beneficial to industry and/or the community; however, if implemented with limited awareness and/or differing interpretations it may be poorly accepted by stakeholders, ultimately resulting in poor compliance. Strategies to implement adaptations that help ensure compliance with this criterion include public education and awareness campaigns, adequate stakeholder consultation, inclusive approaches such as co-management, and promotion of trans-disciplinary collaboration (e.g. Heenan *et al*., 2015).

Managers, stakeholders and user-groups are strongly encouraged to: i) ensure that fisheries adaptation measures are designed to meet local conditions; and ii) implement these measures rigorously and appropriately in the local context. Simply choosing to adopt a good practice adaptation measure does not guarantee its effectiveness.

Climate impacts on fisheries and climate adaptation measures

As noted in the introduction to this chapter, and as described in detail in the individual case studies, climate change is having and will have a variety of impacts on marine ecosystems and fisheries. Changes are expected to occur in ocean currents, sea levels, ocean acidification, rainfall, river flows, oxygen concentrations, the thermal structure of the ocean and other water bodies, and the severity and frequency of storms. Understanding the general impacts of these changes can be a first step to developing climate-adaptive fisheries management measures. The FAO *Climate-Smart Agriculture Sourcebook* (FAO, 2017) includes a non-exhaustive list of the impacts of climate change on fisheries and potential fisheries climate adaptation measures (Table 3). This list provides a starting point for identifying and evaluating existing climate adaptation measures, and for developing new fisheries-specific measures.

Table 3. Examples of climate change impacts on fisheries and potential climate adaptation measures to address these impacts (modified from FAO, 2017)

Impact	Climate adaptation measures
Reduced yield	Access higher-value markets; shift/widen targeted species; decrease fishing capacity/effort; reduce costs/increase efficiency; diversify livelihoods; exit fishery
Increased yield variability	Diversify livelihoods; implement insurance schemes; promote adaptive management frameworks
Change in distribution of stocks	Facilitate mobility of fleets, markets and distribution networks; implement flexible allocation and access schemes, particularly for transboundary stocks
Sea-level change, flooding and wave surges	New/improved physical defences; green infrastructure and habitat restoration; managed retreat/accommodation; rehabilitation and disaster response; integrated coastal management; early warning systems and education
Increased dangers of fishing	Weather warning systems; improved vessel stability/safety/communications; asset insurance; fisher training
Social disruptions/new fisher influx	Support/develop local management institutions; diversify livelihoods
Climate-influenced boom and bust cycles of marine small pelagic stocks	Tailor management measures to capitalize on irregular abundance (e.g. alternative species to supply canneries); protection of key brood stock
Ecological tipping point reached due to climate change and resulting change in abundance and mix of harvested species	Ensure the maintenance of healthy populations of keystone species

Understanding the potential impacts of climate change on any specific fisheries management system provides the background information necessary for selecting adaptation measures for that system. Figure 4 summarizes typical biophysical changes, and their resulting impacts on fisheries resources, fishing operations and the livelihoods of fishing communities described in the case studies. Among the most common of these impacts are shifts in species distributions, productivity, and composition. For example, fish that are adapted to cooler temperatures may experience decreased productivity or may not survive. Others may adapt genetically. Alternatively, if they are able to migrate, they will move out of areas where temperatures exceed their preferred upper temperature thresholds. In contrast, other species adapted to warmer temperatures may increase in productivity, or migrate into these same areas. These shifts in species productivity and/or distribution can lead to changes in the species composition of local ecosystems (e.g. Clark *et al*., this volume; Gullestad and Bakke, this volume; van der Lingen, this volume). Other responses to climate change at the species level can include shifts in age, size and sex composition (e.g. Defeo *et al*., this volume).

Changes in fish distributions, productivity and/or species composition can alter various aspects of fishing operations. These variations can include the timing and areas of fishing, more variable catches, increased costs associated with changing fishing locations and times, and safety-at-sea issues arising from changing weather conditions. Human health issues related to the effects of climate change on the supply of fish for food security can impact individual livelihoods, employment, and communities with high dependence on fisheries.

Apart from the realized or anticipated climate-related impacts, other factors relevant to the local context will influence the choice of appropriate adaptation measures. These factors include the additional technical, human and financial capacity required for implementation (which may vary from one location to another), desired management outcomes, local structures, and the prevailing management regime.

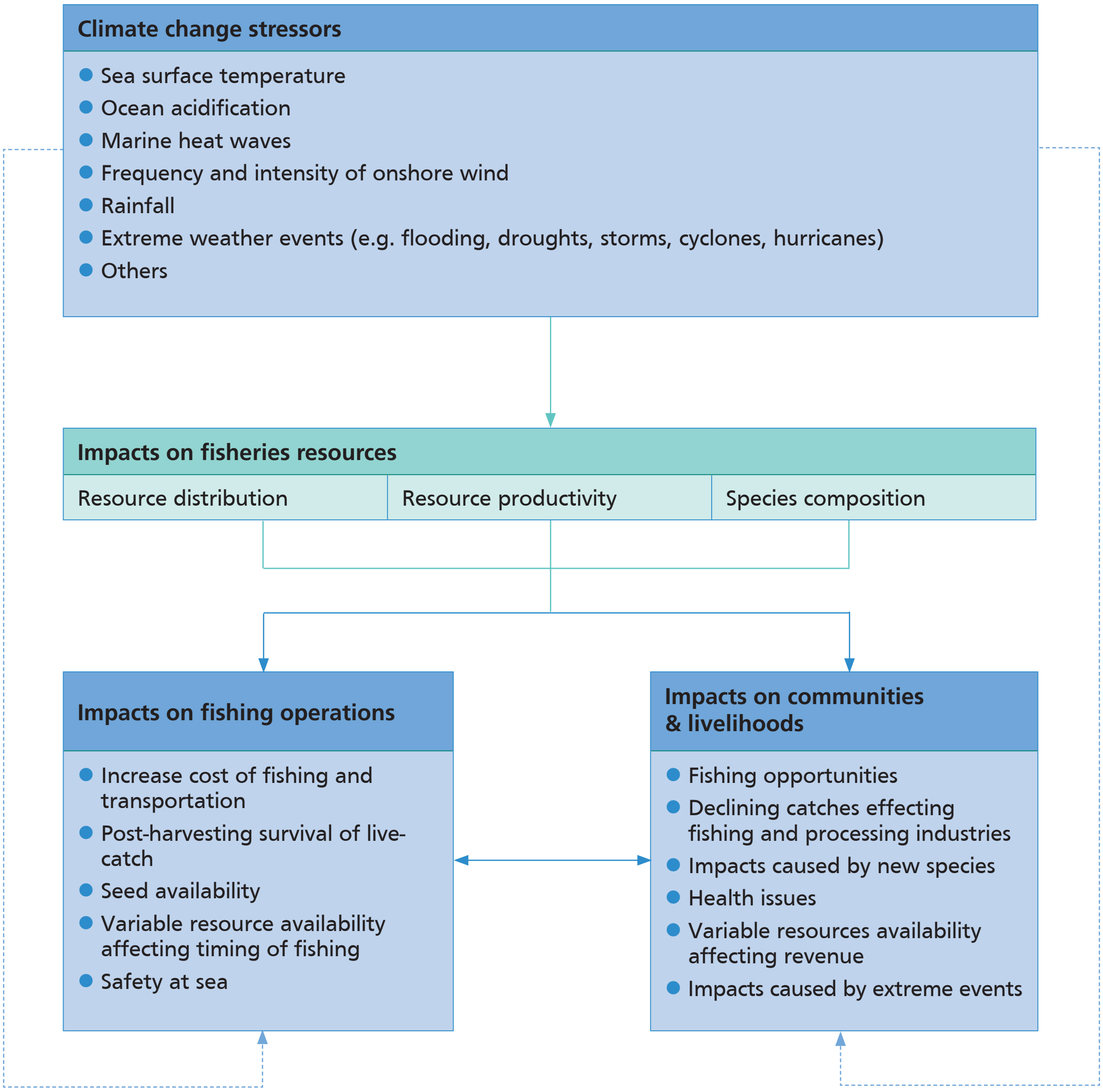


Figure 4. Biophysical changes expected to occur from climate change and examples of the impacts on fisheries resources, fishing operations, communities and livelihoods from the case studies and selected literature. Solid lines represent observed interactions in these examples. The dotted lines show direct impacts that biophysical changes could have on fishing operations, communities and livelihoods that are not presented in the case studies.

4. GOOD PRACTICE CLIMATE ADAPTATION MEASURES

From analysis of the case studies in Part 2 and selected published literature, a total of 15 adaptation measures were identified as meeting the good practice criteria with respect to minimizing the impacts of climate change (Table 4). For each good practice climate adaptation measure, a detailed description is provided in Chapter 3, including a discussion on advantages, tips for implementation, and challenges. To further aid practitioners in understanding the full description of each adaptation measure, examples of practical implementation from the case studies are included in the descriptions of each good practice measure in Chapter 3.

Table 4. Summary of good practice adaptation measures identified from the case studies and selected literature, and the main climate-related impacts on fisheries resources they address.

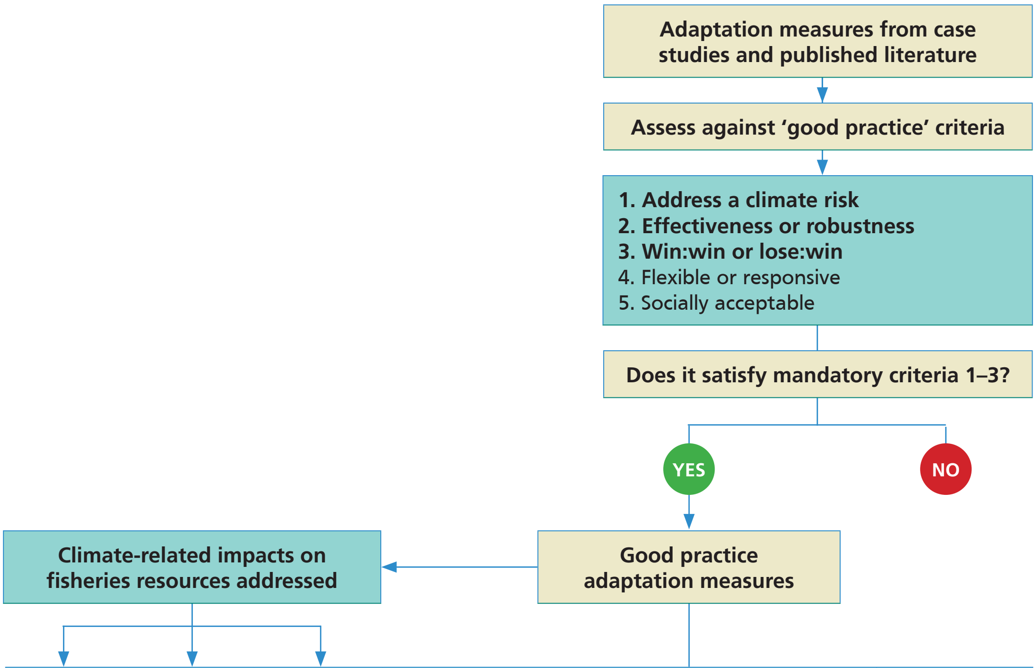
#	Good practice adaptation measure	Reference	Climate impact(s) on fisheries resources addressed	Page no.
1	Enhance monitoring programmes through community-based approaches	Defeo *et al.* (this volume); Fogarty and Pecl (this volume)	Distributional change; productivity change; species composition change	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

Each of these good practice adaptation measures can be linked to one or more of the three climate-related impacts on fisheries resources: (1) distributional change, (2) productivity change, and (3) species composition change. Therefore, these three impacts can serve as practical entry points to guide decision-makers in identifying good practice adaptation measures suitable for local contexts. Note that these entry points may be species- or issue-specific, since different fisheries will face different challenges under climate change. For example, clam fisheries are local, using small vessels close to shore exploiting a resource that normally does not move. If the distribution of clams changes as a result of climate change, putting them beyond the reach of the traditional local communities, then these communities will lose their resource, potentially causing conflicts among communities (e.g. Acheson, 1975). In contrast, human communities in the new distributional areas may have no experience of fishing and no markets for these 'new' species. As a second example, tropical tuna fisheries are conducted by ocean-going vessels that can follow the fish. Such movements will affect access rights, allocation of fishing rights etc. (e.g. Clark *et al.*, this volume). Different management adaptations and strategies will be needed in each of these examples.

A framework to assist fishery practitioners to identify good practice climate adaptation measures, based on the case studies and selected literature, is provided in Figure 5. The framework applies the good practice criteria, providing a means to assess the likely effectiveness and suitability of the adaptation measures and track how the good practices were identified.

These good practice climate adaptation measures should be incorporated into all of the steps of the fisheries management cycle, including planning, monitoring, and assessment (Figure 1). Local technical, human and financial capacities are likely to be key consideration that highlight or limit the choices of appropriate adaptation measures for fishery practitioners. The good practice climate adaptation measures can also be associated with the local management capacity requirements: low (L), medium (M) or high (H). Here, capacity is defined as: 'the minimum resourcing requirements to successfully implement the adaptation measure and includes human resources, financial resources, technical capacity, and/or the need for supporting institutions or entities'. Further guidance is provided to fisheries practitioners by highlighting examples of a range of adaptations that have been applied across different biological, social and governance contexts in response to specific climate change impacts.

Although the framework in Figure 5 relates only to the good practice adaptation measures identified in Table 4, it can also facilitate greater adoption and implementation of good practice adaptation measures in fisheries globally. These measures can be readily updated as stakeholders, user-groups and fishery managers begin to mainstream climate readiness into their activities.



Distribution change	Productivity change	Species composition change	Good practice adaptation measures	Capacity required for implementation
X	X	X	1. Enhance monitoring programs through community-based approached	L
X	X		2. Incorporate environmental variables and risk into fisheries assessment and management advice	H
X			3. Adjust spacial scale of monitoring to be responsive to shifting stocks	M
X	X	X	4. Establish early warning systems for extreme events	M
	X		5. Apply flexible and adaptable fishing seasons	L
X			6. Apply tradable fishing rights/allocations to allow flexibility in response to stocks shifting across international borders	H
	X		7. Close fishery during climate-driven events to support resistance and recovery	L-H
X	X	X	8. Apply in-season management systems that are responsive to rapid climate-driven stock changes	L-H
	X		9. Relocate fishery species to compensate for changes in productivity	H
X	X	X	10. Conserve keystone species complexes to avoid ecological tipping points and related changes in target species abundance	L-M
X	X	X	11. Relocate landing and processing practices	L-H
X	X	X	12. Develop new fishery opportunities to capitalise on distribution shifts or enhances productivity (including for 'new' species)	L-M
X		X	13. Source more diverse supplies of seafood for processing facilities	H
X	X	X	14. Develop new products and markets to maximise fishery value as catches decline	M
X	X	X	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	H

Figure 5. Framework to identify good practice adaptation measures for addressing specific climate change impacts, including: (i) assessing whether adaptation options meet criteria to ensure effectiveness (mandatory criteria 1-3 and beneficial criteria 4-5), and (ii) selecting suitable adaptation measures using the three common climate-related impacts on fisheries resources as entry points. Each adaptation measure is linked to the climate impact it addresses and the level of capacity it requires for implementation – low (L), medium (M) or high (H).

5. RECOMMENDATIONS AND CHALLENGES FOR EFFECTIVE IMPLEMENTATION

The preceding sections provide principles, choices and guidance for fisheries practitioners to select context-specific good practice climate adaptation measures. However, effective and transparent implementation is key to their success. Key guiding recommendations for effective implementation of climate adaptation measures in fisheries are summarized below.

- ***Effective fisheries management*** is the foundation of all climate change adaptations. The case studies where effective fisheries management was lacking show that efforts focused on climate-specific adaptation measures must include the improvement of fundamental fisheries management systems. Without first ensuring that the underlying resilience of the fishery system is supported, specific adaptation measures for climate change are unlikely to be effective. Introducing effective fisheries management as a first step is particularly relevant for regions and fisheries with limited resources and capacity. Many places where effective fisheries management is lacking tend to have low local capacity, including a lack of sustainable resourcing, emphasizing the need for simple approaches that get the basics right. Previous reviews (e.g. Gaines *et al*., 2018) have found that to optimize the resilience of fisheries to climate change, the primary need is to ensure that management frameworks are implemented effectively. However, an underlying theme is also that fisheries management needs to move progressively away from a top-down to a more decentralized management approach that reflects a shared responsibility between local stakeholders and the management authority. One approach that has been successful is the empowerment of relevant stakeholders through co-management and their involvement in decision-making and management processes.

- An ***adaptive and dynamic fisheries management approach*** is required to adjust to environmental variability and to directional climate change. This includes building opportunities for learning and periodic corrections of management systems as new information is incorporated, as well as complete re-evaluation of the objectives and indicators for affected fisheries. Implementing climate adaptation measures is not a one-off event but an iterative process, which includes building on lessons learned from recent and historical events, and is likely to continue over decades as climate change impacts increase and/or emerge. In places where adaptive approaches exist, incorporating tools and processes that speed up the rate of adaptation will be necessary to respond to uncertainty and unforeseen events that will arise due to climate change.

- Regular review of the ***effectiveness of climate-adaptive management measures*** will be needed through repeated/frequent monitoring and evaluation to make improvements and to add effectiveness to fishery management systems. For example, better monitoring to assess changes in life history parameters of fish populations and targeted research and monitoring of climate-related impacts to directly inform management processes are needed to support effective implementation.

- The ***cumulative and synergistic effects*** of climate change and other non-climate drivers need to be recognized. Climate change does not act in isolation but interacts with other drivers, such as pollution, habitat degradation and unsustainable fishing (among others), and these stressors act in a cumulative fashion to disrupt marine ecosystems and the fisheries that depend on them. Monitoring and modelling that is able to identify and quantify the contributions of climate change among other drivers of change is important to inform adaptation targeted at fisheries management, and to identify whether fishing has the dominant effect on the status of a stock. For example, adding fishing to a model of ocean warming and ocean acidification developed for southeast Australia changed the direction and magnitude of the interaction to a synergistic response on biomass (Griffith *et al*., 2012). Such models can include conceptual and qualitative models, which can be particularly useful for systems where the basic relationships between variables are understood but where precise or detailed data are lacking (Dambacher *et al.*, 2009). This will help fisheries management build resilience to future uncertainty and change in the system.

- ***Assessments of fisheries*** that evaluate likely future fishery conditions and identify climate vulnerabilities will be needed to ensure that management goals and objectives are realistic regarding future conditions, and to help prioritize management interventions. This will also enable climate adaptation measures to be targeted to future fish distributions, productivity and species composition under climate change.

- Recognize ***the importance of equity across human gender, race, age and income;*** and how adaptation measures can support and enhance equity. Also recognize the role of equity in helping to ensure stakeholder buy-in and cohesiveness, which is an integral part of adaptation. Individuals and groups with the highest levels of poverty, especially small-scale fishers in developing countries, are frequently among the most vulnerable to climate change. Therefore, climate-related adaptation measures should attend to the particular needs of small-scale fishers, including measures such as livelihood diversification and capacity development (e.g. fisher training).

- Recognize the ***unique role of rights-holders*** in helping to ensure that their access, culture and traditions in relation to fisheries continue into the future. This includes their rights to fish, manage their fishery resources, practise traditional customs, and access the ocean resources of their ancestors. The need to consider fishing rights also extends to other forms of access, for example limited entry permits, individual fishing quotas, and local community-based or co-operative harvesting (e.g. Huppert, 2005).

- Recognize and support the system properties that make a fishery inherently ***resilient to ecological change*** – such as genetic or biological diversity and habitat complexity, among others – and help ensure that fishery management measures minimize disruption to these properties.

Challenges to implementation

A number of challenges remain for effective implementation of climate adaptation measures for fisheries management. There has been slow uptake of climate information into fisheries management systems globally, with limited examples of demonstrated success to date. This highlights the need for the compilation of good practice examples and frameworks, as provided in this report. Many of the challenges to implementing these good practices relate to political will, governance capacity and structures, uncertainty, rights disputes, and inflexible legal frameworks. Some potential solutions developed through consultations with experts and in the literature are provided in Table 5.

Table 5. Summary of key challenges and potential solutions for accelerating greater implementation of climate adaptation measures for fisheries management.

Challenge	Solutions
Political will, including a mismatch in timing between political agendas and climate change	• Evidence of good practice to raise government awareness • Cost-benefit analyses to demonstrate benefits of acting and costs of not acting • Active engagement of relevant stakeholders to generate political pressure for action
Institutional inertia	• Active engagement of relevant stakeholders to generate political pressure for action • Raise awareness in the broader community to pressure politicians for action • Raise awareness that inaction also has costs
Uncertainty in fisheries responses to climate change, appropriate actions, and costs of action or inaction	• Evidence of good practice (e.g. FAO reports) to raise awareness and convince governments • Cost-benefit analyses to demonstrate benefits of acting and costs of not acting • Demonstrate opportunities that exist in the face of these uncertainties
Changes in property rights/ access	• Transnational agreements can facilitate national action • Develop transboundary or multijurisdictional agreements to facilitate regional action • Prevent the occurrence of growing disparity between climate winners and losers • Explicit use of risk-based language and methods to highlight costs and benefits of action
Lack of enabling conditions for collective action (e.g. lack of data, legislation)	• Develop techniques for data-poor fisheries and facilitate their uptake • Develop/apply methodologies for data-poor fisheries stock assessments • Implement long-term management policies (e.g. ecosystem approach to fisheries) • Address inequities within the fishery that prevent the ability of groups to work together
Fishery assessment inertia (often due to lack of data or reluctance to use ecosystem models or other approaches)	• Implement management strategy evaluations and/or bioeconomic approaches where the necessary resources and capacities are available • Raise awareness and promote data-poor fisheries approaches (such as indicator-based) • Tiered classification of assessments to recognize uncertainty around assessments • Research on how to mainstream climate into assessment process effectively for different methods (and the uncertainty involved) to provide guidance
Legal structural change timeframes can be limiting due to time required	• Have actions in policy or regulations which are more flexible than laws • Formulate laws with the flexibility to enable a variety of management responses to climate change, so that the laws themselves do not need to be changed (requires analysis of legal system to prepare and identify obstacles) • Design legal regimes to be responsive to climate-driven changes
Isolation between experts (lack of collaboration and data-sharing)	• Support knowledge exchange and collaboration between disciplines (e.g. biological and social scientists) and fishery sectors • Facilitate a systematic view (so can capitalize on climate winners and minimize losers)
Short planning horizons that limit the ability or desire of stakeholder groups to engage in medium- to long-term climate planning	• Improve status and benefits of fishery so that stakeholders are in improved social and economic conditions and more able to cope with climate-driven changes
Resource limitations for improving the adaptive capacity of fisheries	• Active engagement with the entities that fund climate adaptation (such as the Green Climate Fund, World Bank, Global Environment Facility) to recognize the need for resources to adapt fisheries management

Dealing with issues of scale – for example matching the appropriate scales of the physical environment, the biological system, and the human social and cultural systems, in both time and space – is difficult but crucial for developing climate-adaptive fisheries management (e.g. Perry and Ommer, 2003). McEvoy (1996) notes that 'What a fishery is, descriptively, and what management ought to try to sustain, prescriptively, is an interaction between three variables: an ecosystem, a group of people working (economy), and the system of social control within which the work takes place (management).' This implies there are three distinct features: environmental fluctuations over time and space; species and stock level hierarchies in context with other species in a natural ecosystem over time and space; and the people and institutional hierarchies in time and space that interact with the environment and the species. All three factors are inextricably intertwined, and the development of one is in direct response to the constraints faced by the other two features (McEvoy, 1996). Such issues of matching the appropriate scales for management with those of the environment and fish stock are discussed in the case studies dealing with transboundary management issues (e.g. Clark *et al.*, this volume; Gullestad and Bakke, this volume), but they also apply to single-nation fisheries management (e.g. van der Lingen, this volume). Scale issues need special attention when considering options for developing climate-adaptive fisheries management.

6. FUTURE DIRECTIONS

This chapter proposes 15 good practices to adapt fisheries management to the pressures imposed by climate change. It also proposes a structured framework for selecting which good practice adaptation measures should be considered when addressing specific problems in local contexts. However, the framework is in the early stages of development, and therefore its use is subject to several caveats. These include the limited number of case studies available and therefore the limited number of adaption measures identified, its focus on marine fisheries (including Pacific salmon), issues of transferability (i.e. a particular adaptation measure that worked well in one location may not work well elsewhere), relative costs that may vary from region to region depending on contexts, and the high uncertainty associated with future climate change and the robustness of the proposed adaptation measures (e.g. Watkiss, 2015).

More work is needed to move from 'good practices' to '(normative) guidelines' in climate-adaptive fisheries management. Recommendations that will help this transition are provided below, using a numbered format to facilitate discussion (note the numbers do not imply ordered priority).

1. ***Develop a catalogue of examples***. A catalogue (or database) of examples in which adaptations have been tried and found to be successful, and also examples in which adaptation measures have been tried but found not to be successful, would enable a much more robust evaluation of how these (and additional new) measures function under a wider variety of conditions and contexts. A common template for these examples would greatly facilitate their comparison. The case studies presented in Part 2 followed a template which included the fishery and management contexts, the implications of climate change, the adaptations and lessons learned in the governance, management and stakeholder sectors, and the conclusions. When more case studies become available, they could be analysed using a typology approach to group studies with similar contexts, approaches and outcomes – see for example Guillotreau *et al.* (2018), who developed a response typology for social and governing responses to global changes affecting marine ecosystems. Such a set of good practice climate adaptation measures can be readily updated as stakeholders, user-groups and fishery managers begin to mainstream climate readiness into their activities. Sharing good

practices, extending learnings and building partnerships, particularly among fisheries with low management capacities and resources, will be key to facilitating greater adaptation of fisheries management to climate change.

2. ***Utilize down-scale climate change projections from regional to local scales.*** Information on the potential impacts of climate change on local systems can provide early warnings of the types of impacts for which fisheries management adaptations may be needed. Numerous climate change projections are now available for regional scales (e.g. Barange *et al*., 2018), but in many situations fisheries management occurs on smaller, local scales. Down-scaling projections of climate change impacts, including associated socio-economic scenarios, is needed. This is particularly true of regions with developing economies, and for regions that may be more negatively impacted by climate change. Following from this is the need to identify potential measures relevant to local contexts and climate-related impacts, starting with the case studies and example adaptations in this report but expanding to include additional information as available.

3. ***Focus on developing nations.*** There is an urgent need to understand and meet the specific needs of low-capacity regions for climate-adaptive fisheries management measures. Many of the case studies in this report are from regions with higher technical capacities. Further investigation is needed to understand how well these 15 adaptation measures can be applied to lower capacity regions. This will require assessing the technical and institutional capacity development needs to make fisheries more resilient to climate change.

4. ***Identify enabling conditions.*** Like all management, good practice measures will only be effective when implemented rigorously and appropriately in the local context. Identifying the (local) enabling conditions that help foster and accelerate the development and uptake of climate-adaptive measures, and which address how these enabling conditions can be fostered in a variety of fishery contexts, is a crucial next step in the identification and application of good practices. These enabling conditions will include both social and governance factors, within the natural environmental context. Understanding the local barriers that inhibit identification or application of climate-adaptive fisheries management measures, and their potential solutions, is an important starting point.

5. ***Recognize the roles of synergistic and cumulative effects.*** The focus of this report is on action to address climatic stressors in the fisheries sector. In reality, however, the action/inaction relating to non-climatic stressors and/or events in other sectors are likely to influence the climate resilience of the fisheries sector. Elements of multi-hazard (both climatic and non-climatic stressors) and multi-sectoral (fisheries and other sectors) approaches will be required to increase the climate resilience of the fisheries sector.

6. ***Identify other relevant experiences.*** There will certainly be other experiences than those directly related to fisheries problems and the case studies examined in this report that can be applied to developing climate-adaptive fisheries management measures. These may include local and historical practices that have developed over long periods of time to help human communities adapt to fluctuating environmental (and social) conditions (e.g. Ford, McDowell and Pearce, 2015). These can be evaluated using the fundamental principles described above in Section 2 to assess their utility for climate-

adaptive fisheries. This is a topic that requires the involvement of the social sciences (e.g. Galappaththi *et al.*, 2019).

7. ***Use simple rules-based systems as first-order approaches.*** In situations with under-resourced systems or without established fisheries management, simple rules-based approaches can be used as a start. What these are and how well they work in specific circumstances under climate change is a subject that needs further research.

8. ***Develop a network of practitioners.*** This would be an ideal means to facilitate interactions and the advancement of climate-adaptive fisheries management measures in a variety of circumstances.

9. ***Practise adaptive fisheries management under climate change***. The natural experiments induced by climate change and taking place on a global stage provide ideal opportunities for practising adaptive fisheries management. When things go wrong, management often tries a number of alternative measures and strategies, although if the situation is perceived as a crisis these alternatives can be rushed, haphazard, and poorly conceived and implemented. Recognizing such situations as opportunities for learning, and treating them as practical experiments, would increase their value for adapting fisheries management to climate change. Guidance is needed on how to maximize the information content of such adaptive management experiments, in particular under crisis conditions, and how to better share these learning experiences.

10. ***Inland fisheries.*** These situations require a similar assessment of their climate-adaptive fisheries management needs. Many of the key principles and approaches presented in this report for marine (and Pacific salmon) fisheries will also apply to inland fisheries, as will many of the 15 climate adaptation measures. But which measures to apply, how they might need to be modified, and possible new measures given the different processes at play in freshwater systems (especially small water bodies and rivers), are topics for further research.

7. CONCLUSIONS

Developing climate-adaptive fisheries management systems will require an enhancement of the fundamentals of traditional best-practice management, and new approaches to address the novel features (e.g. directional nature) of many of the impacts that will accompany climate change. For those situations in which management systems are weak, establishing effective fisheries management, including broad participation, and developing precautionary and adaptive approaches are the places to start. Situations with better-developed management systems have a broader range of options for adapting to the impacts of climate change (e.g. Table 4), although the measures selected will need to be appropriate to the specific situation. For example, in international fisheries governance, issues such as changes in management areas and impacts on the allocation of catches among countries may be critical issues; whereas in local fisheries, the critical issue may be adaptation to a change in species composition and development of new markets.

Holsman *et al*. (2019) recognized the problems of spatial and temporal scales of fisheries as an impediment to the successful implementation of climate-resilient management. They argued that regional management tools may not be well suited for managing the same systems under climate change; management policies and climate research studies often occur on mismatched scales; management approaches are poorly adapted to unidirectional change and extreme events; and socio-economic modelling of climate change impacts on fisheries is still developing. They suggested that adaptive and dynamic management approaches are required to address environmental change, and fixed long-term measures are required to address shifting socio-economic and political conditions. Developing climate-adaptive fisheries management systems will require a combination of both these approaches, for example with the measures proposed in Table 4 (and described in detail in Chapter 3 of this volume).

There are several challenges to implementing these good practice climate adaptation measures. These include the need for a compilation of good practice examples, and issues relating to political will, governance capacity and structures, uncertainty, rights disputes, and inflexible legal frameworks. This chapter proposes good practices for developing climate-adaptive fisheries management, under a variety of species, environmental and governance contexts. It represents, however, only a start in developing comprehensive guidelines for climate-adaptive fisheries management. Several recommendations are proposed for the next steps along this path. Foremost among these is the need for further examples and case studies, preferably using a common format to facilitate their comparison. These would make it easier to design specific solutions for specific cases, particularly in relation to the varying geographical scale of fisheries management and the economic structure of the fleets, since these different cases will likely require different solutions.

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Chapter 3: Compendium of measures for adaptive management of fisheries in response to climate change

Chapter 2 of this report described the key elements of good practices in developing climate-adaptive fisheries management. These practices are embedded in the fisheries management cycle, and need to be rooted in effective, participatory, precautionary and adaptive fisheries management systems. Chapter 2 then developed five criteria for identifying good practices from a variety of case studies. Three of these criteria are essential: 1) the adaptation measure has a clear objective to address climate-related risk(s); 2) there is evidence to infer/assess the effectiveness or robustness of the measure; and 3) the measure must ultimately have a positive outcome (win), regardless of the initial cost (loss). There are two additional beneficial criteria: the measure should be flexible/responsive; and it should be socially acceptable.

Applying these criteria to the 13 case studies described in Part 2 of this report and to selected studies in the literature, Chapter 2 identified 15 adaptation measures as being good practices for developing climate-adaptive fisheries management. These 15 measures are not a comprehensive list, but rather a selection of interventions proven to work and produce positive results for marine fisheries, at least in particular situations. In this chapter, a detailed description is provided for each adaptation measure, including a discussion of advantages and tips for implementation, and challenges based on the experiences from the case studies. To further aid practitioners in understanding each adaptation measure, examples of practical implementations from the case studies are included. Technical terms used in the descriptions are defined in the Glossary to Part 1 of this volume. Details of the case studies from which the good practice adaptation measures were selected are provided in Part 2.

ADAPTATION MEASURE #1: ENHANCE MONITORING PROGRAMMES THROUGH COMMUNITY-BASED APPROACHES

Climate impact(s) addressed

- Distributional change
- Productivity change
- Species composition change

Description of the adaptation measure

This adaptation measure involves situations in which the objective is to enhance the spatial and temporal coverage of monitoring due to observed or emerging local climate impacts using community-based approaches. Fisheries stakeholders and communities are frequently engaged in the process of collecting data about their particular fisheries resources. By augmenting traditional fishery-independent information with community-based data collection, the spatial and temporal coverage of monitoring is increased to provide for cost-effective and early detection of climate impacts, including range shifts, extreme events, and productivity changes. This adaptation approach can be incorporated into more formal co-management arrangements (e.g. Gianelli *et al*., 2018; Defeo *et al*., this volume) or 'citizen science' monitoring programmes such as Redmap[1] in Australia (Pecl *et al.*, 2019), which provides broader understanding of distributional changes and better informs climate-related management (Champion *et al*., 2018).

Advantages and tips

This adaptation measure has the capacity to provide cost-effective, higher-resolution monitoring data to develop and inform adaptive management and/or contingency plans for responding rapidly to unexpected climate impacts on the distributions or productivity of target species. This measure also strengthens the relationship and trust between resource users, managers and scientists (Pittman *et al.*, 2019), and is important for taking a joint precautionary management approach. The implementation of this measure should be part of an established co-management arrangement. The formalization of community participation in fisheries monitoring is critical in strengthening local cohesion and empowerment, which underpins greater respect and compliance with management rules. The empowerment of fishers increases their willingness to collaborate in resource and ecosystem monitoring, implementation and management, further enhancing the resilience of fishing communities.

Community-based monitoring is also useful for 1) enabling more extensive data collection, and 2) decreasing management costs for fisheries agencies with limited budgets – an important consideration in developing countries.

Example: Uruguay yellow clam fishery

The Atlantic coast of Uruguay is a global hotspot for accelerated ocean warming (Hobday and Pecl, 2014). After a 14-year closure due to thermal mortality, the yellow clam (*Mesodesma mactroides*) fishery reopened with institutionalized monitoring by fishers as a key factor for detecting fishery changes and strengthening collaboration between stakeholders and managers in the face of climate-driven stressors. Fishers register their activities and report to the management agency through logbooks and voluntary community-based data collection. This allows each fisher to provide fishery data on a daily basis over a broad spatial area to inform management. The interaction among stakeholders has fostered participatory data collection – including ecological, social and economic data – which (1) reduces uncertainty in stock estimates; (2) assesses the relative contribution of different predictors to the short- and long-term dynamics of the fishery; and (3) integrates this knowledge into decision-making processes (Defeo *et al*., this volume).

[1] Redmap is an Australian citizen science project that is mapping and documenting range expansions of marine fish species, potentially due to climate change. See http://www.redmap.org.au.

Challenges

Technical capacity in the fishing community may need to be developed to achieve the reliable and robust data monitoring standards required to inform effective decision-making by managers. This may not be a significant challenge in cases such as Redmap, for example, where photo verification is required along with an expert verification process. The measure also lends itself to an 'early warning system' (e.g. extreme events) as well as detection of longer-term impacts. However, it requires data collection and storage to be supported by appropriate information systems, such as a decision support tool or dashboard that fosters the use of the data to inform adaptive management of the fishery in the face of climate change.

This measure also requires effective and ongoing communication and engagement between fishers, managers and scientists to ensure that the monitoring systems that are established are practical and acceptable.

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ADAPTATION MEASURE #2: INCORPORATE ENVIRONMENTAL VARIABLES AND RISK INTO FISHERIES ASSESSMENT AND MANAGEMENT ADVICE

Climate impact(s) addressed

- Distributional change
- Productivity change

Description of the adaptation measure

Climate change can impact the dynamics of fish stocks in different ways, and consequently it can affect our perception of the status of stocks and the scientific advice needed for management. Sharma *et al*. (this volume) discuss how climate-driven changes in population parameters and fisheries selectivity can act cumulatively and affect the assessment of stocks in relation to thresholds established under assumptions of steady-state or equilibrium conditions. If a reliable and robust relationship can be established between the observed changes in population parameters and environmental factors, this knowledge can be incorporated into the process of stock assessment or harvest control rule settings, and guide the adaptation of management decisions to respond to prevailing environmental conditions. When such a relationship cannot be estimated directly, it is often still possible to address climate risks indirectly by incorporating risk-based decisions into the setting of harvest levels, such as by varying the fishing rate according to changes in biomass indicators (see Kritzer *et al.*, 2019).

A good practice applied in some fisheries relies on the use of empirical methods to determine how fishery production changes with environmental conditions such as temperature, salinity or any climate variable for which data are available. These data can be used in empirical relationships to assess the risks of management decisions under different environmental scenarios. The resulting 'climate change-conditioned' advice shows how fishing pressure on the stock can be adjusted to maintain a similar probability of achieving objectives at the acceptable risk level, given climate change impacts on stock production. By incorporating uncertainty in climate scenarios and in the relationship between fishery production and the environmental variable, a range of possible outcomes can be developed and acceptable fishing strategies derived by applying the predetermined risk level to the distribution of simulated outcomes.

Importantly, this measure improves existing modelling efforts by incorporating environmental change into the evaluation of biological status, and supports within-season management processes (e.g. Grant *et al*., this volume).

Example: Greenland halibut fishery

Greenland halibut (*Reinhardtius hippoglossoides*) is a cold-water, demersal flatfish caught in the Gulf of Saint Lawrence, Canada. The water in the Gulf of Saint Lawrence is uncharacteristically cold for its latitude, and is home to the most southerly exploitable stock for the species. Since 2010, there has been a dramatic increase in the average temperature of the deeper bottom water layer (>200 m). An empirical modelling approach was developed for the Greenland halibut stock in which the relationship of temperature with stock production was approximated and stock biomass projected into the future under various climate scenarios, accounting for uncertainty in population production and temperature variability.

This scenario-based approach enabled the development of risk-equivalent advice under climate change so that the acceptable probability of not achieving an objective was maintained. It also enabled the required reduction in fishery exploitation rate to be determined so that the objective could still be achieved even with climate change (Duplisea *et al*., this volume).

Example: Oregon Coast Northern coho salmon fishery

The Oregon Coast salmon fishery system is comprised of multiple stocks of coho salmon (*Oncorhynchus kisutch*) on the west coast of the United States of America (Oregon), referred to commonly as Oregon Coast northern coho (OCN). These stocks have been managed with high fishing mortality levels, and when ocean conditions changed in the early 1990s the stocks collapsed. A stock rebuilding plan was implemented with an indicator of ocean survival (Marine Survival Index) along with parent spawner abundance. The indicators for survival were determined by a tagging programme run at six sites, and estimated survival of one-year-old fish through a recapture programme. This approach, along with the monitoring of abundance at different sites, provided the basis for target exploitation levels at different stock levels and ocean survival conditions produced by climate-driven processes. The resulting changes are now implemented annually to set targeted harvest rates that are responsive to ocean conditions and climate change, with the aim of preventing the stock from being overfished and to facilitate recovery in the long term (Sharma *et al*., this volume).

Example: California sardine fishery

Distribution and recruitment of the sardine (*Sardinops sagax*) in southern California are almost entirely governed by environmental variations, as exhibited by sea surface temperature (SST). This has led the management authority for the sardine fishery in California to develop a harvest control rule that sets a total allowable catch (TAC) based on ocean conditions. Recruitment models, using SST measured from offshore surveys and the Pacific Decadal Oscillation (PDO) as covariates, have higher predictive power than a model with coastal SST alone, and have been used to set harvest guidelines for this stock (Sharma *et al*., this volume)

Advantages and tips

This measure can be used to develop climate-conditioned advice for a range of situations where a survey index, catch time-series and a climate variable are available. Sharma *et al.* (this volume) provide examples of approaches used in fisheries ranging from relatively data-poor to data-rich situations. This measure can also incorporate a range of possible future climate change scenarios into fisheries decision-making to provide comparative and risk-equivalent advice for developing harvest strategies. It also adds a level of objectivity in providing advice in circumstances where only moderate data are available or as a precursor for more detailed but more demanding modelling approaches.

Simple empirical indicators, such as mean fish length, could also work in some cases to support management advice; and also have the benefit of facilitating community involvement in initiatives with low-cost logbook and fisher-implemented monitoring plans. Given that the majority of the world's fisheries are data-poor, simple approaches are needed. However, for such systems to be effective, a long-term dataset (however coarse the indicator) should form the basis for any action.

Challenges

More complex modelling approaches require substantial data on the fishery, environmental variables and the relationships between them to determine if management objectives can still be achieved under climate change. Climate-conditioned advice can face stakeholder and manager scepticism or distrust, largely due to the uncertainty inherent in the relationships upon which such advice is based, but also the general inability to articulate this convincingly to relevant end-users. Fisheries scientists and decision-makers may need to develop innovative communication strategies to overcome this barrier. The incorporation of local knowledge in the determination and implementation of adaptation measures to climate change can form an important bridge for building trust, especially in co-managed fisheries (see Defeo *et al*., this volume).

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ADAPTATION MEASURE #3: ADJUST SPATIAL SCALE OF MONITORING TO BE RESPONSIVE TO SHIFTING STOCKS

Climate impact(s) addressed

- Distributional change

Description of the adaptation measure

Routine monitoring of fished populations is often used to inform harvest strategies, including annual and seasonal Total Allowable Catches (TACs), to determine the geographic extent of the stock, and for periodic stock assessments. This measure aims to ensure that any monitoring system is responsive to potential range shifts and/or phenological changes in the target species so that appropriate scientific advice is given at the appropriate spatial scale. Such a measure may only require a change in the region of monitoring, or it could entail a more resource-intensive approach, such as increased spatial coverage of monitoring or the complementary collection of environmental data. For example, finer-scale monitoring can be used to better understand, predict and respond to changing abundances and locations of spawning events, while an expansion in the geographic coverage of monitoring can help detect shifts in the locations of target species.

The Bering Sea ecosystem approach to fisheries management is founded on mitigating the adverse effects of climate change and focuses on responses and adaptability at multiple scales (Holsman *et al.*, 2020; see example below). That is, the species being managed is one aspect but stakeholder dialogue, traditional environmental knowledge (from indigenous fisheries) and a whole-of-systems approach help stakeholders prepare for the multi-dimensional impacts that fisheries will face from climate change.

Example: Monitoring the Bering Sea groundfish fishery

The Alaskan Bering Sea groundfish fishery targets walleye pollock (*Gadus chalcogrammus*), Pacific cod (*Gadus macrocephalus*) and rock sole (*Lepidopsetta bilineata*), among other species. These fish stocks have been shifting their geographic extent due to changes in ice cover and sea surface temperature patterns. In recent years, the Alaska Fisheries Science Center has more frequently engaged in a fishery-independent trawl survey of the Northern Bering Sea (an area further to the north than most historic survey efforts) to monitor changes in species distribution and extent as Bering Sea waters warm. Such surveys occurred in 2010, 2017, 2018 and 2019, and documented dramatic changes in species distribution. In particular, there were several-fold increases in the abundance of pollock, cod and rock sole in the Northern Bering Sea region, and an equally dramatic decrease in colder-water species like Arctic cod (*Boreogadus saida*). Data from the Northern Bering Sea surveys are now used within stock assessment models for groundfish, helping ensure that scientific advice is in line with the stock abundance, even as the locations of Bering Sea groundfish stocks move north (Stevenson and Lauth, 2019).

Advantages and tips

This measure is more responsive to changes in stock distributions if it is aligned with environmental data and fishing effort. Therefore, it should involve good cooperation between industry, managers and scientists; which suggests that mainstreaming a more collaborative approach will allow fisheries to be more responsive to future climate-driven changes.

Challenges

This measure is likely to involve higher monitoring costs if the spatial scale of a species' distribution is increased. Further, adopting more cooperative stakeholder approaches to management may also present challenges (e.g. resourcing, political) – but it is nevertheless likely to be beneficial in the longer term.

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ADAPTATION MEASURE #4: ESTABLISH EARLY WARNING SYSTEMS FOR EXTREME EVENTS

Climate impact(s) addressed

- Distributional change
- Productivity change
- Species composition change

Description of the adaptation measure

This measure involves systems or processes that prepare fishers for climate-related changes in the distributions and/or abundances of target species due to severe weather or environmental events such as red tides, sargassum influxes, marine heatwaves and acidic ocean upwelling (see example below). Climate change is bringing extreme environmental conditions that are forecast to continue and can be both short or long-lasting. The use of monitoring systems for early detection of such events can inform appropriate and timely responses by fishers to minimize impacts. For example, for a marine heatwave, fishery managers may invoke pre-agreed management responses, such as adjusting harvest periods, closing the fishery or changing fishing locations. It may also involve greater use of weather forecasting tools by fishers to support decisions on fishing practices, such as postponing trips or changing locations. Early warning systems rely on a finer temporal scale of monitoring than is normally used in fisheries assessments. More frequent monitoring, for example, could be used to better identify changes in the timing of spawning migration runs (e.g. Fraser River sockeye salmon; DFO, 2019).

To date, such measures have been used to provide 1) timely estimates of phytoplankton composition and toxin concentrations (e.g. red tides) so that catches can be inspected effectively before sale to safeguard seafood consumers; and 2) temporary closure of the fisheries with a compensatory extension or reopening to mitigate lost fishing days (Defeo *et al.*, this volume). Other examples include the use of an outlook bulletin to warn fishers of possible sargassum influx events so they can prepare vessels and fishing gear (e.g. Sargassum Sub-regional Outlook Bulletin; Cox and Oxenford, 2019), and a network of ocean buoys that monitor ocean chemistry to detect upwelling-driven acidification events that require changes in harvesting practices for calcifying organisms, e.g. oysters, clams, shrimp, lobster and crab (Dewey, 2019; see second example below).

Example: Uruguay yellow clam

Yellow clam (*Mesodesma mactroides*) in Uruguay experienced mass mortalities during the 1990s due to a shift from a cold-water regime to a warm-water regime, exacerbated by altered wind patterns. Since then the stock has recovered; however its abundance, individual clam size and condition are lower due to the warming waters. Furthermore, unfavourable weather events and an increase in the intensity and frequency of harmful algal blooms (HABs) restrict the number of fishable days. In response, a weekly monitoring programme has been implemented to provide timely estimates of phytoplankton composition and toxin concentrations as early warnings to the local community and to ensure healthy seafood for consumers. These early warnings are used by the fishers to store catches in the certified processing plant to allow continued sales during the banned seasons. Strict inspections of the stored product are carried out to ensure it is safe for consumption.

Also, when HABs occur during the fishing season, the season can be extended or the fishery reopened during the off-season, thereby mitigating the impact of the loss of fishing days. This has been a partially successful adaptive approach to counteract the detrimental effects of climate-driven HABs on the fishery (Defeo *et al.*, this volume).

Example: Pacific oyster fishery and acidification

From 2007 to 2009, shellfish growers in Oregon and Washington State in the United States of America experienced a severe Pacific oyster (*Crassostrea gigas*) seed shortage (75 percent reduction in hatchery production and no wild recruitment), caused by ocean acidification linked to summer deep-ocean upwelling. These corrosive upwelling events are now occurring an estimated 33 percent of the time (11 percent prior to 2007) and are more severe when they occur. Ocean monitoring allows the industry to identify changes in ocean chemistry before mortalities and recruitment failures occur, and to treat hatchery waters to restore larval production. In addition, the industry is expanding or establishing new hatcheries in the state of Hawaii where ocean acidification-related problems have not occurred. In the long term, the industry is exploring selective breeding to develop acid-tolerant oyster larvae and determining whether relocation of juvenile and adult oyster grounds to areas that are projected to have slower and lower magnitude changes in ocean chemistry will avoid growth deformities and mortalities (Cooley *et al.*, 2018).

Advantages and tips

This measure has the advantage of facilitating early detection of potential impacts and the establishment of agreement on appropriate measures to cope with and/or mitigate the potential impact, thereby providing greater certainty to fishers and minimizing impacts on their businesses. The measure can also safeguard fishery catches and seafood consumers from known health threats associated with extreme events.

Challenges

This measure may increase the costs of management through the need for enhanced and routine monitoring of key indicators; access to global, regional or national monitoring data such as ocean observation systems, satellite data or toxicological testing; and timely reporting as an early warning for management and industry. In addition, a system is required to translate monitoring data rapidly to inform management responses.

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ADAPTATION MEASURE #5: APPLY FLEXIBLE AND ADAPTABLE FISHING SEASONS

Climate impact(s) addressed

- Productivity change

Description of the adaptation measure

Enhancing the flexibility and adaptability of a fishery within a fishing season can be thought of as increasing the responsiveness of existing management. This can be delivered through more rapid adaptive management processes, allowing for substantial leeway within co-management arrangements for stakeholders and user-groups to decide how to meet certain management standards or respond to market opportunities. Alternatively it can involve fishery management plans that rely on a framework and standards rather than specific rules. Applying such an approach can help to fine-tune the ways in which closed seasons or seasonal restrictions are put in place, or to facilitate rapid responses to changing environmental conditions, such as through opening and closing fishing seasons in response to favourable or unfavourable environmental conditions. For example, a fishing season may need to be shortened if high sea surface temperatures are causing a spike in the mortality of targeted species. Alternatively, fishing areas may need to be opened or closed quickly to help conserve different species at different life history stages in order to balance harvest and conservation goals. Finally, stakeholders can benefit from this approach if they are given the leeway to time their fishing activities with the period of highest market demand. This latter approach is likely to be effective for fisheries that have high fluctuations in demand and/or market price, and where steady supply is not required for processing facilities or local markets.

Advantages and tips

This measure can help to address both ecological and socio-economic considerations. Economic viability for fishers can be addressed despite seasonal restrictions, and/or the need to set a lower TAC due to changing environmental conditions, by fine-tuning fishing opportunities to market demand.

This measure can also help to deliver greater social acceptability for closures, and provide a buffer for fisheries that are naturally variable in terms of demand and/or market price, maximizing economic benefits with similar effort. Ecological considerations can be addressed by rapidly responding to deteriorating or changing oceanographic situations, thereby helping to maintain stock health over the long term.

Example: Uruguay yellow clam

The yellow clam (*Mesodesma mactroides*) fishery on the Atlantic coast of Uruguay experienced a 14-year closure due to significant temperature-driven mortality, which caused a long-term interruption in the supply of the product for market consumption. As a result, commercial channels opened to frozen product imports (e.g. congeneric surf clam *Mesodesma donacium* from Chile) to fulfil the demand. Once the fishery reopened, and in order to re-enter the market and meet local demand while sustainablly targeting a lower standing stock of yellow clam, a suite of management measures were implemented. These included seasonal restrictions with the harvest season open during summer to coincide with the highest product demand from tourist resorts, which maximizes the value of the fishery despite the short season. Further, seasonal flexibility was introduced to respond to the increasing frequency of HABs (see example under Adaptation measure #4) (Defeo *et al.*, this volume).

Challenges

There is a potential risk that, if demand is not met with regular supply, particularly for processing facilities or local markets, consumers will source a similar product elsewhere. Consumer campaigns to raise awareness about the natural variability in supply and the viable choices that are locally produced can help mitigate this effect while stimulating alternative fishing opportunities (Adaptation measure #12).

Selecting a fishing season that coincides with high market demand and/or price may not be suitable from an ecological or sustainability perspective (e.g. if it is also a spawning season), and these trade-offs should be considered. There is also a risk that greater flexibility in the management system can result in a movement away from sustainability principles if it is not monitored carefully.

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ADAPTATION MEASURE #6: APPLY TRADABLE FISHING RIGHTS/ ALLOCATIONS TO ALLOW FLEXIBILITY IN RESPONSE TO STOCKS SHIFTING ACROSS INTERNATIONAL BORDERS

Climate impact(s) addressed

- Distributional change

Description of the adaptation measure

The implications of climate change for the distribution and demography of shared stocks require improved management. This needs to be multi-jurisdictional and cooperative, and must incorporate climate scenarios. In the development of management regimes for shared fish stocks, the definition of some form of fishing rights, such as quotas or effort allocation, is key (e.g. Environmental Defense Fund, 2018). In general, stock distribution or zonal attachment should have an important impact on agreements on allocation. To be robust, the allocation arrangements need to take potential variations in stock distributions into account. For instance, in the Northeast Atlantic, changes in the distributions of pelagic stocks (e.g. Northeast Atlantic mackerel, *Scomber scombrus*; Gullestad and Bakke, this volume) made previously agreed allocation arrangements obsolete. However, in the tropical Pacific, an effort allocation scheme negotiated among Parties to the Nauru Agreement (PNA) countries has given enough flexibility to ensure that the Parties have access to fishing opportunities even with climate-driven changes in tuna distributions (see Box below).

This adaptation has been used as a formal collaborative measure for multiple jurisdictions (members) that share a migratory transboundary fisheries resource. The measure generally requires all members to jointly agree that fishing effort, defined in terms of fishing days or some other metric, is limited to an annual total allowable effort (TAE), set within the broader range of measures for conservation and management of the stocks that takes into account advice from scientific and technical experts on the management of the species targeted by the fishery (WCPFC, 2015). This advice may be linked to climate-related changes and/or predictions for changes in stock distributions. The TAE is then allocated to each Party as Party allowable effort (PAE), an effort limit for fishing in the exclusive economic zones (EEZs) of each member country. These limits are agreed on a regular cycle (e.g. annual or every two years) and recognize the need of fishing members to maintain their net economic returns from the sustainable use of traditional fisheries resources under a changing climate, while allowing for gradual identification of alternatives for those countries that will not have access to the resources in the medium to long term.

Example: Tropical Pacific tuna fishery Vessel Day Scheme

The eight Pacific Island countries that are the Parties to the Nauru Agreement,[2] together with Tokelau, manage the largest multispecies tuna fishery in the world (Aqorau, 2009). These Small Island Developing States have developed a system to manage fishing effort, known as the Vessel Day Scheme (VDS). The system is an effective adaptation to the impacts of climate variability (i.e. El Niño Southern Oscillation [ENSO]) on the distribution and abundance of tuna within their combined EEZs. The VDS limits purse-seine fishing effort, defined in terms of fishing days, to an annual TAE. The TAE is allocated among the eight sovereign PNA members as a set of PAEs, based largely on recent effort histories. Tokelau has a separate TAE/PAE that is adjusted in relation to changes to the PNA TAE. Parties can trade PAE days, and use a range of other VDS provisions, to adapt to the effects of ENSO on tuna distributions. For example, during La Niña events, skipjack tuna (*Katsuwonus pelamis*) shifts its distribution towards the west of the region, and PNA members located there can buy days from those in the east. The converse occurs during El Niño episodes. The VDS ensures that the benefits of this fishery, which underpin the economies of many of the PNA members, can be distributed equitably, regardless of where the fish are caught. The allocation of PAE is a non-confrontational adaptation to the climate-driven redistribution of tuna, based on an agreement between countries with clear and negotiated rules (Clark *et al*., this volume).

Advantages and tips

This measure allows member jurisdictions to maintain their net economic returns from the sustainable use of the fisheries resources within their EEZs while providing flexibility to respond to climate-driven distributional or phenological shifts. The approach protects the sovereign rights of members, enabling them to implement sustainable fishing limits without bearing a disproportionate burden, and ensures that responsible fishing practices occur throughout the species' distribution. This measure also provides for equitable access to transboundary stocks for member nations, regardless of national fleet size, economy or capacity.

Challenges

This measure requires a formal legal agreement between nations and regular oversight meetings to ensure the trading scheme is effectively implemented. Effective monitoring of the scheme is required to ensure compliance by all member nations and to evaluate its success. This requires a mix of information-sharing, including sharing of electronic monitoring data, and internal oversight and external review processes.

Also, potential issues may arise if climate-driven redistribution of fish stocks results in a proportion of the resources moving from the combined EEZs of member countries to high-seas areas and EEZs of non-member countries in a way that significantly reduces the capacity of the participating countries to control the fishery (SPC, 2019). This might require the extension of the arrangement to allow other countries to participate to maintain its effectiveness.

[2] Federated States of Micronesia, Kiribati, Marshall Islands, Nauru, Palau, Papua New Guinea, Solomon Islands and Tuvalu.

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ADAPTATION MEASURE #7: CLOSE FISHERY DURING CLIMATE-DRIVEN EVENTS TO SUPPORT RESISTANCE AND RECOVERY

Climate impact(s) addressed

- Productivity change

Description of the adaptation measure

This management intervention has been used in response to extreme events, sometimes associated with mass mortalities, such as marine heatwaves and regime shifts from a cold to a warm regime (e.g. Defeo *et al.*, this volume). It may also be used where productivity changes reduce population sizes and their resilience to fishing, or as a tool where effective fisheries management is lacking. In some cases, it may be a necessary measure to support stock recovery. Variations in the use of this measure by fisheries managers could include effort reductions or spatial/temporal closures to protect the spawning stock.

Critical to the success of this adaptation is the early identification of extreme events, or early detection of changes in abundance of target species (preferably using pre-recruit surveys). It also requires flexible harvest strategies with rapidly-implementable control rules to minimize the effects of fishing on poor recruitment and protect the spawning stock. Early management interventions require managers, researchers and industry to work together to establish the systems and flexible harvest strategies necessary to respond quickly to climate-driven events – which are projected to become more frequent in the future.

Example: Western Australia scallop, crab and abalone fisheries

An extreme marine heatwave affecting 2 000 km of the Western Australian coast in 2011 resulted in significant impacts on ecosystems and fisheries. This area is an identified global marine hotspot (Hobday and Pecl, 2014). After the heatwave, scallop (*Amusium balloti*) fisheries in the Abrolhos Islands and Shark Bay were closed for three to five years, and the Shark Bay blue swimmer crab (*Portunus armatus*) fishery was closed for 18 months and introduced lower catch quotas once it reopened. This quick action was made possible by the annual trawl surveys designed to predict future catch, which revealed record low recruitment following the heatwave. Subsequently, these fisheries have shown some recovery due to better protection of spawning stocks and improved environmental conditions. Roe's abalone (*Haliotis roei*) on the mid-west coast also suffered catastrophic mortality and the spawning stock remains very low: restocking is being considered. The Perth abalone stock, which was located south of the main heatwave area, also decreased significantly but the fishery remained open with reduced catch quotas. Lessons after seven years demonstrate the value of early identification of the heatwave event through environmental monitoring frameworks such as the Integrated Marine Observing System[3] (IMOS), its effect on fisheries through fishery-independent pre-recruit surveys, and having flexible harvest strategies to facilitate early management responses to enable stock recovery (Caputi *et al.*, 2016, 2019). The current harvest strategy now includes more frequent monitoring surveys that inform annual catch as well as within season reviews that enable even more responsive action to be taken if conditions necessitate this.

[3] For more information, please see http://imos.org.au.

Example: Marine heatwave in the northeast Pacific

A widespread marine heatwave (from Alaska to Baja, California) occurred in the Northeast Pacific in 2014–2016, with sea surface temperatures more than three standard deviations above normal. These very warm conditions limited the supply of nutrients to coastal waters, reducing the productivity of the food web and changing community composition across multiple trophic levels, drove changes in species distributions, and also resulted in a coastwide harmful algal bloom (HAB). This created ecosystem disruptions that had significant impacts on the fisheries and communities that rely on the marine resources of the Northeast Pacific. These disruptions included closures of valuable salmon fisheries due to elevated mortality levels in adults and fry, and a delayed opening of crab fisheries primarily driven by the HAB and its potential health impacts for consumers. Initially, small-scale fisheries were disproportionately impacted with flow-on economic losses to their coastal communities. Management actions in response to these heatwave-driven impacts on fisheries included a disaster declaration so that response options could be implemented, changes to marine spatial planning and funding to fisheries for short-term mitigation actions. The quick management response is likely to have mitigated the more negative possible impacts (Bograd *et al*., 2019).

Advantages and tips

Given a flexible and responsive management framework, this measure has the ability to protect fishery stocks from potentially irreversible impacts due to climate-induced changes. It is a potentially drastic measure with immediate impacts on fishery actors and so is likely to be more appropriate for extreme events such as marine heatwaves. Under a co-management framework with a pre-agreed harvest strategy, the measure can also provide some level of certainty for industry participants, and act as a safeguard for the fishery and the industry in the long term.

Challenges

Closure of a fishery can have sudden and significant impacts on fishers and the wider community, economically and socially. Diversification, co-management approaches and pre-agreed management interventions can help to mitigate these impacts. Therefore, planning and preparation for such circumstances requires resources and may be costly, likely needing the significant support and involvement of institutions. Further, the necessary monitoring and associated systems to first detect the potential impacts of climate change (e.g. commercial catch data collection, storage and reporting) also require planning and provision of finance for implementation.

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ADAPTATION MEASURE #8: APPLY IN-SEASON MANAGEMENT SYSTEMS THAT ARE RESPONSIVE TO RAPID CLIMATE-DRIVEN STOCK CHANGES

Climate impact(s) addressed

- Productivity change
- Distributional change
- Species composition change

Description of the adaptation measure

To cope with uncertainties in stock assessment and management advice some fisheries adopt an 'in-season' management approach that allows decisions regarding fishing rates (TACs, effort) on the basis of the best available information during the season. This measure, which has been used for instance in the Canadian Fraser River sockeye salmon (*Oncorhynchus nerka*) fishery (Grant *et al.*, this volume), provides a flexible and adaptive management system that reacts in a timely manner to changes in environmental conditions affecting the stock (e.g. Caputi *et al.*, 2019). The implementation of this system requires a framework, with supporting policies and legislation, that facilitates responsive management and that acknowledges the uncertainty associated with the effects of climate change and other stressors on resource abundance and productivity. While this measure promotes an adaptive management approach, it is the capacity for management to be flexible and responsive to rapid and unexpected changes that is important.

This measure explicitly considers environmental uncertainty and large-scale environmental fluctuations that can drive rapid stock changes, and is applicable for stocks that are relatively short-lived, have multiple variable recruitment events that occur within a year, or where the size of exploitable populations is not well known before fishing begins to occur. It involves the use of near-real-time observational data to inform frequent stock assessments, thus facilitating timely responses to rapid spatio-temporal changes that occur in the fishery, allowing a better balance between economic (e.g. attainment of TAC) and ecological (e.g. sustainability of the population through the protection of juveniles) objectives. The use of near-real-time direct observations is critical to being able to quickly adapt management measures to any departure from the assumptions used for stock assessments and adjust the allowable harvest accordingly.

Example: Peruvian anchoveta environmentally-responsive TAC

Peruvian anchoveta (*Engraulis ringens*) is a highly valuable commercial fishery managed as two stocks within Peru's EEZ – north-central and southern, and a shared stock with Chile. Currently, Peru produces more than 50 percent of the global production of fish meal (exporting 1 million tonnes) and 33 percent of fish oil (exporting 100 000 tonnes) (Fréon *et al.*, 2014), with a total value over USD 1 billion (PRODUCE 2018). There is also an artisanal fishery that harvests anchoveta mainly for direct human consumption. Hundreds of thousands of people in Peru are employed directly in the fishery and indirectly in processing. Management of this fishery is data- and resource-intensive, with a comprehensive integrated monitoring approach. It uses remote and in situ methods to collect and use multiple data sets to generate multiple stock and environmental parameters. These are used to conduct regular stock assessments and inform the TAC for each of the two fishing seasons in a year.

This is done through a partnership of managers, scientists and fishers who participate in the monitoring. Extensive in-season monitoring is also carried out. The mixing of juveniles with adults occurs during ocean warming events, resulting in increased catches of juveniles and compromising fishery sustainability. In response, a juvenile TAC is imposed and, once reached, the fishery is closed. Alternatively, areas with a high incidence of juveniles are temporarily closed to fishing. This is possible through the use of electronic monitoring of catches (including juveniles), which provides real-time information to managers, giving them the capacity to respond rapidly with a range of options (Oliveros-Ramos *et al.*, this volume).

Example: Canadian Fraser River sockeye salmon

The Fraser River in western Canada historically supported the largest abundance of sockeye salmon (*Oncorhynchus nerka*) in the world. Currently, however, the levels and survival rates of these iconic populations are exhibiting concerning declines, coinciding with dramatic changes in their marine and freshwater habitats. These are among the most intensely managed salmon fisheries in Canada, and are a priority for stock assessment and fisheries management. For this reason, scientists and fisheries managers are starting to incorporate the effects of environmental change into advice and processes. Stock recruitment models are conducted at multiple time-scales to reflect changes in the stock and environment. In particular, these models are used to: (a) produce pre-season catch forecasts required for pre-season fishing plans, (b) develop biological benchmarks to assess status, and (c) evaluate escapement goals. The assessment timelines allow for consideration of rapid climate variability and impacts on the allowable harvest (Grant *et al.*, this volume).

Advantages and tips

This measure establishes a dynamic management system with agreed management actions that facilitates timely responses to climate-driven stock changes, including unexpected and/or rapid ones. This type of approach will be increasingly necessary as the impacts of climate change accelerate in future years, and can be a successful measure to address multiple climate-related impacts. It is best suited to dynamic fisheries with fast-growing species or those with more than one spawning peak, where change in the stock occurs quickly. This measure also has utility during intense climate events (e.g. marine heatwaves), where additional assessments can be conducted to update the information used for management advice on a TAC.

Challenges

This measure will generally require a high level of capacity, be costly to develop and implement, and have intensive data requirements to function effectively. Nevertheless, in some areas where capacity is limiting, it should be possible to implement simplified management frameworks that allow flexibility and responsiveness while also collecting robust data.

Determining the timescales for conducting assessments requires a fundamental understanding of the system and the relationship between the stock and environmental drivers. Also, models rely on good data and stock-recruitment relationships, which are challenged by stock declines and variability in stock abundances.

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ADAPTATION MEASURE #9: RELOCATE FISHERY SPECIES TO COMPENSATE FOR CHANGES IN PRODUCTIVITY

Climate impact(s) addressed

- Productivity change

Description of the adaptation measure

This measure is a stock rebuilding approach to promote recovery and improve productivity. It will be most effective after abundance has declined below critical levels in parts of the range of a species due to climate change, where there is a large gradient in survival and growth rates within the distribution of a stock, and where there are long distances between regions with large differences in environmental conditions. When translocations of animals are made from areas of slow growth to areas of high growth, production is enhanced and the potential for increases in catch-per-unit-effort (CPUE) improves. This measure is a direct intervention in adapting to climate change; and when combined with appropriate TAC limits it can result in extra biomass for a region, not just catch.

Advantages and tips

Species relocations from low-growth (less suitable) to high-growth (more suitable) regions can benefit ecosystem health by increasing the biomass of declining stocks. This adaptation measure will increasingly have application as conditions become less suitable under climate change in some locations and more suitable in other locations.

Example: Tasmanian Rock Lobster Translocation Program

The Rock Lobster Translocation Program supports stock rebuilding efforts on the Tasmanian east and west coasts (DPIPWE, 2019) in Australia, and also helps control a recent climate-driven invasive species, the long-spined sea urchin (*Centrostephanus rodgersii*). Translocation of southern rock lobsters (*Jasus edwardsii*) from deep-water (low-growth) locations to inshore shallow-water (high-growth) locations has been shown to increase lobster growth, and has merit for increasing the productivity of the fishery (Chandrapavan *et al*., 2010). From 2015–2018, 145 000 lobsters were translocated in this program (DPIPWE, 2019). This initiative is a direct intervention for adapting a fishery to climate change. The additional lobster numbers are 1) resulting in extra biomass for a productive region; and 2) increasing the predation of long-spined sea urchins which feed on macroalgae, providing important habitat for lobsters (Fogarty and Pecl, this volume).

Challenges

As a direct intervention, this measure can be resource-intensive (time and funding) and requires knowledge of suitable growth regions for the species being moved. Further, these locations will likely need to be reviewed over time as climate conditions continue to change.

This type of measure is focused on relocations within the range of a stock, or in keeping with the climate-driven expansion of the range of a stock to avoid any issues relating to genetic diversity or the introduction of species into new environments, potentially altering the receiving ecosystem dynamics (e.g. affecting predator-prey relationships).

There is also a biosecurity risk with the potential for biotoxins, viruses and diseases to be introduced, and decision-makers may want to conduct a risk assessment to control movement between areas. Although this measure will likely have increasing merit in the future, it is a costly and resource-intensive option and the above challenges have the potential for serious consequences. Therefore, it should only be used as a measure when conditions for a stock, or portion of the stock, become extreme. Further, the measure would benefit from the development of best practice guidance, similar to species introductions in aquaculture.

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ADAPTATION MEASURE #10: CONSERVE KEYSTONE SPECIES COMPLEXES TO AVOID ECOLOGICAL TIPPING POINTS AND RELATED CHANGES IN TARGET SPECIES ABUNDANCE

Climate impact(s) addressed

- Distributional change
- Productivity change
- Species composition change

Description of the adaptation measure

Climate change can result in stress on marine ecosystems, causing them to tip into a different state. The new state may be less productive and/or result in a loss of desired target species and fishing opportunities. In coral reef systems, for example, ecological shocks and warming waters can promote the growth of macroalgae that are detrimental to reef-building corals, leading to a loss of habitat, food sources, biological diversity, and overall system productivity. Grazers like parrotfish keep the growth of such macroalgae in check, helping to counteract the effects of climate change and retain overall reef system productivity and diversity (e.g. Hughes *et al.*, 2007). In this case, the measure responds to specific objectives and uses harvest control rules that result in a relatively high abundance of herbivorous fish species to counteract some of the effects of climate change on coral reef systems to maintain productivity and availability of target species. Similarly, Ortiz *et al.* (2013) used ecosystem models to define more holistic keystone species complexes comprising groups of important functional species or species groups, to inform the design of fisheries management, especially for multi-species fisheries. However, this is still a more theoretical approach.

Advantages and tips

Natural marine systems are productive and sustain populations of diverse species. Sustaining this productivity and diversity can make the overall reef system, and the associated fishery opportunities, resilient to the effects of climate change.

Example: Bonaire reef recovery and herbivorous fish conservation

In Bonaire (Dutch Caribbean), a series of disturbances in the late 2000s altered the health of local reef ecosystems, changing the composition from a system with healthy mature coral colonies, large proportions of juvenile corals and low macroalgae growth, to one characterized by coral bleaching, a low number of juvenile corals, and a high cover of macroalgae. In 2010, fishing for parrotfish (Family Scaridae; herbivorous fish species) was banned, resulting in a sharp increase in populations of these species over a period of several years. The increase in parrotfish reduced the abundance of macroalgae, helping the coral reef ecosystem to recover from bleaching events and fostering growth of juvenile corals (Steneck *et al.*, 2019).

Challenges

Many species identified as keystone species may already comprise important local fisheries, resulting in socio-economic impacts to fishers and industries. Further, the complexities and uncertainties of the inter-relationships of different species and trophic levels mean it is challenging to accurately identify keystone species and/or the effects of protecting some species more than others. The effect of this measure can also be difficult to convey to stakeholders due to the series of complex relationships that exist between conservation of one species group and the health of others. A lack of stakeholder buy-in due to these complex relationships can hinder the uptake and implementation of this approach.

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ADAPTATION MEASURE #11: RELOCATE LANDING AND PROCESSING PRACTICES

Climate impact(s) addressed

- Distributional change
- Productivity change
- Species composition change

Description of the adaptation measure

This adaptation measure has been used as a viable option for landing and processing catches in non-traditional locations during periods when local conditions affect the product quality. For example, product landed as live catch during periods of higher than average temperatures, heavy rainfall or rough seas, can compromise the survival and condition of the animal. The relocation of landing and processing practices may also be in response to changes in resource distributions, which may involve travelling longer distances to land catches, and potentially require upgraded or new infrastructure to land and process catches in alternative locations as future conditions change. Climate-ready infrastructure (e.g. vessels, landing facilities, canneries) or practices (e.g. disaster response plans) are examples of potential adaptations. Projections of future climate conditions can help identify suitable locations for landing and processing facilities, where environmental conditions are expected to remain within the optimal range. This type of adaptation will particularly benefit fisheries operating in global marine warming hotspots that are experiencing accelerating impacts of changing ocean conditions (Hobday and Pecl, 2014). This type of adaptation measure may be applied during short-lived extreme events, seasonally due to changing climate averages, or over the longer term as a result of permanent future shifts in species distribution.

Example: Southeast Australia rock lobster fishery

Southeast Australia is a global marine hotspot (Hobday and Pecl, 2014) experiencing accelerated ocean warming. As a result, many southern rock lobster (*Jasus edwardsii)* fishing operators have changed their landing locations so that they unload their live catches in areas with cooler water. This helps to minimize the impact of warmer waters on catch survival and/or quality, and thus catch value. Similarly, some lobster fishers are avoiding landing their catch at ports in times of heavy rain, because freshwater in the surface layer increases lobster mortality (Pecl *et al*., 2019; Fogarty and Pecl, this volume).

Example: South African small pelagic fishery

The second most valuable fishery in South Africa is the industrial-scale small pelagic fishery, which mostly takes sardine (*Sardinops sagax*) and anchovy (*Engraulis encrasicolus*). Changes in west coast and south coast nearshore water temperatures, and in upwelling and ocean circulation, have altered the relative distributions of both sardine and anchovy, resulting in the epicentre of sardine catches moving further east on the south coast. The outcome for the fishery has been increased costs, because processing facilities were located on the west coast. The response was to expand sardine offloading and canning facilities to areas of the south coast, with additional infrastructure identified as needed for anchovy processing for human consumption (van der Lingen, this volume).

Advantages and tips

The main advantage that this adaptation offers is to maintain the benefits of existing fisheries to communities and economies, particularly for high-value fisheries or where local benefits are relatively high. In addition, this adaptation measure provides the potential to develop new landing and processing facilities with subsequent social and economic benefits in those locations (noting the need to avoid maladaptations such as destruction of coastal habitats as new facilities are built, or negative social impacts that are possible as a new industry is established).

Challenges

Potential challenges for this adaptation measure include the loss of benefits from traditional landing and processing areas, and increased costs due to greater travel distances by fleets to new landing sites. Such challenges may require changes to vessel size and fuel capacity, and fishing grounds (e.g. van der Lingen, this volume). Upgrading or building new landing and processing facilities in locations that are projected to remain more environmentally optimal in the medium to long term would also incur increased financial costs.

Biosecurity risks also need to be considered, with the potential for biotoxins, viruses and diseases to be introduced to new areas via additional or new vessel movements. To evaluate such risks, managers can conduct a risk assessment for movements of catch between areas.

This adaptation measure may also create additional pressure to increase fishing effort (to recoup costs or via expanded technological capacity). It therefore needs to be applied in combination with other management actions to ensure long-term fishery sustainability.

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ADAPTATION MEASURE #12: DEVELOP NEW FISHERY OPPORTUNITIES TO CAPITALIZE ON DISTRIBUTIONAL SHIFTS OR ENHANCED PRODUCTIVITY (INCLUDING FOR 'NEW' SPECIES)

Climate impact(s) addressed

- Distributional change
- Productivity change
- Species composition change

Description of the adaptation measure

As climate change alters the distribution and productivity of marine species, there may be opportunities to target new or emerging fisheries, including for species that extend their ranges to enter areas for the first time and then increase in abundance due to the favourable environmental conditions created by climate change. While these changes in species distribution and productivity will impact traditional fisheries, and the 'new' species can damage habitats and outcompete the existing species, they may also create opportunities to target additional and potentially abundant stocks. Diversifying the number of target species to take advantage of the change in species composition could enable fishers to maintain catches and livelihoods, thereby making them more resilient to continued climate change. For example, distributional shifts in small pelagic species in South Africa have created a new fishery targeting mesopelagic species, previously only taken as bycatch species in low quantities (van der Lingen, this volume).

Additionally, catching multiple species reduces variability in revenue for vessels and communities. Targeting new species can also help control or reduce their abundance in stituations where they adversely affect the stocks of existing high-value species and/or habitats. Examples include the introduction of a recreational competition to catch non-native pufferfish in the Mediterranean (Gücü *et al*., this volume), the new fishery developed in Tasmania for the non-native long-spined sea urchin (Fogarty and Pecl, this volume), and replacement of the traditional flyingfish fishery in the eastern Caribbean with almaco jacks in years of high climate change-induced sargassum influxes (Ramlogan *et al*., 2017). Establishing developmental fisheries can also focus on expansion or greater targeting of species that are traditionally caught as bycatch or only occasionally caught when productivity is high.

Example: Tasmanian developmental urchin fishery

In partial response to the significant impacts that the long-spined sea urchin (*Centrostephanus rodgersii*) is having on the Tasmanian marine environment and local fisheries, the abalone (*Haliotis rubra, H. laevigata*) industry and Tasmanian Government have jointly introduced an Abalone Industry Reinvestment Fund (AIRF). The AIRF is an allocation of AUD 5.1 million (USD 3.5 million) over five years through fees collected from abalone licence holders and government input. The funds have been invested into recovery of abalone stocks, subsidizing harvest of the long-spined sea urchin for commercial markets, and technology development and monitoring of these fisheries and ecosystems (DPIPWE, 2019). One solution has been to develop markets for sea urchin roe for human consumption and introduce a new fishery targeting the species. These measures are expected to help balance the ecosystem by reducing the extent 'urchin barrens' are produced by the grazing of this species. This new fishery resulted in 560 tonnes (more than 1.5 million individuals) of long-spined sea urchin being removed from the east coast of Tasmania in 2019, which has helped the habitat in that area to recover (Pecl *et al.*, 2019; Fogarty and Pecl., this volume)

Example: South African round herring and lanternfish fishery

The South African small pelagic fishery is a multi-species fishery that targets sardine (*Sardinops sagax*), anchovy (*Engraulis encrasicolus*), round herring (E*trumeus whiteheadi*) and lanternfish (*Lampanyctodes hectoris*). The sardine population has been depleted, with the biomass estimated by the 2018 pelagic survey as the third-lowest since monitoring began in 1984. There has also been a noticeable eastward shift of the stock since the mid-1990s. In contrast, anchovy and round herring populations are presently abundant, and lanternfish are rarely exploited (DAFF, 2016). A cautious interpretation of 35 years of environmental and catch data suggests that climate change-driven enhancement of the trophic environment for anchovy and round herring has led to larger populations for these species. In response to these changes, management, together with the fishing industry, has initiated an increase in the current low exploitation levels on round herring and is further developing the fishery for the mesopelagic lanternfish. Experimental midwater trawling for small pelagic and mesopelagic fishes in 2010 and 2011 resulted in good catches of lanternfish during winter and successful processing of this species into export-quality fishmeal and oil (van der Lingen, this volume).

Advantages and tips

This is a responsive measure that capitalizes on alternative opportunities in terms of targeting species that are (or will be) experiencing distribution and productivity changes due to climate change. These may be new species that have shifted their distribution or local species that have not been targeted historically. This type of adaptation measure can also help control, reduce or take advantage of populations of new species, thereby reducing any negative impact on existing habitats and fisheries or creating new harvesting opportunities. Better utilization of alternative fishery resources can help to maintain livelihoods and food security into the future as some traditional fisheries resources decline due to climate change. Encouraging fishers to diversify is also likely to make them more resilient to these changes.

Challenges

For new fisheries there is the need to establish sustainable harvest levels for long-term sustainability of stocks. This is often a time-consuming and costly exercise and presents a potential barrier to the sector rapidly changing practices to target different species. Support and financial resources are likely to be required for trialling methods and/or gears, or purchasing vessels to target new and emerging fishery species in determining whether they are commercially viable, and in developing a basic understanding of the stock.

Maladaptation is also a possible unintended outcome when new fishing opportunities are not managed correctly. An example of this risk comes from the development of the Rapa whelk (*Rapana venosa*) fishery in the Black Sea, which required the intervention from fisheries authorities to address impacts on benthic communities (Gücü *et al*., this volume). Similarly, conflict may arise between sustaining a new fishery (e.g. for sea urchin fishers) and achieving desired environmental objectives (e.g. reducing sea urchin abundance to protect habitat). In addition, conflict may arise between fishers of an emerging stock who will want to protect their resource and other fishers who want to maintain habitat condition.

Another possible maladaptation is when vessels targeting new species introduce increased pressure on resources that are already overexploited through bycatch, exacerbating the problem of overcapacity. Whenever possible, the repurposing of existing vessels should be considered a priority option when developing new fisheries. Conversely, support may be required for fisheries to transition away from species that have become more vulnerable. Another important consideration is that the capacity for different fishery sectors to diversify their catch will differ between and within fishery sectors, rights holders and locations. These factors should be carefully assessed before progressing with this measure.

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ADAPTATION MEASURE #13: SOURCE MORE DIVERSE SUPPLIES OF SEAFOOD FOR PROCESSING FACILITIES

Climate impact(s) addressed

- Distributional change
- Species composition change

Description of the adaptation measure

Climate-driven distributional shifts and declines in productivity of fisheries can compromise the supply of seafood for processing facilities, including canneries, threatening local economies, employment and domestic food security. This measure aims to address this issue by sourcing more diverse supplies of seafood for canneries and other types of processing facilities, such as frozen imports, alternative local target or bycatch species. The measure can be temporary to fill a short-term gap due to a climate event (e.g. marine heatwave or storm), seasonal to meet annual variation in local supply, or permanent to maintain the viability of processing facilities as local stocks and catches decline over the long term.

Advantages and tips

This type of measure can help to maintain contributions of seafood businesses to local economies, employment and food supply under climate-driven distributional shifts of target species and productivity declines. It also provides potential opportunities for new markets and seafood products, both locally and internationally.

Challenges

As highlighted in the South African case study (van der Lingen, this volume), care must be taken to avoid potential maladaptation, such as processing imported fish that pose pathogen risks, or producing lower-value seafood products that are more difficult to market. Such risks may be managed with relevant risk assessment and mitigation approaches.

Example: South African sardine cannery

Climate-driven changes in resource abundance of sardine (*Sardinops sagax*) in South Africa have reduced supply to local canneries. To maintain the operation of these enterprises, employment and the supply of fish to meet local demand, frozen sardine are being imported and round herring (*Etrumeus whiteheadi*) is now being canned for human consumption. Frozen sardine have been imported into South Africa for over a decade, with 56 000–71 000 tonnes imported per anum between 2010 and 2014 from countries where Pilchard herpesvirus occurs. This poses a realistic risk of infecting local stocks and necessitates an expanded pathogen-import risk assessment (Macey *et al.*, 2016). Round herring is presently canned only in limited quantities because demand is not high and it costs 15 percent more than canned sardine because round herring is not (yet) considered a basic foodstuff and hence is not zero-rated in terms of value-added tax (VAT) as sardine is (Benguela Current Commission, 2019). Despite these challenges, cannery operations have been maintained with minimal loss of income or jobs (van der Lingen, this volume).

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ADAPTATION MEASURE #14: DEVELOP NEW PRODUCTS AND MARKETS TO MAXIMIZE FISHERY VALUE AS CATCHES DECLINE

Climate impact(s) addressed

- Distributional change
- Productivity change
- Species composition change

Description of the adaptation measure

This adaptation measure focuses on innovation in product development and marketing as the uncertainty in traditional resource availability increases due to changing distributions and productivity induced by climate change. It can include a refocus on target species, and a transition away from low-value fisheries products (e.g. bait or fishmeal) to high-value, value-added and high-quality seafood products (e.g. fillets for human consumption) to increase the benefits throughout the value chain. This diversification of products is aimed at maximizing economic yield from the fishery, thereby providing greater resilience under the uncertainty of climate change impacts.

Example: New markets for the South African anchovy fishery

The South African small pelagic fishery targets multiple species, including sardine (*Sardinops sagax*), anchovy (*Engraulis encrasicolus*), round herring (*Etrumeus whiteheadi*) and lanternfish (*Lampanyctodes hectoris*). Some species (e.g. sardine) are sold for human consumption as fillets or canned, while anchovy and round herring are traditionally reduced to fishmeal and oil. As mentioned in Measure #13, cautious interpretation of 35 years of data suggests that climate change-driven enhancement of the trophic environment for anchovy has led to a positive population response while sardine populations are presently depleted. The population of anchovy has increased since 2 000 due to the influence of stronger summer upwelling on recruitment. Fisheries management is taking advantage of this increasing abundance by developing new higher-value anchovy products (e.g. fillets, dried) for human consumption, and promoting markets for these products, to make up for losses in sardine production (van der Lingen, this volume).

Example: New marketing strategy for yellow clams in Uruguay

The yellow clam (*Mesodesma mactroides*) fishery in Uruguay has gone through different commercialization phases. The product was originally marketed at low prices as bait for sport fishing. When the fishery reopened in 2008, after a 14-year closure, fishers diversified the market with support of government and academia to commercialize fresh products for human consumption in gastronomic restaurants. The transition away from 'bait-destination' towards 'high-quality seafood products' for human consumption was evident not only in the price paid to fishers, but also in the societal valuation of the product. This shift in market strategy maximized economic benefits to the local community, particularly under an adverse scenario of low standing stocks, a narrow fishing season, and unfavourable and pressing environmental conditions (Defeo *et al*., this volume).

Advantages and tips

This proactive measure provides greater industry resilience through diversification and maximizing economic benefits. Unit prices can be set, or a minimum price agreed upon before each fishing season (Defeo, 2015), which can help to avoid conflicts and external intermediaries (e.g. wholesalers or retailers) trying to increase their share of the net income. As well as the economic benefits, this measure has social value associated with local pride and identity for the communities providing a higher-quality product (Gianelli *et al.*, 2015). Development of new markets is often associated with government support programmes, but options are available for industry-focused activities, such as adding value through certification and technological developments to improve the quality of fish in fishing operations (Boonstra *et al.*, 2018).

Challenges

Flexible management frameworks are needed to allow for increased variability in resource abundance. This should include data-driven harvest strategies for species for which new target markets are emerging to avoid overexploitation and ensure long-term sustainability. Management should also be able to provide support and resources required to establish and expand interest in local or international markets for new products and to 'sustain' fishers as the markets are promoted.

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Adaptation measure #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

Climate impact(s) addressed

- Distributional change
- Productivity change
- Species composition change

Description of the adaptation measure

Insurance is a risk-transfer mechanism that provides financial compensation for loss or damage caused by events beyond the control of the insured, including natural and human-caused disasters (Martinez Gutierrez & Van Anrooy, 2020). Insurance services enable fishers to replace and repair their fishing assets after damage and losses from an extreme event, recover their business faster, get compensation in case of crew injuries or loss of life, and can provide increased access to institutional credit and investment. Insurance can encourage investments into safety of vessels and crew, more sustainable climate-smart fisheries practices, and improved technologies.

A specific type of climate risk insurance, which focuses on providing protection against extreme weather events, is parametric or weather index insurance. This type of insurance – commonly used in agriculture – is being tested in the fisheries sector in the Caribbean (CCRIF, 2019) and Pacific regions. Unlike traditional insurance, index-based insurance contracts pay out if the actual measurement of the index (e.g. sustained wind speeds and direction for a given period) during the insurance contract period moves above an agreed index point. The index is created based on time series of reliable weather data, and settlement of claims takes place according to a pre-agreed scale of payment (Tietze & van Anrooy, 2019). Actual loss or damages to assets are thus not considered, and are not being measured or compensated. Weather index insurance avoids costs associated with risk assessment, loss adjustment and indemnity, which results in overall lower product costs.

There are a range of options available to this measure, and it could involve the use of a 'cooperative-commercial' model to provide incentives for members of the cooperative to reduce losses from climate events or impacts through better management practices.

Example: China capture fishery insurance scheme

In China, a weather index-based insurance scheme (i.e. using wind speed and temperature) was developed for seaweeds, mitten crab (*Eriocheir sinensis*) and bivalves. China's central and local governments subsidized 40 to 80 percent of the premium depending on the local government's financial resources. China has a mature commercial and mutual insurance infrastructure which supported implementation. The China Fishery Mutual Insurance Association used its national outreach network in major fishing provinces to promote the scheme. China's commercial insurers used well-trained field operatives, and relied on the expertise of fishery cooperatives in risk identification and assessment. The scheme demonstrated technical and economic efficiencies in administration, reduced insurance fraud, and provided effective compensation for affected fishers. The scheme is suitable for risks that are the direct result of climate variability and change (FAO, 2017).

Advantages and tips

Insurance services for the maritime sector and agriculture are widely available in most countries. Insurance of production assets (e.g. fishing vessels, freezers, ice machines, hatchery equipment) and infrastructure is provided by well-established systems of insurance brokers, insurers and re-insurers. This adaptation measure builds on proven successful and recently piloted schemes to insure fishery and aquaculture assets against climate-driven extreme events (flood, drought, storms, cyclones, heatwaves), biological impacts (diseases, pests, harmful algal blooms), and chemical changes (acidification, salinization of freshwater).

Another benefit is that this adaptation measure empowers fishers and fisheries managers to participate actively in risk reduction and management. While disaster relief funds can be very beneficial they can be prohibitively expensive for some governments. Insurance schemes, a type of risk-sharing approach instead of a disaster relief fund, provide opportunities for a public-private investment partnership between government, commercial insurers, fisher organizations and value chain actors. This reduces the burden of costly disaster relief, recovery and rehabilitation for government agencies. Public-private partnership investments that contribute to insurance access for fishery businesses include climate-smart and precautionary practices and infrastructure, such as safe and secure fishing ports and landing sites, safety training for fishers, disaster reduction plans for fisheries, seaworthiness and safety inspection of fishing vessels, proper registration of vessels and their values, and implementation of vessel marking systems. These measures can reduce risks and make insurance services more affordable for small-scale fishers as well.

Challenges

Worldwide over 85 percent of fishing vessels are not covered by insurance services, and those vessels insured are generally large- and medium-scale in developed countries (Van Anrooy *et al*., 2009). Small-scale fishers' access to insurance services tends to be limited. Challenges in increasing access of small-scale fishers to insurance include, for instance, limited knowledge of fishing operations and demand for insurance by fishers, low profitability of fishing vessel insurance (high transaction costs, small premiums, high monitoring costs), lack of insurance mandates for fishing vessels, and few well-functioning fisher cooperatives that can act as insurance agents. Other challenges are that awareness levels of insurance advantages are low among small-scale fishers, the lack of insurance providers active in fishing communities, available insurance premiums are regarded as too high, insurance policies and claim settlement processes are neither understood nor trusted by the fishers, and because of seasonality of fishing and therefore income, they would require more flexible premium payment arrangements than are provided by the insurance sector. On top of these challenges the limited financial literacy among small-scale fishers, and the fact that many do not have bank accounts, are major barriers to increase insurance access for these fishers (Tietze & Van Anrooy, 2019).

Many of these challenge can be addressed through the introduction of well-designed insurance products and awareness raising and capacity building campaigns that suit the needs of the fishery sector and particularly small-scale fishers. However, while fisheries insurance products offered by commercial insurers to the industrial fishing fleets are generally profitable, the establishment process of insurance for small-scale fisheries often requires government support and an enabling policy and legal framework.

Digital innovations, such as mobile money, together with the wide use by fishers of smart-phones, is rapidly making insurance access easier. The recently initiated 'Global Network for capacity building to increase access of small-scale fisheries to financial services' (CAFI SSF Network) brings together key financial and insurance institutions to promote, develop and facilitate capacity building, knowledge exchange, advocacy and awareness; share experiences of good practices; and provide support and advice to stakeholders to increase access of small-scale fishers to adequate financial services (FAO, 2019).

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Glossary

Acclimation: process of an individual organism adjusting to a gradual change in its environment, such as increasing temperature.

Adaptation: process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate harm or exploit beneficial opportunities. In natural systems, human intervention may facilitate adjustment to expected climate and its effects.

Adaptation measure: a type of action or management response to actual or predicted adverse impacts or beneficial opportunities as a direct or indirect consequence of climate variability or change.

Adaptive capacity: ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences.

Adaptive management: a systematic process for continually improving management policies and practices by learning from the outcomes of previously employed policies and practices.

Aragonite saturation: levels of dissolved calcium carbonate in the ocean that are available for calcifying organisms (e.g. corals) to build their skeletons as they grow.

Artisanal fishing: traditional fishing involving households (as opposed to commercial companies), using a relatively small amount of capital and energy, relatively small fishing vessels (if any), making short fishing trips, close to shore, mainly for local consumption.

Autonomous adaptation: adaptation that does not constitute a conscious response to climatic stimuli, but is triggered by ecological changes in natural systems and by market or welfare changes in human systems. Also referred to as spontaneous adaptation.

Biomass: total weight of a group (or stock) of living organisms (e.g. fish, plankton) or of some defined fraction of it (e.g. spawners), in an area, at a particular time.

Calcification: process by which calcium carbonate is precipitated to form hard crystalline materials that make up the skeletons of many marine organisms (e.g. corals, molluscs).

Capacity: the minimum resourcing requirements to successfully implement an adaptation measure and includes human resources, financial resources, technical capacity, and/or the need for supporting institutions or entities.

Capacity building: practice of enhancing the strengths and attributes of, and resources available to, an individual, community, society, or organisation to respond to change.

Climate change: a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods (United Nations Framework Convention on Climate Change) (see climate variability).

Climate variability: variations in the mean state and other statistics of the climate (such as the occurrence of extremes) on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes in the climate system, or to variations in natural or anthropogenic external forcing (see also climate change).

Coastal fisheries: harvesting of fish and invertebrates from inshore marine habitats to a depth of 50 m, as well as pelagic fish caught in nearshore waters within 10 km of the coast.

Co-management: government and fishery user groups share responsibility for the management and utilization of fisheries resources, with the goal of achieving a balance between economic and social goals, within the framework of preserving the ecosystem and fisheries resources.

Commercial fisheries: harvesting of fish and invertebrates for the purpose of making or intending to make a profit. Commercial fisheries often involve large-scale industrial fishing fleets but may also include small-scale fisheries that target species exclusively for export.

Data poor fisheries: fisheries characterized by (a) uncertainty in the status and dynamics of the stock or species, (b) uncertainty in the nature of fishing (e.g. in terms of fleet dynamics and targeting practices), and/or (c) having only basic or no formal stock assessments.

Demersal fish: species of fish that live close to the ocean floor and in this instance are strongly associated with specific habitats, such as coral reefs (e.g. groupers), seagrass meadows (e.g. mullet) or mangroves (e.g. milkfish).

Destructive fishing: fishing activities (e.g. bombs, derris root, cyanide) that rapidly deplete both target and non-target species, and also contribute to habitat degradation, further increasing the likelihood of overfishing.

Ecosystem Approach to Fisheries (EAF): an approach to fisheries management and development that strives to balance diverse societal objectives, by taking into account the knowledge and uncertainties about biotic, abiotic and human components of ecosystems and their interactions and applying an integrated approach to fisheries within ecologically meaningful boundaries. The purpose of EAF is to plan, develop and manage fisheries in a manner that addresses the multiple needs and desires of societies, without jeopardizing the options for future generations to benefit from the full range of goods and services provided by marine ecosystems.

El Niño–Southern Oscillation (ENSO): abnormally warm ocean climate conditions, which in some years affect the eastern coast of Latin America (centred on Peru) often around Christmas time. The anomaly is accompanied by dramatic changes in species abundance and distribution, higher local rainfall and flooding, and massive deaths of fish and their predators (including birds). Many other climatic anomalies around the world (e.g. droughts, floods, forest fires) are attributed to consequences of El Niño. The two phases, El Niño and La Niña, are the major source of interannual tropical climate variability characterized by periodic variations evolving over 12-18 months.

Entry point: the step or component of a management cycle or process that is amenable or ‘receptive’ to an action being taken.

Extreme event: a weather (or climate) event that is rare at a particular place and time of year. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g. drought or heavy rainfall over a season).

Fish stock: exploited portion of a fish population.

Fisheries management: the integrated process of information gathering, analysis, planning, decision-making, allocation of resources, and formulation and enforcement of fishery regulations by which the fishery management authority controls the present and future behaviour of interested parties in the fisheries, in order to ensure the continued productivity of the living resources.

Fishing mortality at MSY (FMSY): the level of fishing mortality, or intensity of exploitation, that results in the maximum sustainable yield (MSY) being reached.

Geographic range: spatial extent where a species lives. For marine organisms, a distinction must be made between geographical locations that constitute the normal or permanent range of the species, versus locations where it is a 'vagrant' and infrequently found or fails to establish a permanent population.

Good practice climate adaptation measure: an adaptation option that meets all mandatory 'good practice' criteria. The description of the measure should also describe the actual management action and the outcome it is aiming to achieve.

Introduced (exotic) species: species living outside its native distributional range, which has arrived there by human activity, either deliberate or accidental. Some introduced species are damaging to the ecosystem they are introduced into, others have no negative effect and can in fact be beneficial – for example, as additional fisheries species.

Invasive species: introduced species that spread within the habitats they invade, creating adverse environmental, social or economic effects by disrupting habitats or through negative interactions with other species.

Life cycle: period involving all the different stages of a species through reproduction/birth to death, a period from one generation of organisms to the next generation.

Maladaptation: failure to adjust adequately or appropriately to the environment or climate, often an unintended consequence of responding to a climate impact that does more harm than good.

Management strategy evaluation (MSE): a tool that scientists and managers can use to simulate the workings of a fisheries system and allow them to test whether potential harvest strategies ¬– or management procedures – can achieve pre-agreed management objectives.

Maximum sustainable yield (MSY): highest theoretical equilibrium yield that can be continuously taken (on average) from a stock under existing (average) environmental conditions without affecting significantly the reproduction process.

Mitigation (of climate change): human intervention to reduce the sources or enhance the sinks of greenhouse gases (GHGs).

Net primary production: accumulation of energy and nutrients by green plants and by organisms that use inorganic compounds as food. The majority of primary production in marine or aquatic systems is performed by phytoplankton, which are tiny one-celled algae that float freely in the water.

Nursery habitats: distinct habitats used by newly-settled or juvenile life-stages of marine organisms before they move and recruit to habitats occupied by adult individuals.

Ocean acidification: reduction in the pH of the ocean over an extended period (typically decades or longer) caused primarily by the uptake of atmospheric CO_2. Changes to pH associated with ocean acidification lead to major changes in the carbonate chemistry of seawater, which together with the decreasing pH may have implications for a wide number of marine organisms and ecosystem processes.

Overfishing: generic term used to refer to the state of a stock subject to a level of fishing effort or fishing mortality such that a reduction of effort would, in the medium term, lead to an increase in the total catch. Often referred to as overexploitation and equated to biological overfishing, it results from a combination of growth overfishing and recruitment overfishing and occurs often together with ecosystem overfishing and economic overfishing.

Pathogen: a biological agent that causes disease or illness to its host.

Pelagic species: organisms that live near the surface or in the water column of coastal, oceanic and lake waters and are not dependent on bottom habitats or habitats at the water's edge.

Phenology: relationship between biological phenomena that recur periodically (e.g. development stages, migration) and climate and seasonal changes.

Phase-shift: fundamental and persistent changes in ecosystem state, which indicates a lack of resilience (e.g. the archetypal phase-shift on coral reefs involves declines in the abundance of habitat-forming corals and marked increases in the abundance of macroalgae).

Phytoplankton: tiny one-celled algae that float freely in the water, and consume nutrients and light energy to produce biomass. In particularly nutrient-rich conditions (including eutrophication) phytoplankton blooms may occur and can be toxic.

Planned adaptation: a coordinated decision, based on an awareness that conditions have changed, or are about to change, and that action is required to return to, to maintain or to achieve a desired state.

Post-larval fish: fish that have undergone transformation from the larval form to the very first stages of juvenile or adult form.

Primary production: assimilation of energy and nutrients by green plants and by organisms that use inorganic compounds as food. The majority of primary production in marine or aquatic systems is performed by phytoplankton, which are tiny one-celled algae that float freely in the water.

Primary productivity: rate at which energy is stored (i.e. the amount of energy fixed in a given time) by photosynthetic and chemosynthetic activity of producer organisms (chiefly green plants) in the form of substances which can be used as food materials. Much primary productivity in marine or aquatic systems is made up of phytoplankton, which are tiny one-celled algae that float freely in the water.

Recruitment: process by which juvenile marine organisms effectively join the adult population. For species which utilize distinct nursery habitats, recruitment relates to the stage at which individuals leave the nursery habitat and start living in habitats or locations occupied by adult individuals of the same species.

Reference point: estimated value derived from an agreed scientific procedure and/or model, which corresponds to a specific state of the resource and of the fishery, and that can be used as a guide for fisheries management. Reference points may be general (applicable to many stocks) or stock-specific.

Representative Concentration Pathways (RCPs): set of scenarios of anthropogenic forcing used to assess and forecast future possible changes in the climate system. These scenarios simulate possible ranges of heat or radiative forcing values in the year 2100, relative to pre-industrial values. They include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs) and aerosols and chemically active gases, and are based on socio-economic assumptions (possible future trends, e.g. population size, economic activity, lifestyle, energy use, land use patterns, technology and climate policy), which provide flexible descriptions of possible futures.

Resilience: the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain the same essential function, structure, identity and feedbacks. A resilient ecosystem resists damage and recovers quickly from stochastic disturbances.

Sea-level rise: changes in the height of the ocean as a result of changes in its volume. Human activities that have driven increased global temperatures have resulted in an accelerating rate of sea-level rise due to thermal expansion and the addition of water from melting glaciers and other landlocked ice bodies.

Sea surface temperature (SST): water temperature close to the surface of the ocean; 'surface' generally refers to depths of less than 5-10 metres.

Spawning biomass at MSY (SBMSY): level at which the spawning biomass of a fish stock will fall if the maximum sustainable yield is harvested on a continuous basis.

Subsistence fishing: harvesting of fish and invertebrates to meet basic food requirements without any surplus for trade.

Surplus production yield curves: surplus production is the difference between production (growth and recruitment) and natural mortality. Surplus production represents the amount a population biomass will increase in the absence of fishing, or the amount of catch that can be taken while maintaining the biomass at a constant size. The yield curve is generated at different levels of biomass and the corresponding catch that maintains the biomass at that level.

Sustainable: a practice or approach that is environmentally non-degrading, technologically appropriate, economically viable and socially acceptable and that insures the long-term viability of a managed natural resource-based system.

Time-scales:

Operational: day-to-day operations.

Tactical: within-season to annual decision-making.

Strategic: multi-year and longer periods of management.

Thermal optima: range of temperatures in which individual performance (e.g. growth, reproduction, movement) is maximized.

Translocated species: species that have been transported within their natural distribution to establish populations in new habitats.

Unsustainable: a practice or approach that is environmentally degrading, non-technologically appropriate, not economically viable and not socially acceptable and that does not insure the long-term viability of a managed natural resource-based system.

Upwelling: upward movement of cool and nutrient-rich sub-surface waters towards the surface often leading to exceptionally rich areas. There exist various types of upwelling. For fisheries, the most important type is the wind-induced coastal upwelling where the upward movement is a consequence of wind stress (along shore) and Eckman transport (offshore).

Vulnerability: propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts including sensitivity or susceptibility.

Chapter 4: Biological reference points within the context of climate change

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Summary

To demonstrate the potential consequences of climate change on fisheries assessments, we developed a simple age-structured model that shows scenarios of how hypothesized elements of the model might change due to changes in productivity, carrying capacity, life history or fishery selectivity. The implications of these changes on derived assessment reference points for management, yield and population persistence are presented using a tuna stock as an example. Fisheries interact with these changes and can adversely affect the long-term viability of these stocks under the influence of climate change. We develop a simulation framework to assess limit reference points under different climate scenarios, and how they may affect the species we manage. Using cumulative distribution functions to assess frequency of events, we demonstrate hypothesized situations where climate change could affect the resiliency of the species. Finally, we describe examples of fisheries that attempted to take into account the uncertainties in productivity in a changing environment to make management systems more robust to climate change.

Introduction

Fisheries and wildlife managers (Kuhn, 1996) perceive that nature is in balance, even though ecologists have been questioning this perception for several decades (Egerton, 1973; DeAngelis and Waterhouse, 1987). Stability has been searched for in metrics ranging from the collective biomass of communities to species densities or relative abundances. Individual populations seldom adhere to or even cycle regularly around equilibrium abundances (Connell and Sousa, 1983; Tilman, 1996). Although population stability may increase when ample resources are available to younger life stages but are limited to adults (in theory; Mueller and Huynh, 1994), species persistence may stabilize at large spatial scales due to several hypothesized steadying mechanisms (DeAngelis and Waterhouse, 1987), and in some studies the collective biomass of the community was shown to be more or less constant (Rodriguez, 1994; Tilman, 1996; Doak *et al.,* 1998). Regardless, most research suggests that it may be more reasonable to conceptualize individual populations as fluctuating stochastically within bounds (Connell and Sousa, 1983). The density-dependence we observe with respect to mortality and natality in some species (e.g. Beverton and Holt, 1957; Ricker, 1975) implies there is a carrying capacity which defines the upper bound.

However, within the context of a changing environment, these equilibria or stochastic bounds can change or come to different stable equilibriums, and it is difficult to assert that changes have occurred until after the fact, e.g. North Atlantic cod (Frank *et al.,* 2005). Consequentially, due to changes in the ecosystem in a changing environment, stocks can experience changes in productivity, carrying capacity, growth, natural mortality and distribution (Pankhurst and Munday, 2011). These have obvious implications on equilibrium reference points and dynamic equilibrium yields like MSY.

In order to determine whether a stable state change has occurred, we would need to examine the stock dynamics under the influence of natural variation, and observe whether we see a pattern that deviates from a long-term pattern. If a change has occurred then the ability of the system to adapt is key; in order for a stock to remain resilient under a changing climate regime, the management system would need to adapt quickly if the resource were to be properly utilized. For instance, the definition of the lower bound or threshold abundance below which a population cannot return within a reasonable amount of time is often used as a limit reference point for management decisions. This limit must be robust to the changing environmental conditions. Setting thresholds too low limits future production and yield and can expose populations to greater risk of extinction; setting thresholds too high unduly limits harvest. Understanding how long it takes for populations to recover from low abundances, and that recovery cannot be defined as adherence to equilibrium, will help managers and resource stakeholders set limits on the extent to which populations can be exploited.

The approach presented here takes into account these ideas of stochastic variation around some equilibrium points, and the underlying consequences of fishing at rates that are near optimal for a hypothetical stock. We develop a simple model to illustrate these points, under different hypotheses, discuss the consequences of these changes, and illustrate solutions being used in different fisheries to address this issue in management advice.

Simulation model used

A standard age structured model was used:

$$N_{a+1,t+1} = N_{a,t}(1-u_t v_a)s_a \quad \text{for } a>1,\ a<n \qquad \text{eq. 1}$$

$$N_{n,t+1} = \left(N_{n,t} + N_{n-1,t}\right)(1-u_t v_n)s_n \quad \text{for } a = n \qquad \text{eq. 2}$$

$$E_t = \sum_a N_{a,t} f_a \qquad \text{eq. 3}$$

$$N_{1,t+1} = g(E_t) \qquad \text{eq. 4}$$

Where the functional forms of the stock-recruitment relationship described in eq. 4 are given in eq. 8, 9 and 10 below. The only difference is that process error is used, and has some auto-correlation built in it, so equation 4 is modified to

$$N_{1,t+1} = g(E_t)e^{\varepsilon} \quad \text{where } \varepsilon \sim \sigma^2 N(0,1) \qquad \text{eq. 5}$$

Auto-correlation in the process error term is defined as

$$\varepsilon_t = \phi\varepsilon_{t-1} + (\sqrt{1-\phi^2})\varepsilon_t \text{ where } \varepsilon_t \sim \sigma^2 N\left(0,\sigma^2\right) \qquad \text{eq.6}$$

$$C_t = \sum_a u_t v_a N_{a,t} w_a \qquad \text{eq. 7}$$

Where

$N_{a,t}$ number of individuals age a time t
u_t fraction harvested time t
v_a vulnerability to fishing age a
n oldest age considered
s_a survival from natural mortality
E_t spawning biomass time t
f_a egg production age a
g recruitment function (B/H, Ricker etc)
C_t biomass of catch
w_a mass at age a
ϕ is the autocorrelation term, and can be between 0 and 1.

Estimating risk of falling below safe population thresholds

The probability π_i that a stock would meet the criterion of being below a safe threshold (threshold below which the stock cannot recover within reasonable time) in a given year i can be estimated with the simulation approach presented here. These simulations would:

1) be based on an estimated stock-recruit relationship (which can change due to climate change);
2) be stochastic with variation in:
    2a) process error (i.e. variation in true recruitment strength due to biotic or abiotic processes, which can get larger due to climate change);
    2b) maturation and selectivity rates;
    2c) harvest rates; and
    2d) measurement error in estimates of future spawning biomass.
3) have an optimal fishing mortality, as estimated using stable state assumptions of the age structure of the stock;
4) have many iterations;
5) be robust to initial conditions; and
6) evaluate spawning biomass levels and associated probabilities of occurrence.

Note that in the simulations we are only varying process error on recruitment, as growth, maturation and selectivity rates are assumed constant over time. Changes to these parameters as a consequence of climate change will be demonstrated, but they are not stochastic in nature. Fishing mortality is varied and is a specified management control. Finally, in the simulation developed we assumed spawning biomass could be estimated perfectly, i.e. without observation error. However, stochastic variations within bounds could be introduced on all these variables.

Average harvest rate (F) in each simulation is set to the estimated optimal rate to be consistent with the management goal of MSY, which can be estimated using equilibrium assumptions. Influence of initial conditions on the simulations is reduced by disregarding results from earlier iterations (a ‘burn-in’ period).

The probability π_i is estimated from the remaining iterations (N 'years' in the simulations) by dividing the number of years in which the criterion was met (n events that show the stock goes below a threshold) by N. While this calculation ignores that 'years' in each simulation are not independent, this dependence should be inconsequential with large numbers of iterations. Figure 1 is a graphical representation of the results of a series of such simulations of an optimally fished stock across a spectrum of spawning biomass levels.

With one modification, simulations as described above can represent trajectories expected when climate change drops productivity, thereby implying overfished stocks. If all other factors are as before, including the average harvest rate, overfishing can be simulated by reducing the density-independent parameter (α, defined below) in the estimated stock-recruit relationship.

Remembering that overfishing occurs with a reduction in productivity (this can be one adverse effect of climate change), a reduction of κ (x100%) in productivity is represented as a change in eq.9:

$$N_{1,t} = \frac{\alpha S_{t-1}}{\beta + S_{t-1}} \qquad \text{eq. 8}$$

Where

$$\alpha = \frac{4hR_0}{5h-1} \qquad \text{eq. 9}$$

and $\beta = \frac{B_0(1-h)}{5h-1}$ eq. 10

Where h is steepness (base case h=0.8 was used in the simulations), R0 and B0 are recruitment at virgin biomass (carrying capacity), and virgin biomass respectively, α and β are parameters related to the density independent and dependent terms in the Beverton Holt relationship.

Thus: $$\alpha' = \frac{\kappa(4hR_0)}{5h-1}$$

is used in simulations instead of α. Figure 1b shows the effect of reducing productivity by 50 percent on an estimated relationship between π and stock biomass.

Note that for each spawning biomass level there are two values of π. The first value, call it π, is the probability of meeting the criterion (going below a threshold limit) under optimal fishing (Figure 1a). The second value, called π, is the probability of meeting the criterion when climate change influences a change in productivity. In the example in Figure 1b, simulated harvest rates remained at levels estimated to optimally harvest a stock with normal productivity, while the actual productivity was reduced by 50 percent to simulate the effect of climate change. Note that the probability of falling below the threshold for the same level of stock biomass increases considerably under the climate change scenario. The scenario would be equivalent to a situation of stock overfishing.

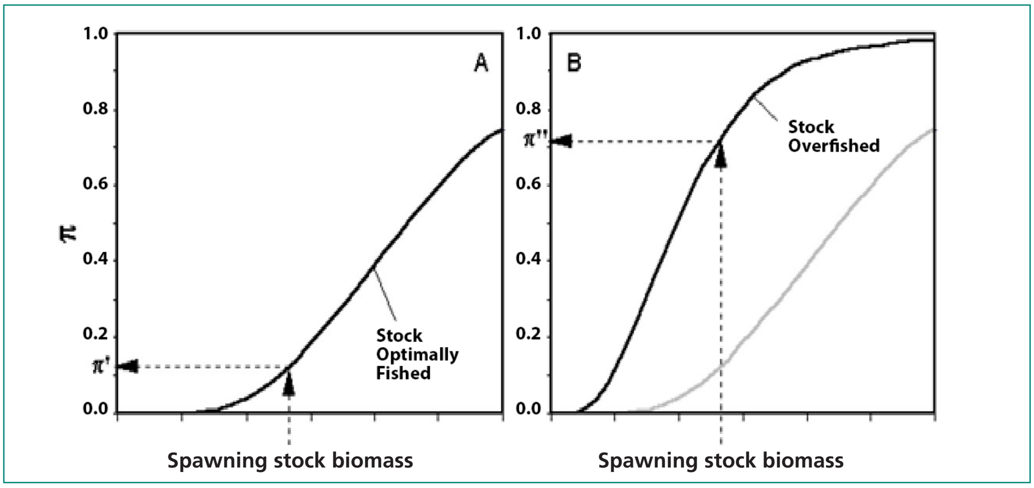

Figure 1. Estimated probability π of a stock meeting the abundance threshold criterion in a particular calendar year as a function of a spawning biomass under optimal fishing (Panel A) and when the same optimal harvest rates are simulated under a reduction of 50 percent in productivity caused by climate change (Panel B). Curves are based on interpolations from individual simulations.

As independence is the assumption used to estimate the probability of an event, the chance of being below a threshold given you were below the threshold in the previous year is also π_i and having an event occur two years in a row is (π_i^2). Normally such successive events are extremely low, and if we note this to happen, then the chances of overfishing are probably high; or if this occurs in multiple successive years the chance that a system has changed from one state to the other could be a probable consequence of a persistent change in productivity caused, for instance, by climate change. This approach is similar to what climate science uses to detect the likelihood of a 100-year event occurring every two years, implying a major system change with a new dynamic equilibrium.

Simulated population parameters

The parameters of the simulated population were those estimated for the North Atlantic Ocean albacore (*Thunnus alalunga*) stock (Sharma, 2016) (Figure 2).

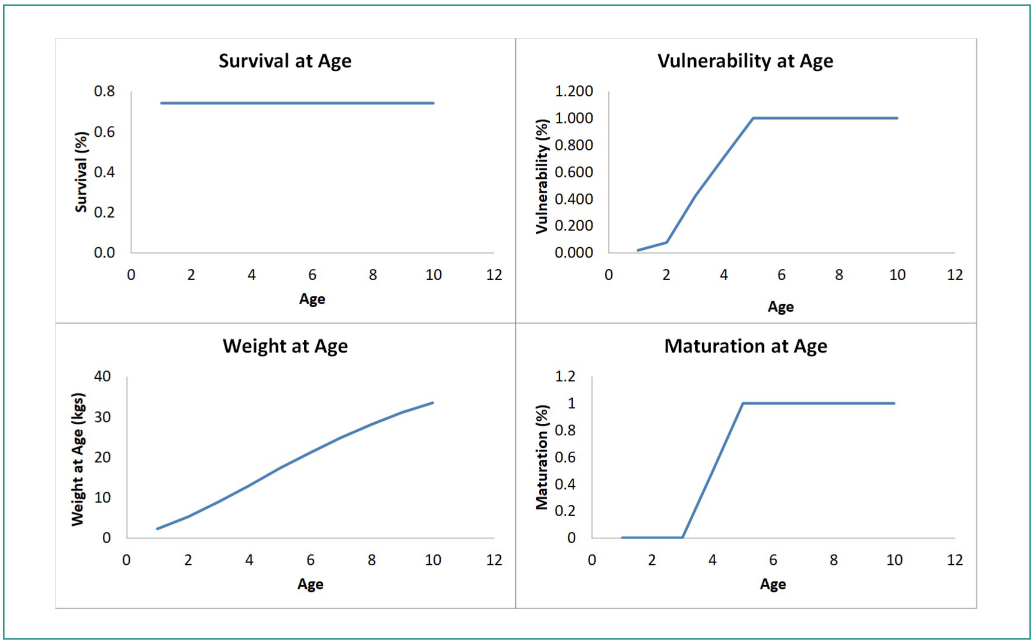

Figure 2. Survival (S_a), gear-specific vulnerability (i.e. selectivity) at age (V_a), weight at age (W_a)and maturation at age (related to fecundity at age f_a) used for simulating North Atlantic albacore stock trajectories.

Scenarios examined

Decline in recruitment and carrying capacity

Baseline assessment parameter values show how fishing under optimal targets would give us different dynamics as productivity or capacity (represented in the model by R_0) drops and the F target becomes too high. This is clearly shown in Figure 4, where the target reference point (if managing under FMSY target) does not change if B0 changes, but decreases by more than 50 percent if productivity drops. In addition, if productivity drops by 50 percent, the yield targets also drop substantially in all cases from 39 300 tonnes to 25 000 tonnes. Optimal yield targets decline between 20 000 and 25 000 tonnes (depending on if F_{40} or F_{MSY} is used for management) if capacity drops by 33 percent, and to 15 000 tonnes if both productivity and capacity drop by 50 percent and 33 percent respectively. Note that the converse would happen if there was a greater habitat availability for albacore, or more food that was favourable for a higher productivity as well (also possible as northern latitude habitats get more suitable for temperate species, K. Marshall, Alaska Fisheries Science Center, Seattle, WA Pers Comm).

In addition, if we observe from empirical data or assessments that our spawning biomass is now below some threshold levels (say 40 000 tonnes, as an example of a lower bound in Figure 3) almost 50 percent of the time, we know that recruitment overfishing may be occurring, and both effort and overall TAC should probably be reduced if this is observed in our monitoring and evaluation system.

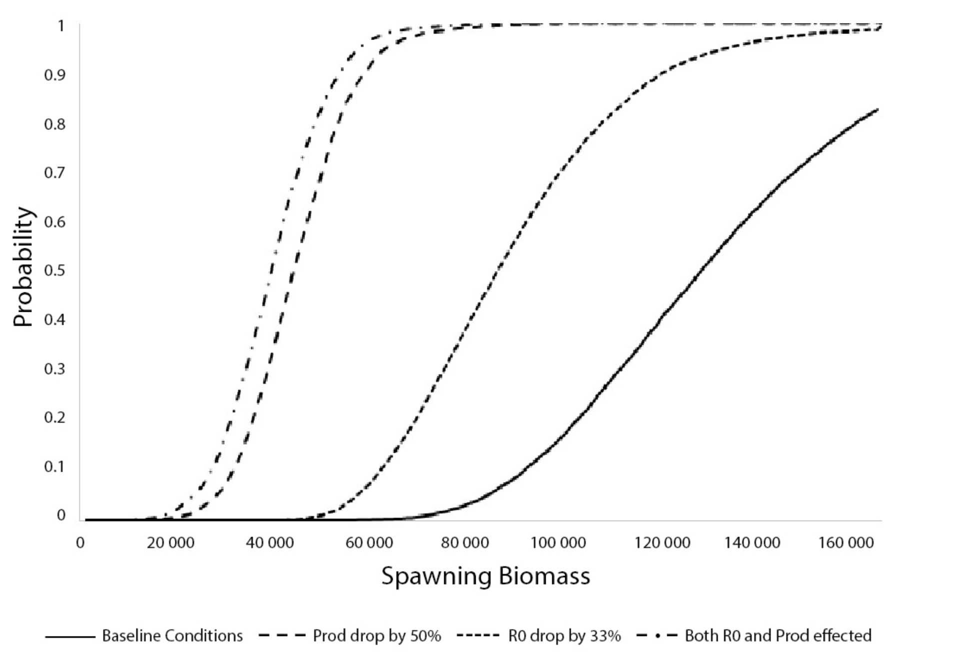

Figure 3. Probability of stock falling below spawning biomass thresholds when fished at FMSY= 0.34 and according to different scenarios of climate change impacts on productivity and carrying capacity.

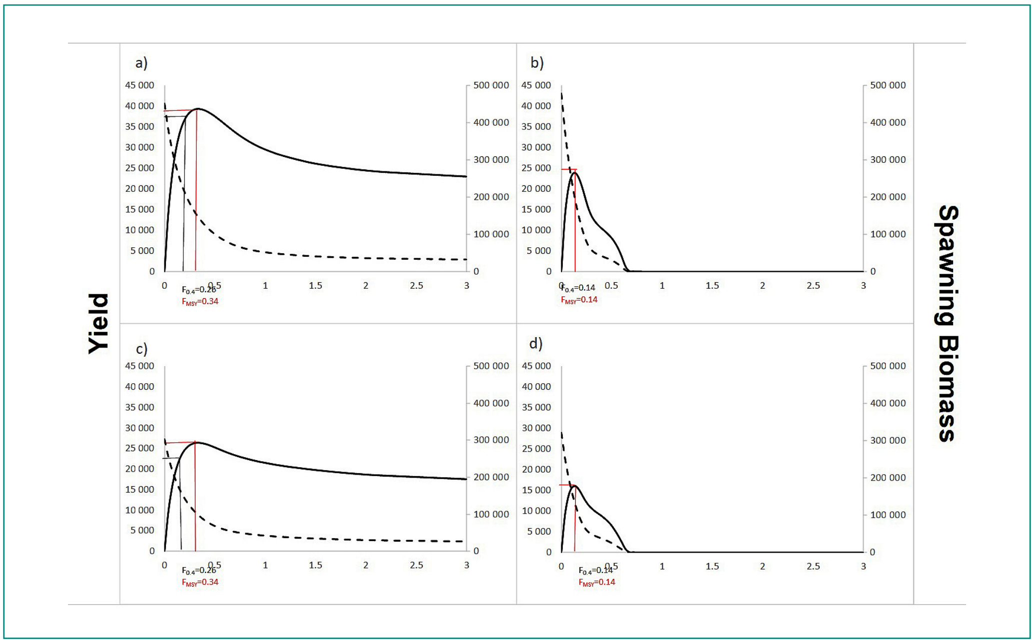

Figure 4. Effect of climate change on F reference points, simulated by changes in productivity and carrying capacity (R_0 and consequently B_0). a) is the base case assessment, b) productivity declines by 50 percent, c) capacity, R_0 declines by 50 percent; and d) both productivity and capacity decline by 50 percent and 33 percent respectively. Dashed line is the spawning biomass, and solid line is the yield curve.

Changes in life history parameters

As a consequence of changes in the environment, life history parameters (growth rate and natural mortality) could also change (in fact this is more likely as the parameters are more likely to vary based on external conditions and resonant cohort effects; Bornstad *et al.*, 2005), and thereby have an impact on estimates of resiliency and/or yield targets, as is shown in Figure 5 below.

As a function of higher natural mortality (M), a higher F reference point could be used. However, the overall yield declines as growth declines as well. Once again, as indicated by the probability plot (upper panel, Figure 5), if there is a change in growth and or change in M, the data will indicate whether climate change has induced a rapid change.

For illustrative purposes we show the declining trend, but this can work in both ways, i.e. lower M, and faster growth that would indicate a lower F and higher total yield. Note that if only growth changes then the target MSY will decline or increase, or if only M changes then the F target will increase or decrease.

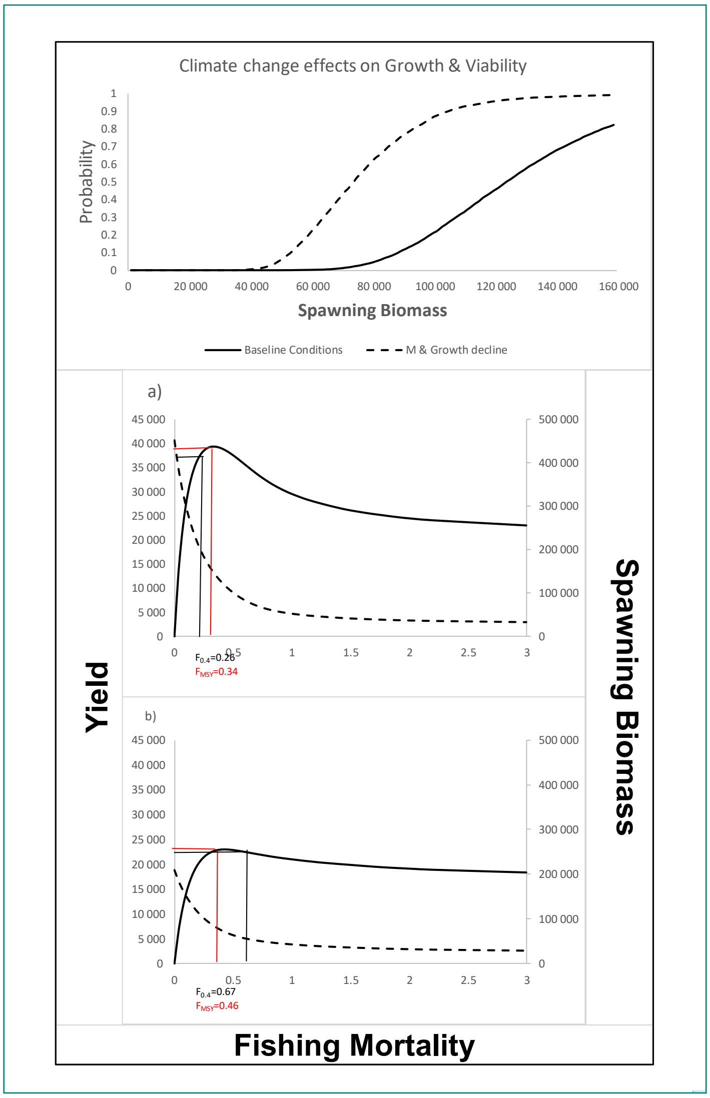

Figure 5. Top panel: probability of stock falling below spawning biomass thresholds when fished at FMSY. Lower panels: estimated changes in F reference targets according to different scenarios of change in life history parameters, upper panel shows the difference in cumulative probabilities as a function of growth and M changes, panel a shows the baseline assessment and changes to reference parameters with changes in growth and M.

Fishery effects: changes in selectivity and catchability due to distributional changes

From equation 7, catch is proportional to abundance:

$C_t = \sum_a u_t v_a N_{a,t}\, w_a$, hence if $N_{a,t}$ increases and all other factors remain constant, the C at time t will increase.

At the same level of effort, the catch increases could imply that the underlying abundance has increased possibly due to redistribution of the stock. Conversely, a decrease in catches could be observed due to a shift in distribution of the stock away from the fishing ground where the fishery operates. For instance, under the same level of fishing effort, changes in the latitudinal distribution of the North Atlantic swordfish stock could lead to a decrease in catches in tropical areas around the Caribbean and an increase in other areas like temperate waters of northeast Canada (Michael Schirripa NOAA Fisheries, SEFSC, Miami, pers comm).

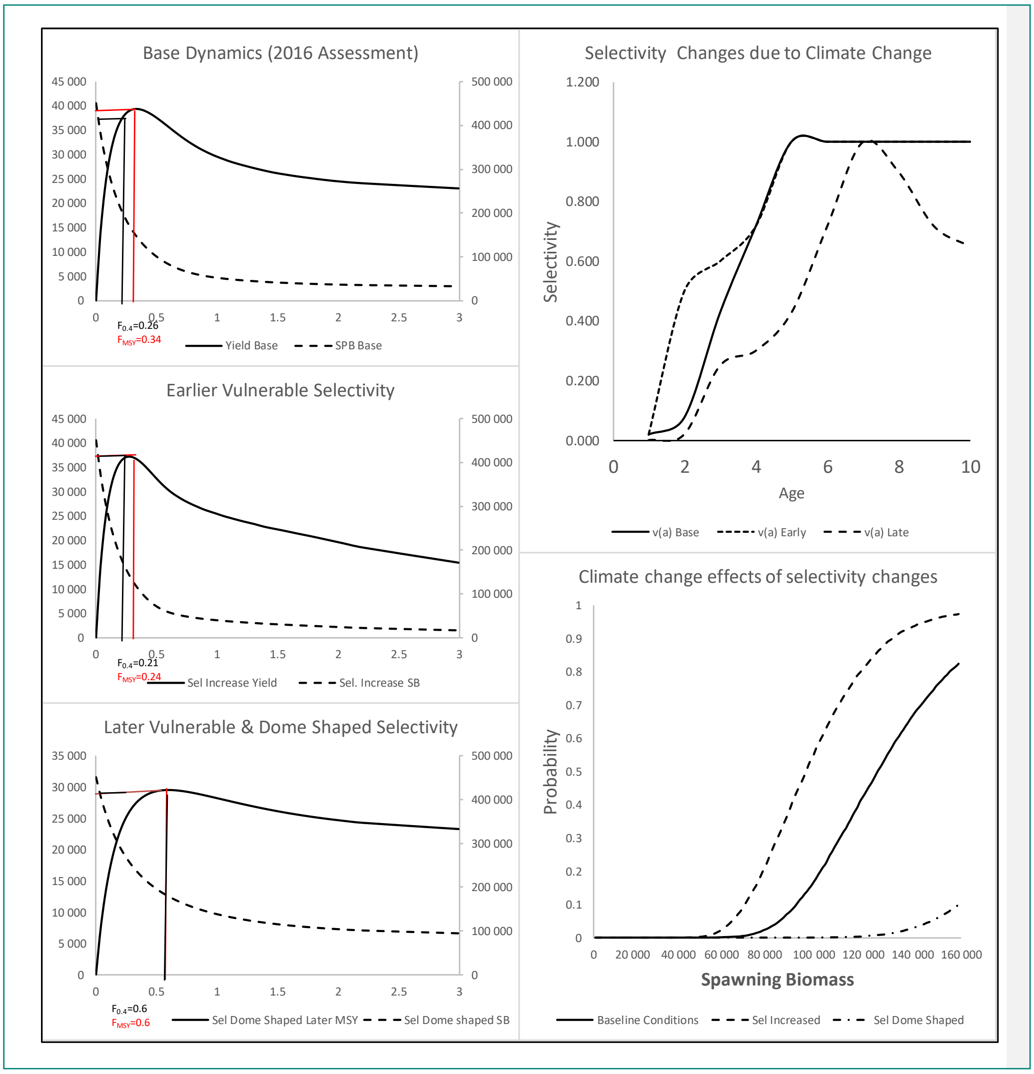

Figure 6. Optimal yield targets if selectivity changes due to climate-driven shifts in distribution which makes fish of different ages more or less vulnerable to a gear (assumed selectivity is on the upper right-hand plot). The consequence of these changes in target reference points is shown in the left panels while the resulting risk of falling below spawning biomass thresholds is shown in the bottom right panel.

On the other hand, if selectivity changes (v in the equation above), as fish have a different catchability (e.g. move to a different depth due to climate-driven changes in temperature) it can make them more or less susceptible to the fishery. In the example shown in Figure 6 we simulated two types of selectivity change: an increase in the selectivity of earlier ages; and a shift in selectivity to later ages with a resulting dome-shaped selectivity pattern with age. These changes would affect the optimal fishing mortality targets (lower Fs when earlier ages are more vulnerable), the estimated maximum yield (lower with dome-shaped selectivity), and the risk of falling below stock biomass thresholds. The risk of overfishing increases when earlier ages becomes more vulnerable to the fishery.

Cumulative effects

In cases where all climate-driven processes described in the above sections affect the dynamics of a stock, it would be difficult to isolate the underlying cause. We would possibly detect a change in the trajectory of a stock, and see more frequent occurrences of rarer events, and hence be able to detect a change. The consequences of productivity decreasing, carrying capacity decreasing, growth slowing, mortality increasing, as well as the changes in selectivity due to distribution shifts, are likely to be cumulative so we would observe an effect across all these factors. Through stock assessment these changes will be detected by the increased frequency of occurrence of biomass values below threshold biomass levels expected under steady-state or equilibrium conditions. The association between these changes with climate-driven processes will require the availability of time series of environmental data and a reasonable level of understanding of the impacts of climatic-oceanographic processes on fish populations.

Risks in the context of adaptive management controls

If the probability of an adverse event (such as very low abundances) grows, it could implicitly be hypothesized that some change in the system has occurred. The relationship between the observed changes in population and environmental factors, such as spatial-temporal changes in sea surface temperature, could indicate the importance of climate-driven processes as an underlying cause of change. If abundance is below the expected threshold, it is most likely we are fishing too hard, and should reduce fishing pressure to ensure a recovery in population abundance. If even after a decrease in fishing pressure we are still seeing low abundance (like the New England Cod, Frank *et al.,* 2005), it is possible that the entire ecosystem has changed, and thus we need to understand how to rebuild such systems through possible mitigation and adaptation measures. At the very least, we have an early warning system that could point us in the right direction to mitigate for low abundances as a consequence of climate change.

In systems that have seen dramatic shifts in abundance, like Newfoundland cod (Frank *et al.,* 2005) and bluefin tuna (Hillary *et al.,* 2016), adaptive management feedback control systems have been developed primarily to get agreement between stakeholders on a common management framework to help rebuild/manage these populations. In the case of southern bluefin tuna (Figure 7; Hillary *et al.,* 2016), a process was initiated that involved: 1) establishing target and limit reference points; 2) evaluating where the stock is with respect to these points; and 3) agreeing, through a negotiating table, how a fishery would operate if below a target and limit reference point with some objectives to be met with a high level of certainty.

With respect to point 2, we can either use a full assessment or an empirical control rule as was done by the Commission for the Conservation of Southern Bluefin Tuna (CCSBT) (Hillary *et al.,* 2017). This provides an indicator by which a management target is specified in the case of being below a target/limit reference point. Note that the indicators will also tell us how we are doing with respect to the abundance and target fishing mortalities for the stock. If we have these reference points, we can manage the stock biomass to achieve these targets within a specified amount of time. Having these rules in place would preclude us from a situation of severe overfishing, as we would have an indicator to inform us of that change as shown in the previous sections.

In the next section we briefly describe four systems that incorporated some indicator (either from an environmental signal or fisheries signal) to inform the occurrence of an adverse event and established rules to reduce the overall fishing mortality – either through a total allowable catch (output control) or through effort reductions (input control) – to achieve the target reference points in a specified period of time.

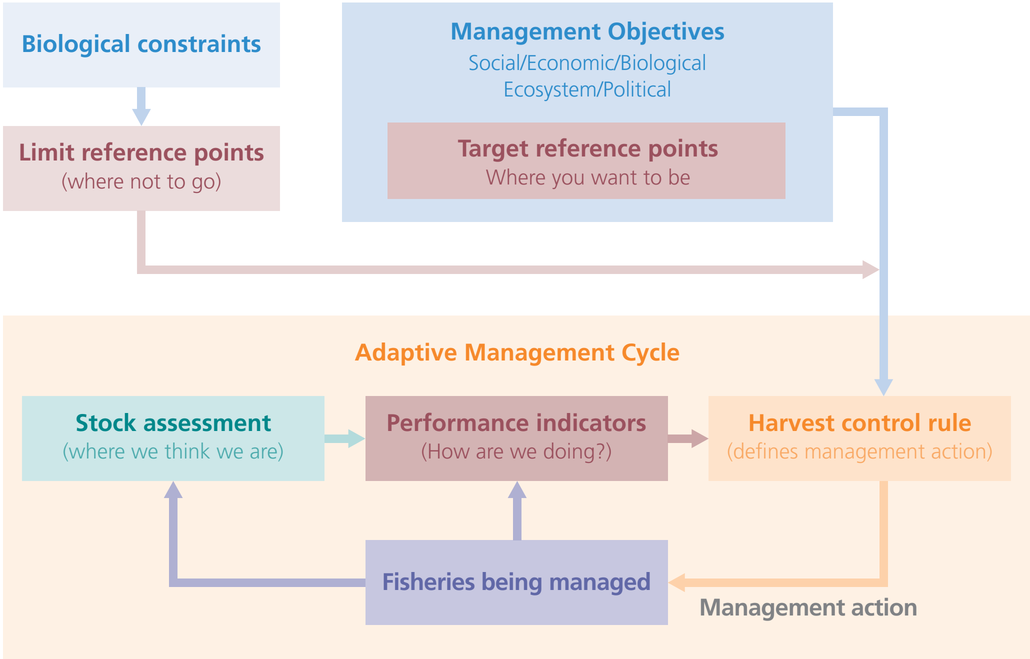

Figure 7. Control rules applied within the context of the Management Strategy Evaluation for the Southern Bluefin Tuna (from CCSBT; Hillary *et al.*, 2016).

Case study 1: Oregon coast coho salmon (*Oncorhynchus kisutch*), the United States of America

The Oregon Coast salmon fishery system is comprised of multiple stocks of coho on the west coast of the United States of America (Oregon), referred to commonly as Oregon Coast Northern Coho (OCN). These stocks have been managed with high fishing mortality levels (Figure 8), and when ocean conditions changed in the early 1990s, the stocks collapsed. The United States of America Endangered Species Act (ESA) was petitioned in the early 1990s and under this Act the stock was listed as ‘threatened’ in 1995. Under the ESA consultation standards, Amendment 13 (PFMC 1999) established a recovery and rebuilding plan for coho which:

(1) defines individual management criteria for four separate stock components;

(2) sets overall harvest exploitation rate targets for OCN coho that significantly limit the impact of fisheries on the recovery of depressed stock components;

(3) promotes stock rebuilding while allowing limited harvest of other abundant salmon stocks during critical rebuilding periods;

(4) is consistent with the Oregon State recovery plan; and

(5) has been adopted by NMFS as a consultation standard for OCN coho.

The rebuilding plan was implemented with an indicator of ocean survival (marine survival index) along with parent spawner abundance (Table 1). The indicators for survival were determined by a tagging programme run at six sites and estimated survival of one-year-old fish through a recapture programme. This, along with abundance monitored at different sites, provided the basis for target exploitation levels at different abundances, ocean survival conditions (which are affected by climate-driven processes) and areas as shown in Table 1 below.

The resulting changes are now implemented annually for targeted harvest rates that are responsive to ocean conditions and climate change, with the aim to prevent the stock from being overfished and recover in the long term.

Table 1: Target harvest rate matrix for OCN according to different levels of spawner stock abundance and marine survival index. The marine survival index refers to the predicted wild adult coho survival based on environmental conditions (adapted from PFMC FMP, 2014).

Parent spawner abundance	Marine survival index			
	Extremely low (< 2%)	Low (2–4.5%)	Medium (4.5–8%)	High (> 8%)
High	< 8%	< 15%	< 30%	< 45%
Medium	< 8%	< 15%	< 20%	< 38%
Low	< 8%	< 15%	< 15%	< 25%
Very low	< 8%	< 11%	< 11%	< 11%
Critical	0–8%	0–8%	0–8%	0–8%

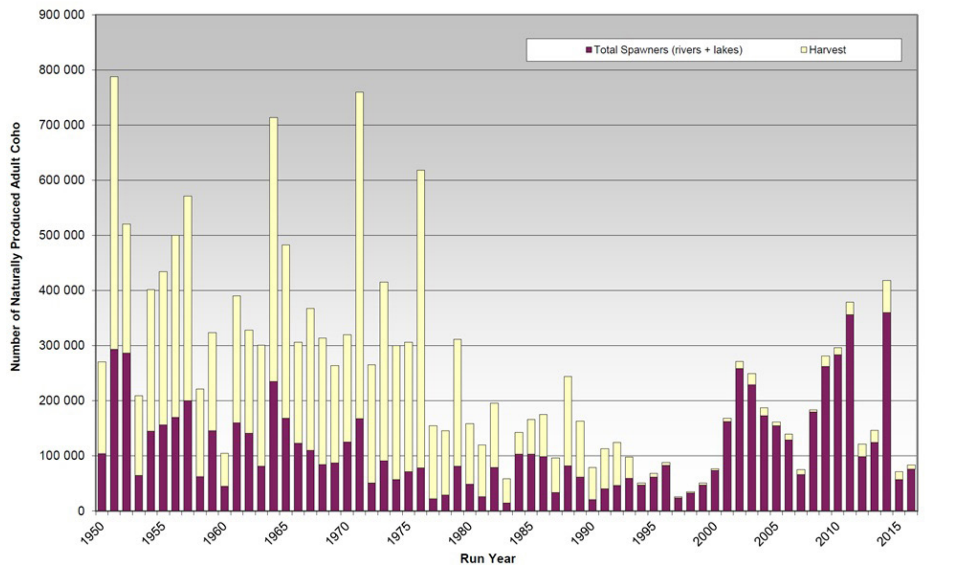

Figure 8. OCN abundance changes over time, note the high harvest rates prior to 1990 and the consequential decline after the control rule (Table 1) was implemented.

Case study 2: California current sardine (*Sardinops sagax*), the United States of America

This case study demonstrates that if we use an environmental indicator to govern management, we need a reliable predictor. As demonstrated here, we need to be careful about using indirect measures when setting harvest control rules. Over time, these indicators have changed as the reliability of a better indicator was used to describe the dynamics of this system, as an earlier indicator failed.

Zowlinski and Demer (2017) studied a boundary system (where ocean fronts change from the California current to the Southern California Bight) examining sardine and anchovy on the west coast of the United States of America, that indicated that there really was large variation in recruitment. This variation was explained when put in the context of sea surface temperature (SST) that can vary drastically off the California coastline (Figure 9). The SST, based on measurements at Scripps Pier in La Jolla, was shown to be a good indicator of sardine abundance, which eventually failed. A harvest guideline was based as function of available habitat and a SST indicator (Zowlinski and Demer, 2017).

However, the Scripps Pier SST was not able to capture the dramatic decline in reproductive success in the 2000s, and was eventually dropped in 2011. In hindsight, it shouldn't have been unexpected, as the Southern California Bight has its own dynamics, and is decoupled from the California current. Recently however, a new index temperature was developed based on mean annual temperature measured during four seasonal surveys off southern California (Lindegren and Checkley, 2013). This has been verified by the California Cooperative Oceanic Fisheries Investigations (CalCOFI) surveys run off the coast of California.

The CalCOFI survey footprint encompasses part of the sardine spawning area. In certain years all spawning occurs outside CalCOFI. However, CalCOFI SST was a relatively accurate predictor of sardine's reproductive success from 1983 to 2010, and CalCOFI SST was adopted, after the Scripps Pier indicator failed, by the PFMC to inform the harvest guideline (Higher SST => higher exploitation). Recruitment models using SST from this and the Pacific Decadal Oscillation (PDO) as covariates have a higher predictive power, and have hence been used to set harvest guidelines for small pelagic sardine as they are almost entirely governed by environmental variation as exhibited by SST in southern California.

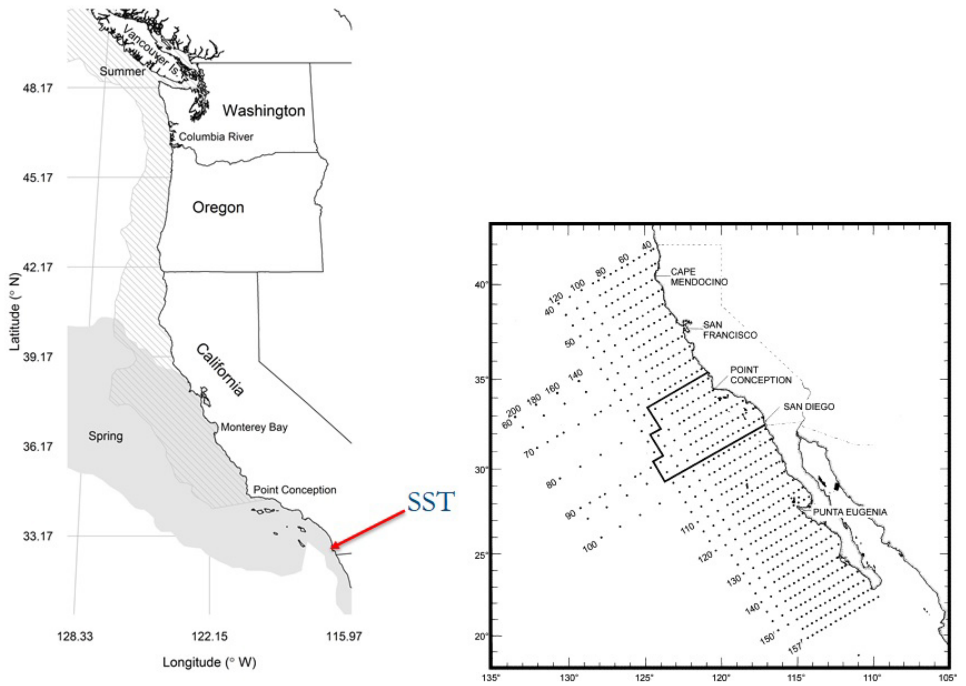

Figure 9. California current system and SST at Scripps Pier used to set allowable catch targets versus CalCOFI survey areas derived SST used as harvest guidelines in recent years (pers comm. J. Zolownski, SWFSC. NOAA Fisheries, La Jolla, CA). Note the location of Scripps Pier where the initial indicator was developed is found at the southern range of the stock, and stopped being effective when the distribution moved mostly out of this range – hence the subsequent creation of a more reliable indicator mapped from the surveys.

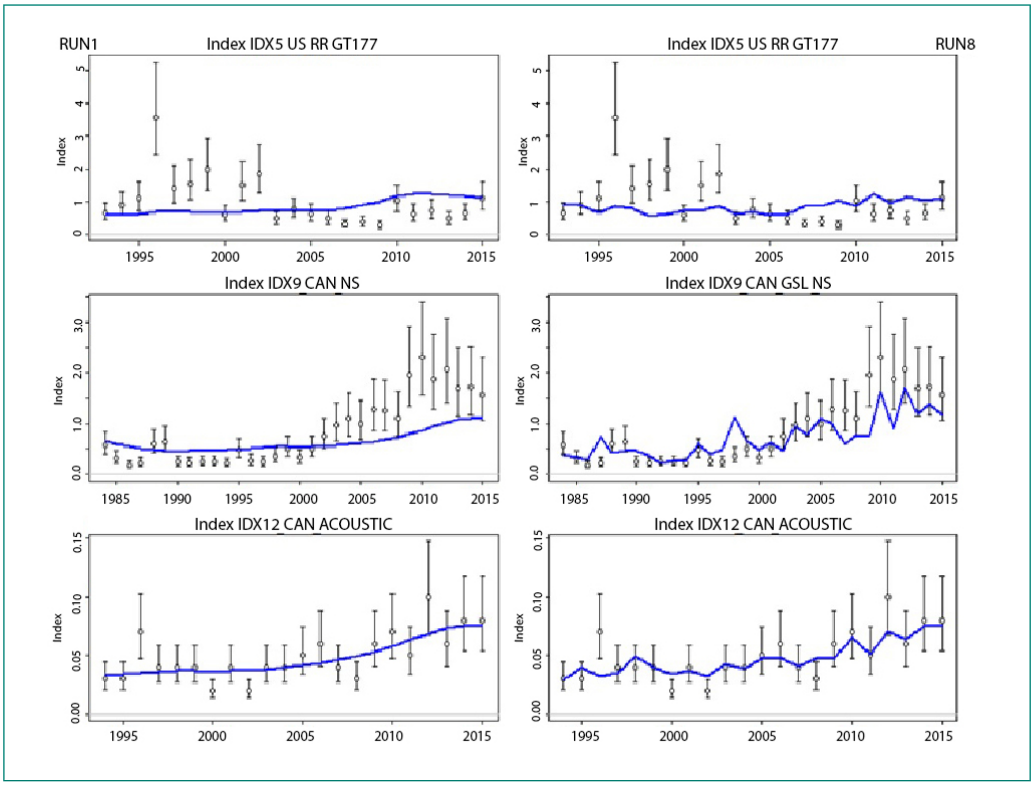

Figure 10. Fits to West Atlantic data using the Atlantic Medial Oscillation Index indicating q is changing by area (Courtesy John Walter, NOAA Fisheries, Miami).

Case study 3: Atlantic bluefin tuna (*Thunnus thynnus*)

Atlantic bluefin tuna are managed under the auspices of ICCAT. The current management models account for environmental indices within the model in the west and as a larval index in the east. While no specific control rule or management plan is used to determine the quota or TAC as with the previous two case studies, these are being used in the model directly to assess biomass through an external indicator in the assessments. Options to explore this within the context of an MSE are also being developed (Caruthers and Butterworth, 2018). Figure 10 shows how the catchability (q) is changing by area as a function of environmental change (right panel plots versus the left panel plots), i.e. the catch rates are going up in Canada and decreasing in the United States of America primarily as the stock distribution has changed over time, a case discussed in the scenario above when catchability changes as a function of changes in distribution. The management response is implicit as the indicator is used in the fitting procedure which will set the estimated biomass and allowable TAC, as it is part of the model fitting.

Case Study 4: Gulf of Carpentaria banana prawn, Australia

The penultimate case examined here is the Gulf of Carpentaria Banana prawn fishery (Plagyani *et al.*, 2019), located in Northern Australia. This is an example of a data-poor scenario (Figure 11). Data indicates a relationship between abundance and environmental conditions as exhibited by the Southern Oscillation Index (SOI), an indicator of warming in the tropical Pacific (Figure 11). Taking the CPUE estimated from this fishery and data observed, a relationship was built (Figure 11 upper panel) with the SOI, indicating how CPUE is qualitatively associated with abundance. This provides an early warning signal to plan the season, as shown in the bottom panel of Figure 11. In years a downturn occurs in the population, it could be useful guidance on fishery planning, particularly for bad years. However, we also know that fishing effort in this multispecies fishery also depends on performance relative to fishing the other species and economic considerations, and hence there is a need to understand other drivers of low vs high effort (and CPUE) in the area. An alternative scenario that could drive the CPUE up or down could be related to the revenue per unit effort in different regions implying a good or poor year, and shift effort from one species to the other thereby showing a decline in CPUE rates that have nothing to do with the environment. Currently, the Australian government is revising its harvest strategy to include rules based on environmental and economic conditions (Plagyani-Lloyd *et al.*, 2019).

The SOI is a good qualitative predictor of prawn fishery CPUE. There is a weak relationship between abundance and the El Niño Southern Oscillation index (ENSO). During a La Niña, abundance is negatively correlated, and during an El Niño there is a positive relationship with abundance. These relationships and how they affect CPUE under the different regimes are shown in Figure 11. Although these relationships are weak, we can still qualitatively use them in a management context as they are related to overall abundance.

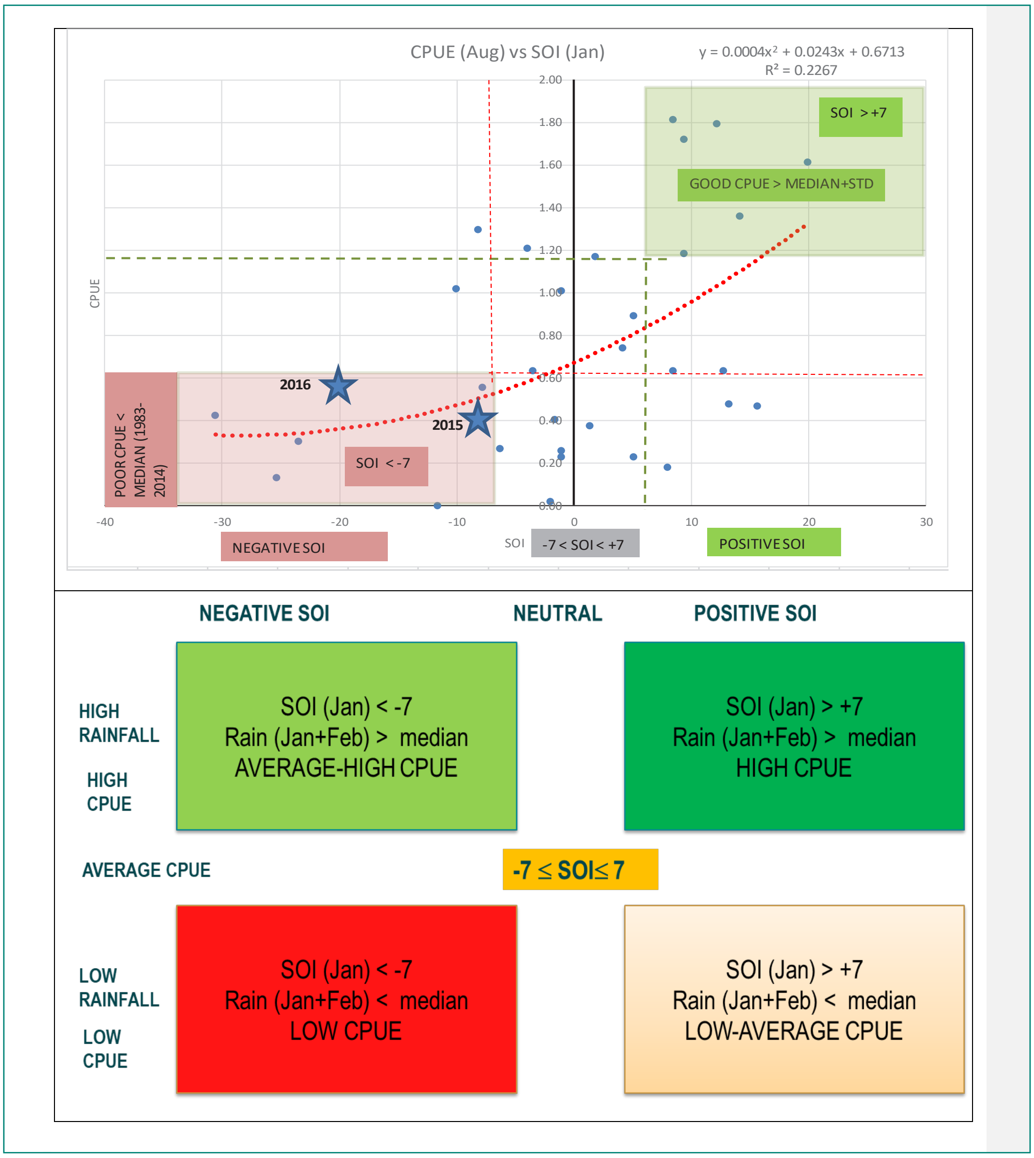

Figure 11. Qualitative guidelines for available biomass and harvest as a function of ENSO, and SOI. The above panel shows the relationship between CPUE and ENSO over time and is related to positive and negative SOI values, the bottom panel indicates a heuristic that shows how one may plan based on the SOI index, that may relate to banana prawn abundance (Source Eva Plagányi-Lloyd, CSIRO, Brisbane, Australia).

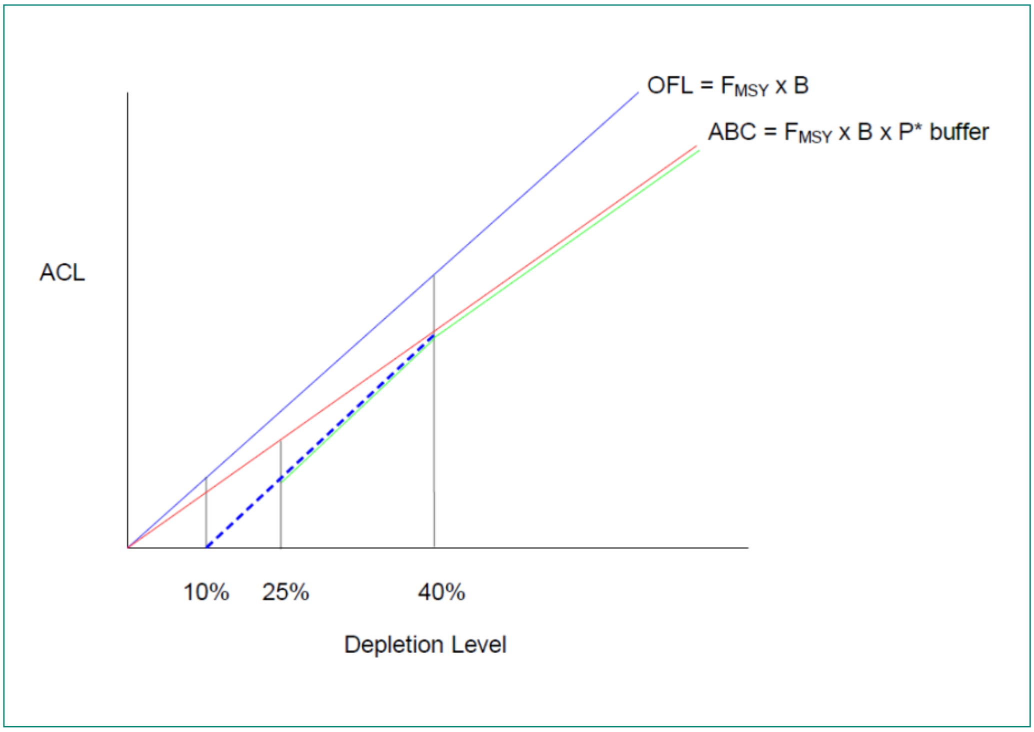

Figure 12. Illustration of the Pacific Fishery Management Council's 40-10 harvest policy. As the stock declines from B40, the allowable biological catch (ABC, determined as biomass x FMSY x uncertainty buffer) declines in concert. However, the policy specified by the 40-10 harvest control rule results in a catch that is less than the ABC, eventually reaching zero when stock biomass reaches B10 (source: PFMC 2019)

Case study 5: Pacific Coast groundfish, the United States of America

This is a case study of the harvest control rule that is used in the United States of America Pacific Coast groundfish fishery, often referred to as the 40-10 harvest policy. This is an example of a harvest control rule that can be considered adaptive to changing ocean conditions, even when there is little or no data regarding how such a change is affecting stock productivity. This harvest control rule can be described as one that sets the harvest rate at FMSY when the stock biomass is at BMSY (estimated as B40) or higher. As the biomass declines from BMSY the fishing rate is reduced linearly until it reaches zero at B10 (PFMC, 2020).

When this policy was put in place it was largely considered a measure that would foster rebuilding when a stock declines below B40 by helping ensure that fishing pressure is reduced as the stock biomass drifts below the target size. This in turn helps the stock to recover back to desired population levels and generate desired benefits for the fishing community. Now, more recent research has investigated the use of these types of ramped harvest control rules for addressing uncertainties related to climate change.

One of the major sources of uncertainty regarding climate change is detecting when changing ocean conditions result in a change in stock productivity. It can be difficult to detect such change in a timely fashion. When a change in productivity occurs but goes undetected, the risk is that overfishing will ensue unknowingly. Recent research indicates that ramped harvest control rules which adjust the fishing rate in response to changes in stock abundance indicators, and with no knowledge regarding underlying change in productivity due to climate change, can perform nearly as well as a policy which is able to perfectly detect productivity change and implement responsive policies instantaneously (Kritzer *et al.*, 2019). This finding shows that the utilization of ramped harvest control rules like the one described here, that adjust fishing pressure in response to changes in biomass indicators, are robust to climate change uncertainty even when there is no knowledge as to whether climate change is affecting that stock's productivity.

Conclusions

While climate change has obvious implications for fisheries management when demonstrated through a simple simulation model, the ultimate objective is to manage the stocks and fisheries sustainably for long-term yield and sustained economic benefits. Static reference points that are used for management are thus a thing of the past, especially if there are directional autocorrelational processes at work, as a consequence of climate change. Hence, management needs to adapt to the system changes, possibly using a system such as management strategy evaluation (MSE), with control rules dependent on environmental changes. We demonstrate how some of these rules could be developed based on a data-rich, full MSE (California coast sardine) or data-poor situations (banana prawn).

In a recent special issue that focused on recruitment dynamics and assessment models, three issues were addressed by the research presented in a focused population dynamics symposium (CAPAM, Center for the Advancement of Population Assessment Methodology, Sharma, 2019). In essence, three general approaches for dealing with recruitment uncertainty driven by climate change have emerged (Sharma *et al.*, 2019; for further details see the Special Issues, Sharma, 2019). While the first approach mostly relates to statistical and parameter estimation issues with stock and recruit models, i.e. is more related to model fitting processes and issues of parameter estimation that are more a theoretical statistical issue (see Sharma, 2019 for details), the other two approaches are particularly relevant here. The second approach examined (Sharma, 2019) is to explicitly link recruitment variation to underlying environmental drivers, as shown in the case of bluefin tuna and California coast sardine. In some examples, the stock-recruitment relationship has been assumed to be stationary (Crone *et al.*, 2019), and the annual deviates are modelled as functions of environmental covariates. Alternatively, the parameters of the stock-recruitment relationship have been allowed to vary over time, either as regime shifts or as functions of covariates (Berger, 2019). This could allow for management to be responsive to climate change and other factors. However, it requires a great deal more information than the first approach, and several studies have suggested it may not perform as well in practice as might be expected (Brooks *et al.*, 2019; Kolody *et al.*, 2019; Plagányi-Lloyd *et al.*, 2019).

The third approach (Sharma, 2019) is MSE and involves using simulations conditioned on the available data to identify management procedures that perform well over a plausible range of recruitment processes and other sources of uncertainty (Plagányi-Lloyd *et al.*, 2019; Thorson *et al.*, 2019b; Haltuch *et al.*, 2019; Punt, 2019). MSE may incorporate many of the elements of the first two approaches, but does not necessarily use recruitment models in a predictive capacity within the management procedure. As described above, this approach has been used with Oregon coast coho salmon, Pacific sardine and the Australian banana prawn fishery. The use of such an approach can be considered a good practice to stock assessment management advice when taking climate variability and change into account in management decisions.

Acknowledgements

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Chapter 5: Building effective marine fishery management and governance in Myanmar: a foundation for climate resilience

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Abstract

Myanmar is one of the 25 largest seafood producing nations in the world, yet available information indicates that the status of Myanmar's marine fisheries is relatively depleted, with substantial room for improvement in both ecological and social terms. Indeed, the current condition of Myanmar's marine fisheries suggests a system that is not resilient and that struggles to appropriately respond to large-scale change, such as climate change. Over the course of several decades, the ecological structure of Myanmar's marine ecosystems appears to have been altered significantly by relatively unmanaged fishing practices. This has included reductions in overall fish biomass at levels that indicate unsustainable fishing practice, with especially large removals of upper trophic level species, and a corresponding ecological release of low trophic level species. Myanmar's people have a high poverty rate, with indications that rates of poverty in coastal areas are worse than the national average. In addition, Myanmar's fishery governance and management systems are highly centralized and have historically had limited effectiveness. This is compounded by limited scientific capacity regarding fisheries in general, as well as limited scientific capacity regarding the ongoing and future of effects of climate change on fisheries. All together, these characteristics point to a system that is lacking in many dimensions of socio-ecological resilience and that will struggle to plan and respond constructively to the impacts of climate change. However, several developments are occurring in Myanmar's marine waters to address these shortcomings and bolster the resilience of marine fisheries. These range from measures spelled out in Myanmar's National Adaptation Programme of Action (NAPA) to Climate Change, to local groups that are working to build primary fishery management capacity. These efforts aim to secure biodiversity, stabilize fishery harvests, and implement adaptive capacities of fishers. The goal is to buffer climate effects on ecological systems, helping enable fishers to plan for longer term time horizons (which can facilitate climate change planning), and enable greater capacity for adaptation to change as it occurs.

Fishery context

Myanmar's coastal region is ecologically diverse, consisting of large coral reef areas, river deltas, estuaries, mangroves, and productive offshore regions. From these ocean and coastal waters nearly 1.5 million Myanmar fishers harvest fish at some of the highest

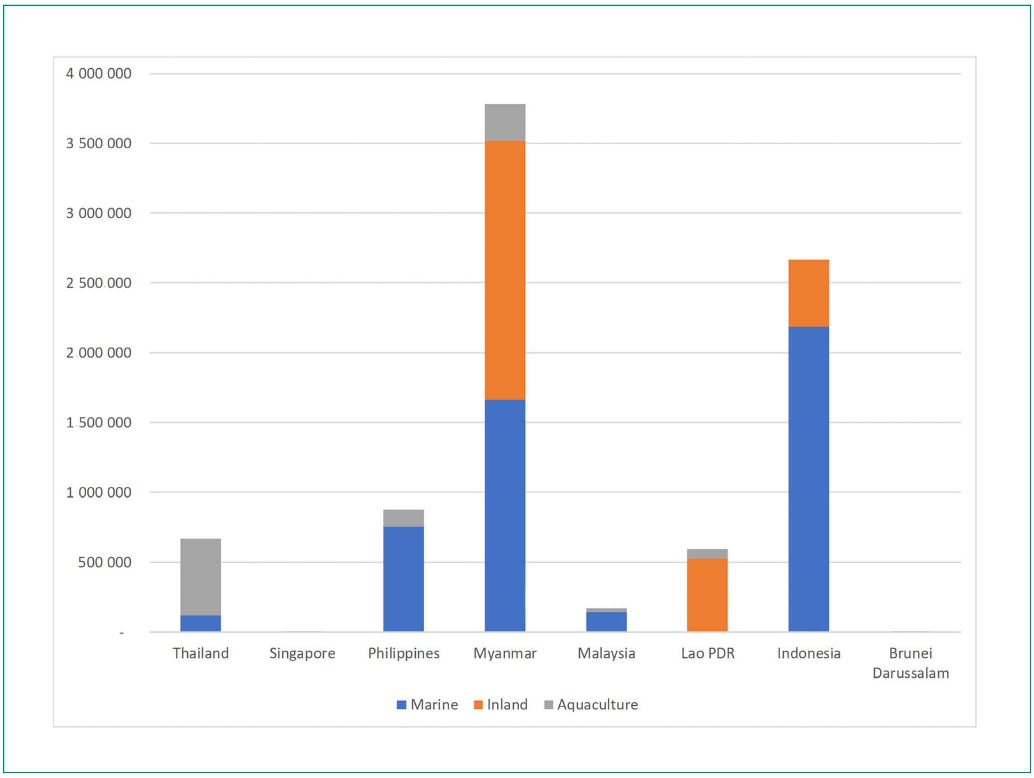

Figure 1. Millions of fishers and fish farmers in selected Southeast Asian nations in 2014 (source: SEAFDEC, 2017)

levels of all Southeast Asian nations (SEAFDEC, 2017). Statistics from the Myanmar government indicate wild fish production reached 4.7 million tonnes during the 2017-2018 season, of which 3.15 million tonnes was derived from marine fisheries. Both small- and large-scale fishers employ a diverse set of techniques, using trawl gear, purse seine gear, gillnets, handnets, longlines and more, while pursuing a variety of different fish species (Department of Fisheries, 2017). Large numbers of Myanmar fishers participate in small-scale coastal fisheries (Figure 1), while much of Myanmar's capture volume comes from offshore fishers predominantly using trawl gear and – increasingly – purse seine gear. Recent government statistics report 21 886 small vessels and 3 177 off-shore vessels in Myanmar's marine waters (Department of Fisheries, 2018); although evidence also points to large numbers of illegal and unreported fishing activities not captured in such statistics (BOBLME, 2015).

Historical records from the late 1880s suggest that Myanmar's coastal waters once abounded with a great diversity of fish species (Day 1889). Myanmar's marine fisheries were considered to be lightly exploited until the late 1960s, owing largely to a preference for freshwater fish among the domestic population and a lack of major investments in seagoing vessels, ports and other infrastructure (Soe, 2008). Several milestones appear to have contributed to the rise of fishing pressure in the marine environment: in 1962, the People's Pearl and Fisheries Board was established, and domestic marine fishing activity using motorized vessels began to develop; in the 1970s, international agencies contributed to fishing capacity enhancements by providing funds for fisheries development; and beginning in 1989, Myanmar passed the Law Relating to the Fishing Right of Foreign Vessels, according to which foreign countries began to lease fishing rights from the Myanmar government to fish in offshore waters (Soe, 2008). This influx of foreign vessels appears to have increased fishing mortality and stock depletion substantially during the 1990s.

The Myanmar government continues to remain focused on the development of its fisheries and aquaculture sectors, and much of this motivation appears to stem from an economic downturn in the 1980s. This downturn spurred the government to invite foreign investment and led to the establishment of policies that encouraged fisheries and aquaculture development as a way to improve the nutritional and livelihood demands of its population. In addition, fishery exports continue to be an important source of foreign exchange, something that also traces its roots back to the 1980s. Presently fisheries are a major contributor to Myanmar's national economy, with official statistics indicating a contribution between 8 to 10 percent of GDP, and 2017 exports valued at over USD 600 million (World Bank, 2019). However, although fisheries are undoubtedly a major source of livelihoods, food security and income generation, there are questions regarding the accuracy of Myanmar fishery statistics. For instance, the FAO estimates total fish production volume (marine fisheries, inland fisheries and aquaculture) at levels that are 2 million tonnes lower than Myanmar government statistics (Tezzo *et al.*, 2018).

Fisheries assessment-related activity is infrequent, but data from the R/V *Nansen* survey points to a system that has been significantly altered by fishing, especially since the 1980s. The R/V *Nansen* is an oceanographic and fishery research vessel that conducts research surveys in Africa, Asia and Latin America. It is owned by the Norwegian Agency for Development Cooperation (NORAD) and was built to support FAO-related research efforts under the EAF-Nansen programme 'Supporting the Application of the Ecosystem Approach to Fisheries Management considering Climate and Pollution Impacts'. Data from the R/V *Nansen* programme suggest that a significant prey release has occurred as a result of relatively unmanaged fishing activities and the subsequent reduction of upper trophic level predators (Figure 2). The resulting reduction in overall biodiversity and fish abundance may put the ecosystem at risk of collapse, as has been seen in other regions of the world (McClanahan *et al.*, 2011; Karr *et al.*, 2015).

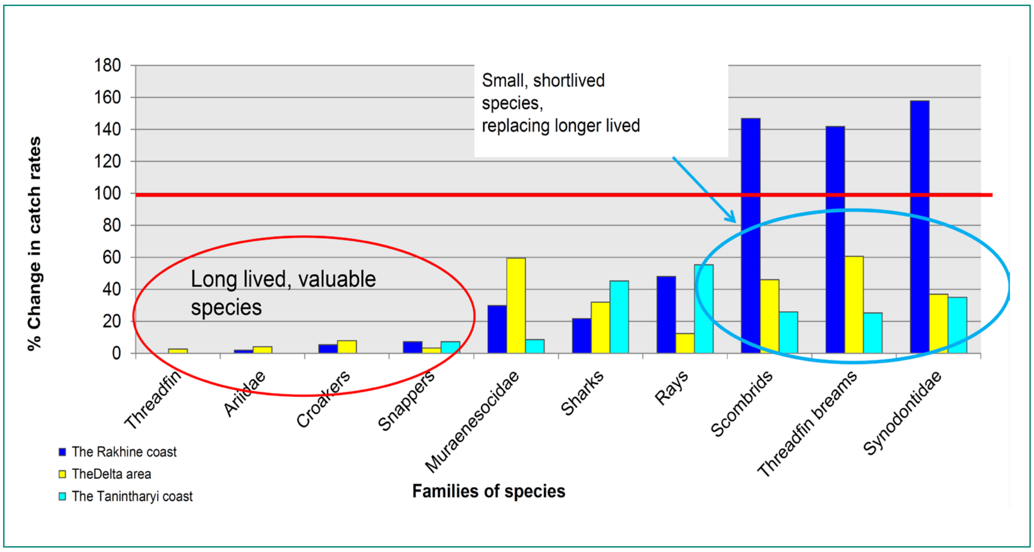

Figure 2. Relative catch rates of marine species in Myanmar waters from the 1979/1980 time period to 2013 (Figure provided by Wildlife Conservation Society, Myanmar and created from the R/V Nansen project data)

B) Management context

The governance of Myanmar's marine fisheries has a tendency for high degrees of centralization within a structure that has limited capacity and resources (Figure 3). However, the legal ability to decentralize exists, and in recent years there has been some movement in this direction. This is important for the adaptive capacity of fishery management. Developments include the relatively recent formation of local government offices (*Hluttaws*), and the more recent formation of formally recognized community co-management entities.

In addition, in recent years Myanmar's government has made efforts to improve the management of marine fisheries. Policies have been established which attempt to limit the amount of participation in fisheries, limit the amount of fishing activity that can occur with trawl gear, and implement time and area closures, among others. In practice these measures have been fairly ineffective: this is due to many factors, primarily the Myanmar government's limited enforcement ability and a lack of buy-in from fisher groups. Furthermore, illegal fishing activity appears rampant throughout the country, with undocumented landings, foreign incursions into Myanmar's waters, fishing at times and in locations restricted by formal policies, violations of licensing and permitting requirements, and other infractions.

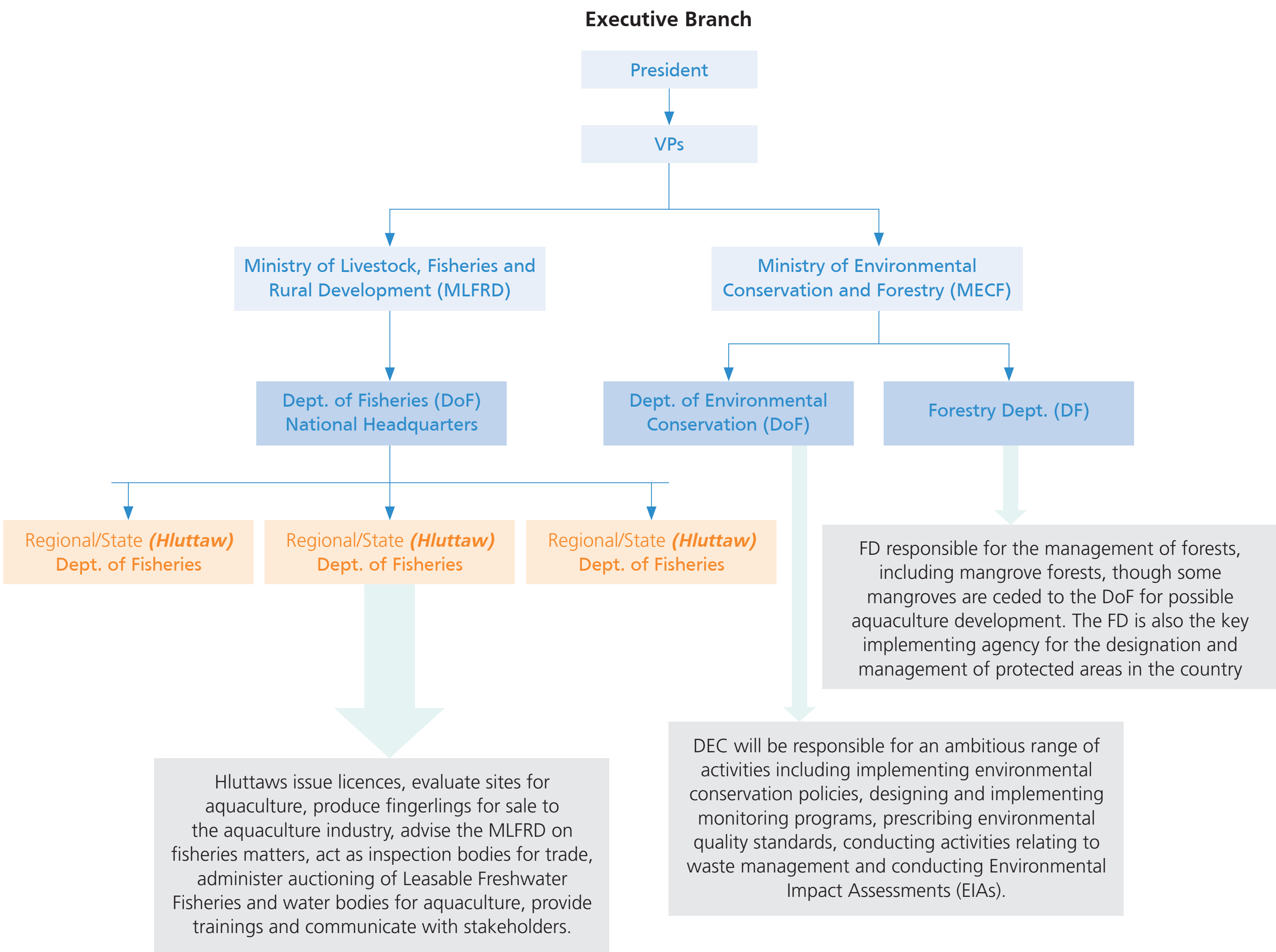

Figure 3. Myanmar fisheries governance structure

The country of Myanmar has several laws and amendments which affect fisheries and fish production.[1] These include laws that relate to the rights of foreign fishing vessels, aquaculture, Myanmar's domestic marine and freshwater fisheries, and related amendments. The Myanmar Fisheries Law itself focuses substantially on permitting, registration, and the collection of fees. Rule-making concerning fisheries largely occurs within the Department of Fisheries.

The Department of Fisheries has recently outlined a vision and set of objectives stating the intention to manage fisheries in ways that improve fishery resources and improve the lives of people dependent on them (World Bank 2019). This vision statement is consistent with the Sustainable Development Goals, the Code of Conduct for Responsible Fisheries and generally accepted best practices for fishery management. Several types of federal regulations exist concerning the management of fishery resources and habitats. These include:

- Licensing: Moratorium on new or additional licences
- Input controls: All fishing subject to licensing and registration system
- Closed areas: Nursery areas have been protected and managed for juvenile survival, shark conservation, and other wildlife
- 7 fish conservation areas, 12 crab protected areas, 1 lobster area, and 1 Indian threadfin area
- Prohibition on fishing within 300 yards of mangroves
- Seasonal restrictions: An annual country-wide closed season has been put in place, and has generally extended from May to August
- Gears: Banned gears include pair trawling, electric fishing, poisons, chemicals and explosives, push net (from boat), bottom trawling within 5 miles of shore
- Species restrictions: various limits on size, time, area, bag; and other restrictions

Myanmar's National Adaptation Programme of Action (NAPA) to Climate Change outlines several courses of action for enhancing the resilience of marine and coastal systems. One particular priority concerns the conservation of marine biodiversity through the use of 'community-based MPA [marine protected areas] management and ecosystem sensitive fishery practices' at the Myiek Archipelago. In 2017 Myanmar officially recognized the creation of three locally managed marine areas (LMMAs), which are community-based areas established to help conserve the diverse coral ecosystems within the Myeik Archipelago. The management of these areas is accomplished through the granting of exclusive fishing rights to these communities via co-management.

[1] These laws include:
- 1989: Law relating to the fishing rights of foreign fishing vessels
- 1989: Aquaculture Law
- 1990: Myanmar Marine Fisheries Law
- 1991: Freshwater Fisheries Law
- 1993: Law amending the Myanmar Marine Fisheries Law
- 1993: Law amending the law relating to the fishing rights of foreign fishing vessels.

In addition to the Myeik Archipelago LMMAs, other forms of co-management have recently been created as a way to improve the status of fisheries elsewhere on the Myanmar coast. The Organisation for Economic Co-operation and Development (OECD) defines co-management as '…a process of management in which government shares power with resource users, with each given specific rights and responsibilities relating to information and decision-making.' In the case of Myanmar's marine fisheries, the government has given specific rights to communities to help manage fisheries in specific geographic locations, and subject to certain conditions and approval. In particular, several nearshore fisheries co-management areas have been established in Rakhine and Mon State, with more along the coast in development (see Figure 4 for a map of Myanmar provinces). Supporting the development of these co-management entities have been the Myanmar Department of Fisheries, several non-governmental organizations (NGOs), universities, aid organizations and fisher groups. Means of support have included financial assistance, technical assistance and capacity development.

In order to be conferred fishing rights, co-management associations are required to develop a management plan and petition the federal government for permission to establish a co-management area. Regulations crafted by co-management entities must abide by federal regulations (such as closed seasons and mesh sizes) and must be approved by the state-level Department of Fisheries. This process of approval is relatively new and, at the time of this writing, the formal processes involved with such a submission are unclear. However, in general co-management associations must draft their management plan to include proposed regulations, enforcement, and information regarding participation in the co-management area. The Department of Fisheries will not grant exclusive fishing rights to a co-management area unless it is satisfied with the plan and believes it will be successful without substantial governmental involvement.

Figure 4. Map of Myanmar provinces (source: CartoGIS Services, College of Asia and the Pacific, The Australian National University, 2020)

C) Climate change implications

Climate change is already affecting mangroves, sea grasses and coral reefs in Myanmar's marine waters, compromising different life history stages of marine species (Wongbusarakum et al., 2019). One example relating specifically to fishing opportunity concerns the spawning, migration, growth and survival of hilsa (Tenualosa ilisha) – an important species for fisheries in the region. Sea level rise, changing sea surface temperatures and more are affecting its life history patterns, growth and survival; and these in turn are affecting the amount and distribution of hilsa available to fishers in the region (Miah, 2015). In many instances the precise role of climate change in the transitions being observed is not known, owing largely to the multiple anthropogenic stressors acting upon Myanmar's coastal waters (including overfishing, pollution, sedimentation and others) and the difficulties in untangling their effects from one another.

Regional climate model projections suggest more erratic and severe rainfall as a result of climate change (The World Bank Group, 2020). Such a change in rainfall patterns is expected to result in greater inter-annual variability of stock abundance and larger sediment inputs, among other possible effects. Greater sedimentation will tend to negatively impact coral cover and seagrass habitats. Nutrient inputs from upland farms, increased freshwater flow into nearshore waters and projected increases in sea surface temperatures also tend to drive frequent and severe mass coral bleaching (Donovan et al., 2020). Sea level rise in Myanmar is also projected at rates that exceed the global average (Vivekanandan et al., 2016). This will tend to negatively impact mangroves, seagrass meadows and coral reefs – all of which have maximum vertical accretion rates which, if exceeded, can result in the loss of biogenic habitats (Stevenson et al., 1986; van Woesik et al., 2018).

Collectively these impacts will tend to drive an ecological transition toward a system increasingly characterized as unvegetated mud bottom habitat. These changes would in turn have significant effects on species composition, abundance and distribution, and hence on the amounts and kinds of seafood produced by Myanmar's capture fisheries, as well as on fishing-related jobs and revenue.

The intensity of cyclones has been increasing and is expected to continue doing so with climate change (Wehner, 2020). While there is debate regarding the change in number of cyclones globally over time, there is reason to expect the frequency of cyclones in the region surrounding Myanmar to be higher than the historical average. Prior to 2000 cyclones made landfall about once every three years, but in the period between 2006 and 2010 three major cyclones made landfall. Cyclones can cause economic destruction and disruption, and also generally reduce fishing effort and fishing mortality. This can allow heavily fished stocks to recover somewhat (due to temporary dissipation of fishing pressure) but they will also tend to result in extensive habitat damage, particularly to habitats with biogenic structure such as the mangrove forests, seagrass meadows and coral reefs which make up much of Myanmar's nearshore ecosystem mosaic.

Because Myanmar's coastal zone is generally low-lying, the effects of sea level rise and storm surge are expected to be dramatic (Vivekanandan et al., 2016). Large portions of the low-lying Ayeyarwady Delta are likely to be inundated, for example, and this will alter the production dynamics of this important delta-estuary system. This could also directly impact the fishing communities by forcing entire villages to relocate, increasing their poverty and thus reliance on fishing for nutrition and livelihoods.

Although dramatic changes are expected to occur which will undoubtedly lead to significant changes in species composition, the outlook for the overall fisheries productivity potential of the Bay of Bengal in the face of climate change is highly uncertain. The limited information that is available suggests that productivity under a climate change future may be similar to today (Kay *et al.*, 2018). The overall maximum sustainable yield (MSY) for the country as a whole – currently thought to be slightly over 1 million tonnes – may remain similar, but the nature of species available to fishers may change substantially.

Past fishing practices have reduced fish biomass below levels that can generate MSY, so there is substantial room for sustainable fishing practices to improve the state of Myanmar's fisheries as climate change takes hold, except under the most extreme climate change scenarios (Free *et al.*, 2020). However, even under dire scenarios, the implementation of good management can offset some of the losses that are likely to occur due to climate change.

D) Adaptations and lessons

A fishery context like that of Myanmar makes it difficult to develop and implement actions that are tailored to specific climate effects. Unfortunately, this scenario is also the case for much of the world. The lack of capacity for developing targeted measures is a function of several things that include: 1) the lack of scientific capacity to identify specific effects of climate change on fisheries, 2) the lack of capacity to link specific management actions to outcomes in the face of climate change, 3) the lack of integrity in the management system due to regulatory and enforcement shortcomings, and 4) relatively short time horizons on the part of stakeholders due to poverty and livelihood constraints.

Several collaborative efforts are underway to address existing shortcomings in the fisheries system. These include two FAO projects (FishAdapt and My-Coast) and the Myanmar Fisheries Partnership, an initiative intended to assist the Myanmar government in strengthening effective collaboration for the sustainable development of the nation's fisheries and aquaculture sector. Priority actions are described below.

A sound fishery management foundation

The first concerns the further development of Myanmar's fishery management system, including policy development and technical capacity among other areas. With this in mind, FAO's FishAdapt project has 'strengthening of the national, regional, state and township level regulatory and policy frameworks to facilitate adaptive capacities' as its first component. When it comes to addressing climate change, ensuring effective fishery governance and management is in place is a necessary foundation.

Co-management

Co-management measures are being deployed to foster adaptive capacity – and greater buy-in to management – on the part of fishers. Adaptation is built in to these institutional arrangements by way of their decentralization, and the process of implementing rules, monitoring their effects, and adjusting. Furthermore, the immediate priority of these institutions is to stabilize the fishery system (as opposed to attaining MSY), which they are doing with simple and practical measures to conserve marine resources. Tools that are being put in place include closed areas and gear restrictions, in addition to renewed compliance with previously listed national fishery laws. Management rules have been developed with input from local fishers and supporting entities (NGOs, DoF, etc), and basic monitoring of fishery catches to determine their effectiveness is ongoing.

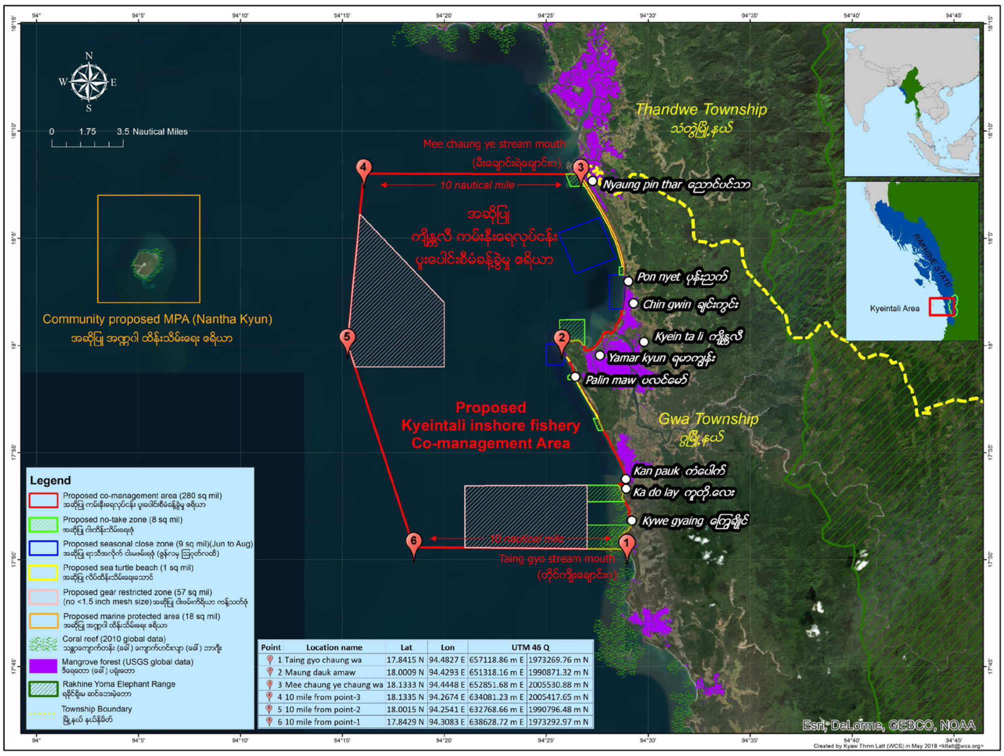

Figure 5. The Kyentali fisheries co-management area in Rakhine state (image courtesy of Wildlife Conservation Society, Myanmar)

Conservation of diverse and vulnerable ecosystems

Measures that are being put in place to conserve biodiversity are highlighted in Myanmar's NAPA to Climate Change. The conservation of coral ecosystems in the Myeik Archipelago is being carried out specifically to conserve their biodiversity, which is one aspect of fostering climate resilience. Here a co-management model – in this case an LMMA – is also being used to achieve biodiversity conservation objectives.

In Myanmar, two forms of co-management are in use: LMMAs like in the Myeik Archipelago, and fishery co-management institutions in Mon and Rakhine states which have also recently been established (see Figure 5 for an example). The LMMAs can be considered as examples of co-management, but they have a purpose more heavily focused on conservation and a requirement to follow specific LMMA rules established by the central government. The co-management relationships in Rakhine and Mon states are not subject to the same central government rules as the LMMAs. As such, the ways in which fishing activity is managed in these places differs, but both types of entities rely heavily on forms of spatial measures (areas closed to fishing or restricted to certain types of fishing).

In spite of the challenges and the hurdles that remain, there are important lessons to be learned from Myanmar's experience with marine fisheries management in the face of climate change. One is that, due to technical and regulatory capacity constraints, actions are better geared towards general resilience to climate change. In contrast to specific resilience – where actions target identified disruptions in a specified part of the system – general resilience refers to the capacity of a system to withstand all hazards, including new and unforeseen ones, while continuing to provide essential functions (Walker *et al.*, 2009). This is the route currently being taken in Myanmar, which will enable its marine fisheries to withstand and adapt to climate change effects in a general sense.

E) Conclusions and key recommendations

The history of Myanmar's fisheries is one characterized by large levels of stock depletion, a shift in the ecological structure of marine food webs due to largely unmanaged fishing (in addition to other anthropogenic stressors), and a livelihood status of fisher groups characterized by high levels of poverty. These outcomes have weakened the resilience of both the ecological and the social systems, and this is problematic when considering the effects of climate change.

Climate change promises to alter many aspects of Myanmar's marine ecology. While there is hope that the overall productivity of the system will remain similar to today, the nature of the climate impacts in Myanmar is such that habitats are changing and will continue to change dramatically for years to come. This means that the composition of species in Myanmar's waters will change, which in turn means that fishers will need to adapt to new fishery opportunities.

While building the foundation for good fishery management is currently a high priority for Myanmar and will remain so for some time, actions have already been taken in this context to help confer resilience and aid adaptation to climate change. One action spelled out in Myanmar's NAPA to Climate Change calls for the conservation of biodiversity via the protection of diverse coral areas in the Myeik Archipelago. Action has already been taken through the creation of a co-management relationship between the federal government and local fisher groups, reflecting the fact climate-resilient management actions are possible even where foundational aspects of fishery management are underdeveloped. Another action has been the establishment of co-management arrangements. These arrangements have the effective purpose of establishing Primary Fishery Management as described by Cochrane *et al.*, 2010, but the manner of implementation is enhancing the adaptive capacity of fisher groups – a management characteristic that will be necessary to handle climate change effects in future.

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Chapter 6: Combining rights-based management with science-based marine protected area networks to sustain fisheries against climate impacts in Belize

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Abstract

The waters of Belize sustain very important revenue fisheries for spiny lobster and conch, as well as complex finfish fisheries that are disproportionally important both for local sustenance and to the health of reef ecosystems and the critical tourism industry, the nation's greatest economic driver. All of these fisheries are heavily dependent on coral ecosystems, including not only the reef per se, but also nearshore mangrove and seagrass beds, all heavily threatened by warming waters, rising seas and intensifying storms driven by climate change. After 30 years of investing in large marine protected area (MPA) networks, as a primary fishery and ecosystem management strategy, Belize has refined its approach by linking expanded MPA networks to nationwide rights-based fisheries management, called 'Managed Access'. Managed Access zones now completely cover the nation's waters, and serve as the framework to which new, data-limited approaches are being applied, first for the revenue species, and now for a novel multispecies management approach for the hundreds of finfish species. Effective finfish management will be critical as climate impacts worsen, as new science shows that total abundance of fishable-sized finfish is directly correlated to coral reef ecosystem integrity. Belize will be the first to attempt integrated management of such complex finfish assemblages as an active strategy for helping to counter the negative effects of climate-induced warming. Buy-in with this approach led to fishers' active support for the recent expansion of the MPA system, from 4 percent to nearly 12 percent coverage, and for the adoption of new legislation that will sustain this integrated approach to fisheries management.

A) Fishery context

Belize's fisheries are overwhelmingly dependent on the largest coral reef in the Western Hemisphere, the Mesoamerican Reef (MAR), that stretches over 1 000 km from southern Mexico down to Honduras and Guatemala (Figure 1). The MAR ecosystem includes a continental barrier reef as well as several offshore atolls, notably Glover's Reef, Turneffe Reef and Lighthouse Reef in Belize, as well as the inshore mangrove and seagrass habitats that help sustain reef species' life histories and interact intimately with the reef itself (Gress *et al*., 2019).

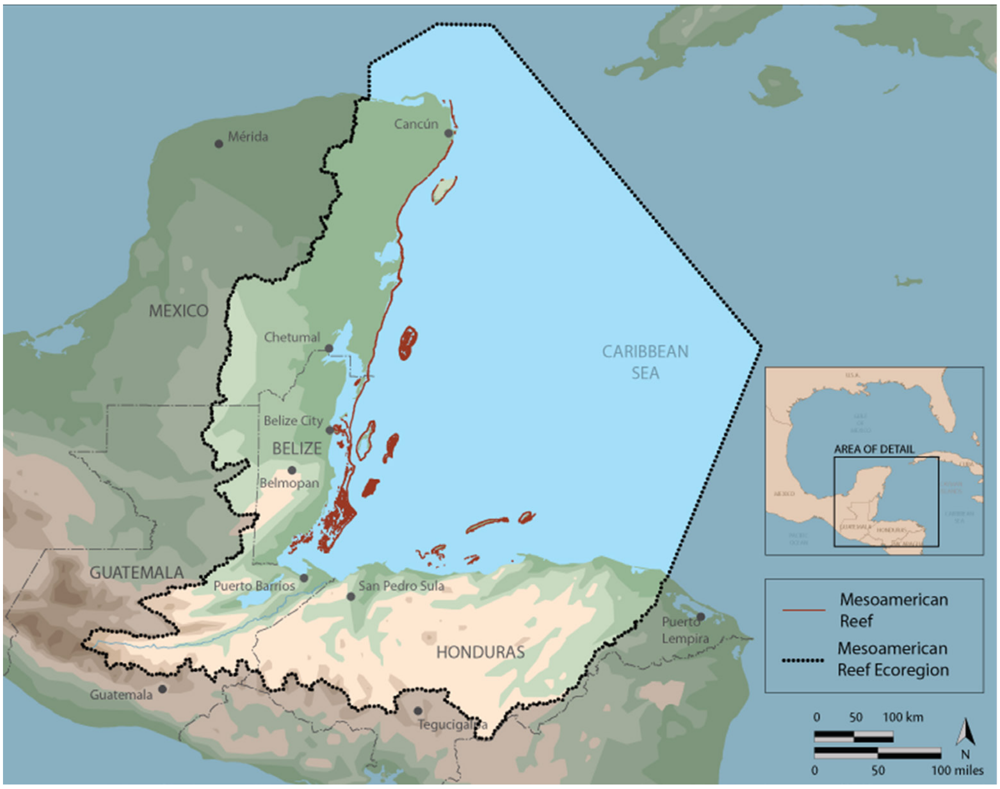

Figure 1. Mesoamerican reef ecoregion. Image courtesy of MAR Fund.

As with all major coral ecosystems, local threats are grossly exacerbated by climate warming and other cascading effects of large-scale atmospheric change, including acidification, rapid sea level rise, storm intensification and other effects that threaten not only corals *per se,* but also associated mangrove and seagrass habitats. Symptoms of declining reef health include not only coral bleaching and mortality, with associated decline in coral cover and diversity, but also overgrowth by macroalgae and sponges, and declining fish abundances. At present, the health of the MAR ecosystem remains in doubt, although the most recent MAR 'Report Card' noted an improvement from overall poor condition to fair, based largely on the joint effects of the evolution of the fishery management system and science-based networks of MPAs (Healthy Reefs, 2018).

This ecosystem is species-rich, with more than 500 species of finfish and large numbers of invertebrates. New information suggests that, as in the Indian Ocean, the total abundance of fish large enough to catch of all trophic groups is highly correlated to overall reef ecosystem health, and this could create an opportunity for targeting finfish abundance as a management goal (Karr *et al.,* 2015). Of course, abundant reef fish populations also contribute to the tourism draw related to the MAR and its economic value to adjacent countries.

Nearly 3 000 Belizeans are engaged in fishing on MAR-associated resources; most of them are small-scale operators, and most work within a cooperative structure for marketing purposes (Mayhew and Basurto, 2016; Fujita *et al.*, 2019). Key revenue fisheries focus on spiny lobster (*Panulirus argus*) and queen conch (*Lobatus gigas*), since each sustains key export markets. Both of the revenue fisheries experienced significant increases in intensity through the 1990s, with a fairly stable though fluctuating production level since about 2004 (lobster at about 250 000 kg/yr of tails, and conch at about 400 000 kg/yr) (Fujita *et al.* 2019). Note that population dynamics for both of these species depends upon higher-order metapopulation dynamics in the Caribbean Basin; conch is listed in Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), and is thus restricted from trade except as allowed by exception – which Belize currently has.

In addition, the MAR ecosystem supports more diverse fisheries for finfishes: reef fish such as snapper/grouper, cross-shelf and long-distance migrators (jacks, tunas and sharks), and nearshore soft-sediment species (mojarras – fishes in the family Gerreidae – and others). These finfish fisheries depend for the most part on the health of the reef ecosystem, and are also especially important for local markets and nutrition. Many of the more highly sought-after species, including Nassau grouper (*Epinephelus striatus*) and goliath grouper (*Epinephelus itajarra*), aggregate to spawn, making them especially vulnerable, and have been actively targeted for many years. They are also regionally depleted; both are listed in the International Union for Conservation of Nature (IUCN) Red List of Threatened Species, Nassau as critically endangered and Goliath as vulnerable. As in other places throughout the coral world, high finfish diversity and low values from production for each individual species makes traditional species-by-species management difficult, especially given the limited resources available for management in the developing tropics.

B) Management context

Belize has been a leader in some aspects of marine conservation for many years. There have been major investments by the national government, private philanthropists, non-governmental organizations and others in establishing a network of multi-use MPAs – including only a few poorly enforced no-take areas – beginning back in the late 1980s with the establishment of Hol Chan marine reserve. However, while these were important first steps towards ecosystem-based management, only limited fisheries management was possible under existing laws. Important but limited regulations were added in 2009, when the take of algal grazers (parrotfishes and surgeonfishes) was prohibited, and the harvest of depleted Nassau groupers was more strictly managed through a combination of minimum/maximum size limits and closures of known spawning aggregation sites (Usher, 2018). However, even large MPA systems by themselves are known to be inadequate to achieve conservation of coral ecosystems at scale, and that was the case in Belize (Cox *et al.*, 2017).

In 2008, Environmental Defense Fund (EDF) started working directly with the Belize Fisheries Department (BFD), local fishers and local NGOs to expand fisheries management in Belize, with an eye towards putting in place a comprehensive management regime that would be robust in the face of climate change. That partnership led to the establishment of two area-based pilot management sites in 2011, at Glover's Reef and Port Honduras Marine Reserve, to test the effectiveness of providing secure fishing rights within designated areas to eligible fishers who were already fishing in those areas. The purpose of these pilots was to test whether and how cooperative management could incentivize improved catch reporting and better compliance with conservation regulations, and help reduce illegal fishing.

These pilots were highly successful. Fishers who historically depended on these areas for their livelihoods were granted secure and exclusive rights to fish there, but were expected to become actively engaged in management design and integrated into co-management committees for each site. Fishers were able to reap the potential benefits associated with adherence to regulations, including higher sustainable catch rates. Fishing permits were no longer issued to ineligible out-of-area fishers, which

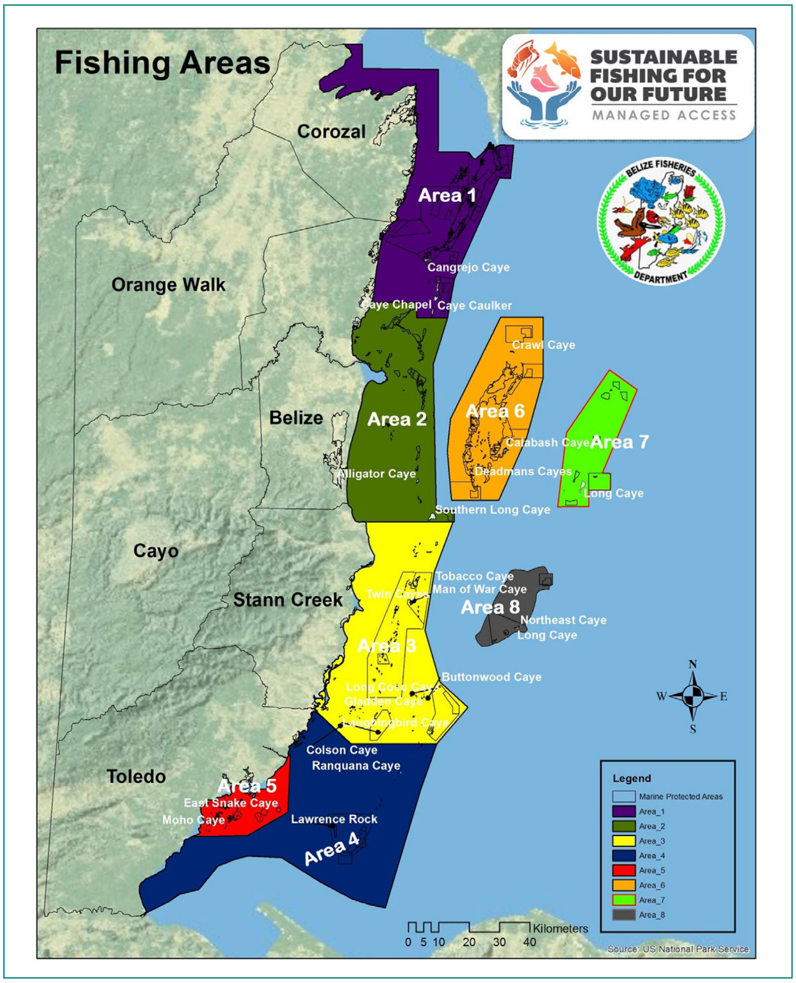

Figure 2. Belize Fishing Areas. Image courtesy of the Fisheries Department of Belize.

reduced the total number of fishers fishing in the areas. Illegal fishing violations reportedly dropped by more than 60 percent in the pilot sites. Catch rates appear to be increasing in Glovers Reef Managed Access Area, and seagrass, mangrove, and coral cover appear to have stabilized in both Managed Access pilot sites (Fujita *et al.*, 2019), countering the regional trend of decreasing coral cover (Healthy Reefs, 2018). Importantly, fisher support is broad and deep (TIDE, 2015). In 2015, the Belizean government expanded the Managed Access programme to all of the territorial waters of Belize, implementing this national roll-out in June 2016 (Figure 2) (Government of Belize, 2015; Fujita *et al.*, 2018; Fujita *et al.*, 2019; Wade *et al.*, 2019).

The pilots also made clear that data limitations were rife in this system, and that both better data and new scientific approaches were required. EDF and partners assembled a team of scientists working in data-limited systems. Significant progress has been made in recent years with respect to overcoming key scientific challenges of managing poorly-understood multispecies fisheries systematically, beginning with the development and implementation of data-limited assessment and management approaches (summarized in Apel *et al.*, 2013; Honey *et al.*, 2010; Fujita *et al.,* 2016a and 2016b). The central idea in building out this still fairly new, but increasingly available, toolbox is to develop and deploy stock assessment tools that can generate management guidance using data that are likely to already exist (however incomplete) or be readily obtainable. Recent applications have also used combined methods to assess complex species assemblages (e.g. Fujita *et al.,* 2013).

Data-limited stock assessment and management protocols are simpler to apply and require less data, time and money than conventional methods. Moreover, available performance information (including simulation studies) suggests that such tools properly applied can effectively prevent overfishing and generate desirable levels of sustainable yield, when key assumptions are met (Caruthers *et al.*, 2014; Fulton *et al.*, 2016; Babcock and MacCall, 2011).

In Belize, the approach of constantly improving the information most needed for effective management, and then constantly improving the management approaches that better information can allow, is called 'the Adaptive Management Framework' (AMF) (McDonald *et al.*, 2017; Fujita *et al.*, 2019). This approach was first applied to management planning for both lobster and conch, where NGOs are now working with the fishery cooperatives on their implementation. Conch had a hard quota for the first time ever in 2017-18, and the season closed when the quota was met.

The success of the Managed Access programme also helped stimulate a resurgence of interest in expanding the MPA networks in Belize. The government proceeded to work with all stakeholders through a formal consultation process, and then in 2019 expanded the no-take reserve component of the nation's MPA network from 4 percent to 12 percent, including key areas on Belize's border with Honduras and Guatemala that will also help with controlling illegal, unreported and unregulated (IUU) fishing and national security (Government of Belize, 2019). This expansion would not have been possible without the success of the Managed Access programme.

In addition, the general agreement about the success of the national expansion led to a sweeping revision to Belize's fisheries management law, adopted in February 2020. The new law, perhaps a pioneer in the developing tropics, not only memorialized the Managed Access programme and the MPA programme, but also added new requirements for fishery management planning, and new compliance and enforcement programmes that together constitute a key step towards climate-resilient fisheries management.

C) Climate change implications

Climate change poses severe risks to the fisheries of the MAR ecosystem. Waters are demonstrably warming, and significant coral bleaching events are becoming more frequent, with the most recent major bleaching event in Belize occurring in 2015-16 (Healthy Reefs, 2018). Intensive coastal development throughout the MAR region potentially threatens reef health with sediment and nutrient pollution that can damage corals and aid the growth of coral competitors like macroalgae. In addition, overfishing of finfishes threatens to reduce populations of herbivores that limit algae growth, and predators that help regulate overall fish and invertebrate community structure and strengthen resilience in coral reef ecosystems. Ocean acidification from CO_2 absorption may exacerbate these risks, though little is yet known specifically about the nature of that threat to the MAR. Finally, rapidly rising seas and intensifying storms may also threaten reef ecosystems, both corals themselves and the associated nearshore habitats – mangroves and seagrass beds – that reef fauna depend upon to complete their life histories.

Taken together, these negative drivers are already affecting living coral cover, both in Belize and throughout the Caribbean. Living coral cover has declined significantly in Belize, from 70-80 percent back in the 1970s, to 30 percent on average in the mid-1990s, to about 11 percent by the mid-2000s (Healthy Reefs, 2015). The impending loss of mangrove forests and possible oil and gas exploration (and ultimately their exploitation) caused UNESCO to add the Belizean Barrier Reef to its List of World Heritage in Danger in 2009.

Some important progress has been made in recent years in taking steps that could help promote climate resilience at the MAR scale. Grazing fishes were protected in 2009 and have begun to recover. The Managed Access programme is beginning to show significant benefits (Healthy Reefs, 2018). UNESCO removed the MAR from its Danger List in 2018, after the government of Belize imposed a full moratorium on oil and gas development in all offshore waters in Belize in December 2017.

Unfortunately, though, risks continue to grow, as climate-forcing emissions expand, and as each of the factors listed above unleashes ecological cascades that remain poorly understood. The direct threats to corals from the depletion of herbivorous fishes are obvious, mediated through proliferation of overgrowing macroalgae, whereas other less direct threats are less so. One fairly straightforward example is the proliferation of three-spot damselfishes that can occur when predator populations are depressed. These damselfishes are territorial algal gardeners, nipping and damaging adjacent corals and using their nitrogenous excretions to enhance algal growth on reefs. While a single fish would make little difference, thousands of such territories on a reef crest can induce serious damage (Brawley and Adey, 1977). Reef ecosystems are so complex that depletion of nearly any category of reef fishes can have similar effects.

Managing fisheries in coral reef ecosystems has always been difficult, because there are so many species – Belize has more than 500 finfish species. Even using newer data-limited approaches, species-by-species management would be impossible, given the limited resources that are available to countries like Belize. In addition, it may be difficult to set sound goals for future fish abundances based on past abundances that were possible under historical conditions. Models of future fish production under climate forcing generally predict that total fish production capacity in the developing tropics may decline significantly, by as much as 20-40 percent (Lotze *et al.*, 2019), and this would likely be exacerbated by habitat losses from reefs and mangroves (Sippo *et al.*, 2018). In addition, the species makeup of reef ecosystem fisheries is also very likely to change, both in overall diversity and relative abundance of individual species. Thus, past abundances, species-by-species, will be poor targets for management for the future.

Not only does climate warming affect coral reef health, and coral reef health determines the abundance of fish on the reef, but the opposite is also true: fish abundance can help determine reef ecosystem health. One well-known example is that herbivorous fishes (parrotfishes and others; here blue tangs) help sustain reefs against coral overgrowth. However, new science shows that the total abundance of all types of fish big enough to catch is closely associated with coral reef health. Peer-reviewed science from both the Indian Ocean and the Caribbean shows that there are clear break points in total fish biomass that distinguish excellent from good reefs, and good from poor reefs (McClanahan *et al.*, 2012, 2015; Karr *et al.*, 2015). Thus, multispecies finfish management can provide a direct benefit for future reef health, and a hedge against the impacts of climate change (Selkoe *et al.*, 2015). Partners working on climate-resilient fisheries in Belize (government, NGOs, fishing interests and academic scientists) are trying that out for the first time, as explained below.

A coral reef ecosystem conservation target for finfish management can potentially be based on non-linear relationships between metrics of coral reef status and fish abundance. For example, McClanahan *et al.* (2012, 2015) showed that coral reefs in the Indian Ocean exhibit non-linear thresholds in several coral reef status metrics (e.g. coral cover, macroalgal cover, species diversity) that are statistically related to certain levels of overall fish abundance. Karr *et al.* (2015) demonstrated the existence of similar thresholds in coral reef status related to total fish abundance in Caribbean coral reefs. These studies both suggest that total fish densities of between 50 and

100 percent of unfished levels are associated with coral-dominated states with high species diversity, while several coral reef status metrics exhibit non-linear changes at fish densities between 30 and 50 percent of unfished levels. Fish densities below 30 percent of unfished levels are associated with macroalgal dominated states with low biodiversity.

It remains uncertain as to whether these relationships are correlational alone, or whether active management for specific total finfish abundance can maintain – or at least extend – overall reef health. Regardless, having an additional target for management that recognizes these thresholds, and perhaps adds a higher aggregate fish target than traditional fisheries management (i.e. for single-species maximum sustainable yield, MSY) would suggest, may well be a prudent strategy for climate resilience in coral-based tropical ecosystems.

D) Adaptations and lessons

The gravest challenge for fisheries management in Belize, and many other places throughout the developing tropics, is how to promote outcomes that sustain people and nature together, given the likelihood of declining maximum fisheries production expected under most of the achievable climate change scenarios. It will be essential for the whole region – and for the MAR – for climate-forcing emissions to be reduced, and it will be critically important that strong fishery management systems are emplaced as soon as possible to help reduce those negative effects.

In terms of marine ecosystem-based management opportunities, the first and most obvious lesson from the Belize marine ecosystem experience is that even large, numerous and well-designed MPAs by themselves can go only so far in protecting and restoring marine ecosystems that are subject to multiple threats associated with climate change. The corollary is that those networks can serve as a strong foundation if they are supplemented by effective fishery management systems. It is also very clear that in the small-scale fisheries world, rights-based fisheries management and interactive co-management (Managed Access in Belize) are excellent approaches that can create management systems that work, with positive incentives for enduring engagement by fishers, even in systems where harvests are likely to decline. This very strong and consistent message from around the world – that successful management of small-scale fisheries requires the buy-in and active participation of the fishers – cannot be overstated. Thus, the investment in MPAs from the late 1980s laid an essential foundation for reform, but it needed to be coupled to fisheries management systems that fishers believed in and understood before that power could be effectively leveraged.

Another key lesson was that building out the Managed Access system from the first two pilot sites to a nationwide system depended upon a process that created management system attributes that met fishers' needs, resulting in buy-in that helped accomplish nationwide implementation. That engagement and buy-in was also critical to the expansion of the MPA network, which was accomplished in 2018. Finally, the trust built among all actors has directly contributed to the development and now imminent passage of the new legislation: this will create a firm foundation for future fisheries management, as a key step towards climate-ready fisheries.

The evolution of fisheries management towards climate-readiness in Belize also depended upon the use of the AMF, where each fishery component must be managed using assessment systems and accounting and accountability tools that make the most of available data and create a clear process to improve management systematically as data availability improves. Critically, each of these components will change as climate impacts unfold – both on the biology of particular species and on the ecological system in which those species exist. Thus, managing for past conditions using purely historical data is doomed to failure, and this challenge is magnified in the developing tropics, where complex groups of species are shifting through time as a result of climate change impacts. This is why the scientists working with the AMF are looking to establish management mechanisms and targets that reflect future realities and key ecological circumstances that will change through time, adaptively.

In each fishery management planning process so far in Belize (lobster and conch), a group of external scientists (including EDF scientists) has been available to determine the best approach using available data, and also what additional information would best reduce uncertainty and improve performance through time.

A recent management strategy evaluation of the data-limited AMF developed by BFD and partners for Belizean lobster and conch – applying the AMF – indicates that superior outcomes are possible relative to other assessment and management approaches, including size limits and seasonal closures (Harford *et al.* 2016). More importantly, the use of data-limited methods can actively facilitate improved outcomes, through adaptive management that includes partnerships with fishers and fishing enterprises, including consistent improvements in performance (Fujita *et al.*, 2014; Fujita *et al.*, 2016a).

More small-scale fisheries are starting to use data-limited stock assessment methods (Karr *et al.* 2017). In Belize, Babcock *et al.* (2013) used length-based sustainability indicators to assess the status of several Belizean finfish species at Glover's Reef. The Belize Fisheries Department now uses data-limited methods to help manage conch, and the team focused on lobster are doing the same, working with the fisher collectives.

The key remaining step for climate-ready fisheries in Belize, then, is adding effective finfish management onto the Managed Access system, using the AMF, based on the best data-limited approaches. While all Belizean fisheries remain relatively poorly known, and data-limited, this is especially true for finfish. However, even the best low-data, stock-specific approaches are likely to be unsuited to complex, multispecies coral-reef fisheries; many species are caught at the same time with the same gears, and they interact ecologically. Even the best data-limited approaches would require assessment and then management for each of many dozens of finfish species, for which resources often remain insufficient, not just in Belize but throughout the developing tropics. We are therefore exploring how to employ management for groups of similar species, recognizing that such approaches could pose a risk of serial depletion of less productive stocks. The key, then, is in how to group species and make sure that individual species within groups are not subject to overfishing. Another benefit of using appropriately constructed species groups is that they can readily be adjusted to accommodate shifting species compositions and abundances.

A species grouping approach has been used in multispecies fisheries in the United States of America – though not with the aggregation of total abundance used as a secondary fisheries goal – using multispecies 'stock complexes' that aggregate ecologically similar species for collective management (Cope *et al.* 2011). Perhaps the most relevant example for Belize comes from the United States of America Caribbean, where there are currently 35 stock complexes identified and theoretically subject to management: Caribbean groupers (minus Goliath and Nassau, which are managed separately), parrotfishes, snappers, tilefishes, an aquarium trade mixed-species complex, and three geographically explicit complexes each for triggerfishes/filefishes, angelfishes, boxfishes, goatfishes, grunts, jacks, scup/porgies, squirrelfishes, surgeonfishes and wrasses. Note, however, that relatively few of these complexes have been scientifically assessed to date.

In Belize, BFD and EDF are working with other groups and fishers to develop a novel application of this approach to the finfish of Belize. It includes targets for total fish biomass based on non-linear thresholds in the relationship between coral reef status and total fish biomass (McClanahan *et al.* 2012, Karr *et al.* 2015). To simplify management and prevent serial depletion of weak (lower productivity) stocks that mix with and are caught together with stronger (higher productivity) stocks, species will be grouped into stock complexes according to their biological and ecological relations, as well as vulnerability to overfishing (estimated with Productivity Susceptibility Analysis; Patrick *et al.* 2009) and their abundance relative to unfished levels (estimated with data-limited methods; reviewed in Fujita *et al.*, 2013). These complexes can then be managed with different fishing mortality targets and limits suited to their vulnerability and depletion status. Fishing mortality will be controlled by using a multi-indicator AMF (Fujita *et al.*, 2013, MacDonald *et al.*, 2017) which includes fishery performance indicators, targets, harvest control rules, harvest management measures, and accountability measures to ensure that economic, ecological and social goals are met.

This framework is an adaptation of the Framework for Integrated Stock and Habitat Evaluation (FISHE; Fujita *et al.* 2013; EDF 2019). The FISHE process was used to develop the basis for managing conch and lobster fishing mortality within Belize's Managed Access governance system, which we anticipate will incentivize managers to control fishing mortality in accordance with scientific evaluations of fishery performance against these targets, and incentivize fishermen to accept and comply with the management measures necessary to ensure that targets are achieved. The goal now is to apply this same step-by-step process to improve the management of the multispecies finfish fishery within these same Managed Access Areas.

The Belize team – BFD staff, representation from the Wildlife Conservation Society, the Audubon Society, the Nature Conservancy and Toledo Institute for Development and the Environment (TIDE), along with Dr. Kendra Karr of EDF – carried out an initial workshop in 2017 to identify finfish management goals and a workplan for moving forward on multispecies management. Dr. Karr then presented this approach to stakeholders. BFD reinforced the concept in a workshop to walk through applying the FISHE framework using the 'fish baskets' approach to practise the steps, focused on 18 priority finfish species.

The team is moving forward now to turn this theoretical concept into a working model, using Turneffe Atoll as the location for a prospective pilot; EDF has funded the Turneffe Atoll Sustainability Association to hold the first workshop to consider how such a pilot should be designed, expected in January or February 2020. We expect that a successful pilot at Turneffe Atoll could spread this idea rapidly throughout the Managed Access system and become the centrepiece of a nationwide finfish management plan over the next few years.

E) Conclusions and key recommendations

Belize has made tremendous progress in building a climate-ready fishery management system, by coupling nationwide spatial co-management (achieved through the Managed Access programme) to its longstanding but only moderately successful MPA network. Belize also added cutting-edge data-limited science to the assessment and management system, using the AMF, which has now been applied to the two important revenue fisheries, and which is now also being applied to the finfish fisheries that are essential not only to subsistence fishing communities, but also to the future of coral reef ecosystems. Fisher buy-in to Managed Access also led directly to the expansion of the original MPA network to be greater than the 10 percent MPA target; new MPA zones were chosen also to help reduce fishing pressure on areas near Belize's southern border, where IUU fishing is challenging to control. These advances are now in the final stages of being memorialized in sweeping new fisheries legislation, which is expected to be adopted imminently.

While all of these advances contribute to the establishment of climate ready fisheries, this final step – including effective management of coral-reef-associated finfish – will be the most important step yet, since the best available science suggests that the future health of coral ecosystems in the Caribbean is directly tied to total finfish abundance. Because we know the threshold levels for coral system change, we can tune finfish removals to leave behind adequate abundance of those species groups not just to prevent overfishing but also – we expect – to help sustain corals. Belize will be the first trial of this new idea in the world. Belize is also exploring targeted investment in mangrove and seagrass habitat protection and enhancement – these also sequester carbon – and the potential for such blue carbon investments to help achieve ancillary reef ecosystem benefits directly by habitat provisioning for the finfish that help sustain the reefs.

To keep at the cutting edge of climate-readiness in the developing world, Belize should: 1) ensure the effective implementation of its newly revised fisheries management laws, 2) emplace finfish management pilots that are scaled to meet coral ecosystem needs, 3) use the new law – including the coupled Managed Access and MPA programmes – to expand those pilots nationwide, using flexible new tools developed through the AMF, and 4) supplement directed fisheries management with a national habitat plan focused on future needs, taking climate-forcing into account. Of course, all of this is best achieved in ongoing partnership between government, scientists, NGO experts and fishers.

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Chapter 7: Climate change and the Philippine sardine fisheries: status of stocks, stressors, threats and measures for sustainability

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Abstract

Small pelagic fish make up over half of the total marine capture fisheries production in the Philippines. Of these, sardines make up the majority. Sardine fisheries are one of the main economic drivers in the Philippines, contributing significantly to food security and providing livelihoods for millions of Filipinos. Local sardine stocks are, however, already impacted by overfishing, having been harvested beyond sustainable levels as early as the 1970s. There are existing management measures that aim to increase and protect the Philippines' sardine fisheries resources, but a better governance system is needed to implement and enforce them more effectively. Furthermore, a lack of measures that take into account environmental variability make fisheries resources more vulnerable to the impacts of climate change. Climate stressors and risks to the sardine fishery will likely vary among the six major sardine fishing grounds in the country, considering the differences in the drivers of primary production and vulnerability of communities. Though the effects of climate change are still being understood and documented, several consequences may well follow for the sardine stock and fishery. These include an intensification of upwelling, stronger stratification of the water column, a decrease in drying capacity, the relocation of fishers along the coast, increasing vessel safety concerns and a reduction in effective fishing days. In terms of climate change adaptation in fisheries management, the country's current priority is addressing overexploitation to help improve resource sustainability and build resilience to future changes. There are several obstacles making this task more difficult, and they apply to capture fisheries in the country in general.

Fishery context

The Philippine archipelago is located between latitude 4.7°N and 21.2°N, and longitude 116.7°E and 126.6°E. It consists of more than 7 000 islands with a total land area of approximately 300 000 km^2 (Cinco *et al.*, 2014) and over 2.2 million km^2 of highly productive ocean (Green *et al.*, 2003). Ocean circulation and stratification within the archipelago are influenced by complex interactions between bathymetry, a seasonally reversing Asian monsoon wind system, and the tidal and non-tidal circulation between the South China Sea and Western Pacific Ocean (Han *et al.*, 2008; Gordon *et al.*, 2011) (Figure 1). These characteristics explain the high marine biodiversity in the country's seas as well as the high productivity supporting the various sardine fisheries.

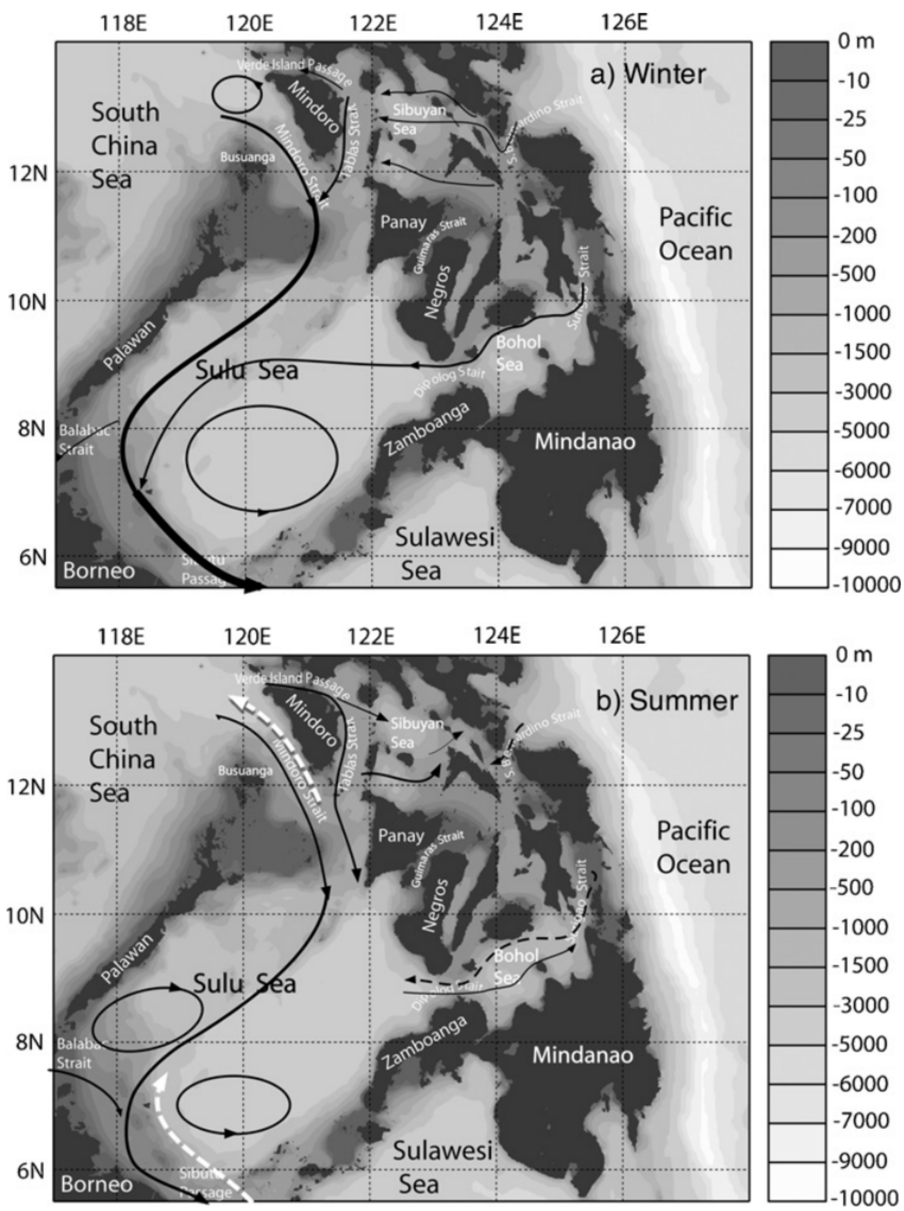

Figure 1. Seasonal surface water circulation in the Philippine archipelago. Surface currents exhibit strong variations or reversal from (a) winter to (b) summer. The dark dashed lines at the San Bernardino Strait, Surigao Strait and in the Bohol Sea in (b) indicate opposite surface flow at 40 m depth during summer. The white dashed lines at the Sibutu Passage and Mindoro Strait in (b) indicate the April-June current reversals at 40 m depth. Image adapted from Han *et al.* 2008.

There are six major fishing grounds where sardines make up a substantial (>30 percent) part of total catches (Figure 2). These include: (1) Ragay Gulf/Ticao Pass/San Bernardino Strait, (2) Visayan Sea, (3) Northern Mindanao – Butuan Bay and west to Iligan Bay, (4) Zamboanga Peninsula, (5) Illana Bay to Moro Gulf, and (6) Sulu Archipelago (Figure 3) (Campos *et al.*, 2017). The drivers of primary production influencing the abundance and diversity of sardines in these areas range from the convergence of water masses to the mobilization of nutrients from land and upwelling.

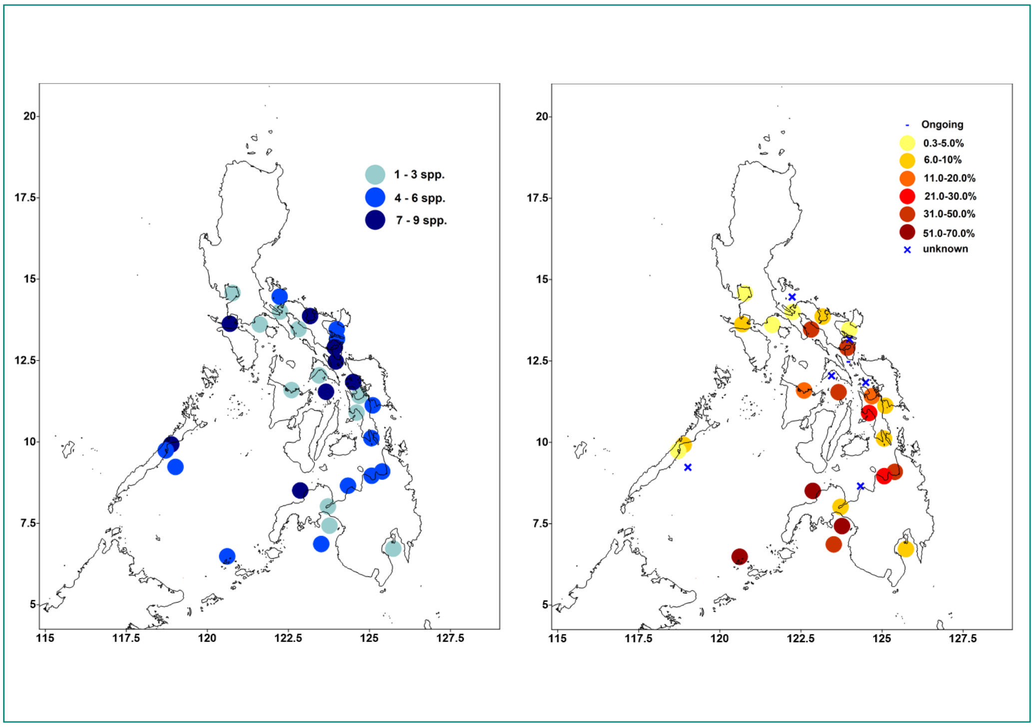

Figure 2. Left: Clupeid diversity (nine species) (in number of species) in various fishing grounds in the Philippines based on available information. **Right:** The relative contribution of clupeids to total annual landings for 30 fishing grounds reviewed in the Philippines. Map adapted from Bagarinao and Campos (2018).

Seventeen species of the Clupeidae family occur in Philippine waters, 15 of which are listed in FAO identification sheets (FAO, 1999). The remaining two are *Sardinella goni,* newly recognized by Stern *et al.* (2016), and *S. pacifica,* previously misidentified as *S. fimbriata* (Hata & Motomura, 2019). Philippine sardines are very diverse, and the literature shows they have been subjected to inconsistent identification or possibly shifts in species composition (Seale, 1908; Herre, 1953; Whitehead, 1985; Conlu, 1986; Quilang *et al.,* 2011; Campos *et al.,* 2017). However, shifts in species composition can no longer be verified and will remain uncertain, because of problematic identification of species historically reported in various fishing grounds. Figure 2 shows clupeid diversity in various fishing grounds in the Philippines. The main sardine stocks that dominate the fishery are *S. lemuru, S. gibbosa* and *Amblygaster sirm,* followed by *Herklotsichthys* quadrimaculatus (these are more restricted to inshore areas than *S. fimbriata*). Of all the sardines found in the country, *S. lemuru* is the most abundant and commercially important; but it does not dominate sardine stocks in all areas (see Figure 3) (Campos *et al.,* 2017).

Small pelagic fish make up over half of the total marine capture fisheries production of the Philippines. Of this, sardines make up the bulk (16.8 percent). The sardine fishery is one of the main economic drivers in the Philippines, comprising 7.7 percent of the total value of all fisheries, equivalent to approximately PHP 10 billion (~USD 220 million) (Santos *et al.,* 2014). It contributes to food security (comprising 11 per cent of the total fish food supply in 2017) and provides livelihoods for millions of people (fishers, bottlers etc.) (Baticados, 2019). Sardine landings peaked in 2009 (461 692.78 tonnes) but have declined ever since, averaging 341 931 tonnes/yr from 2011–2017 (Figure 4).

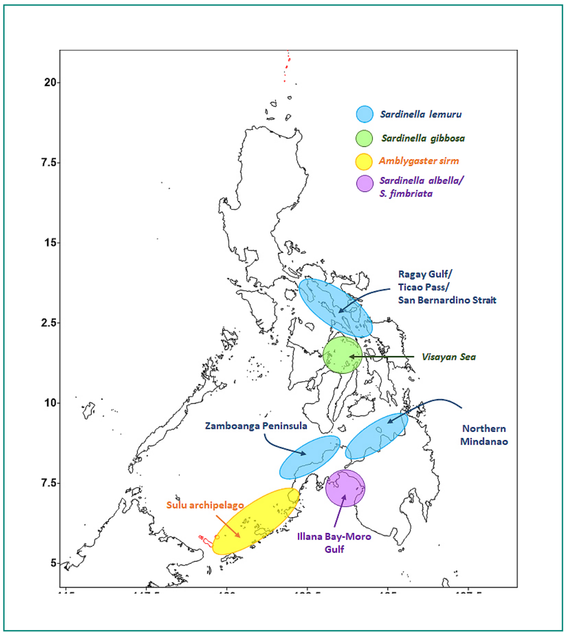

Figure 3. The six major fishing grounds in the Philippines where sardines make up a substantial part (>30 percent) of the fishery and the corresponding dominant sardine species (Campos *et al.* 2017).

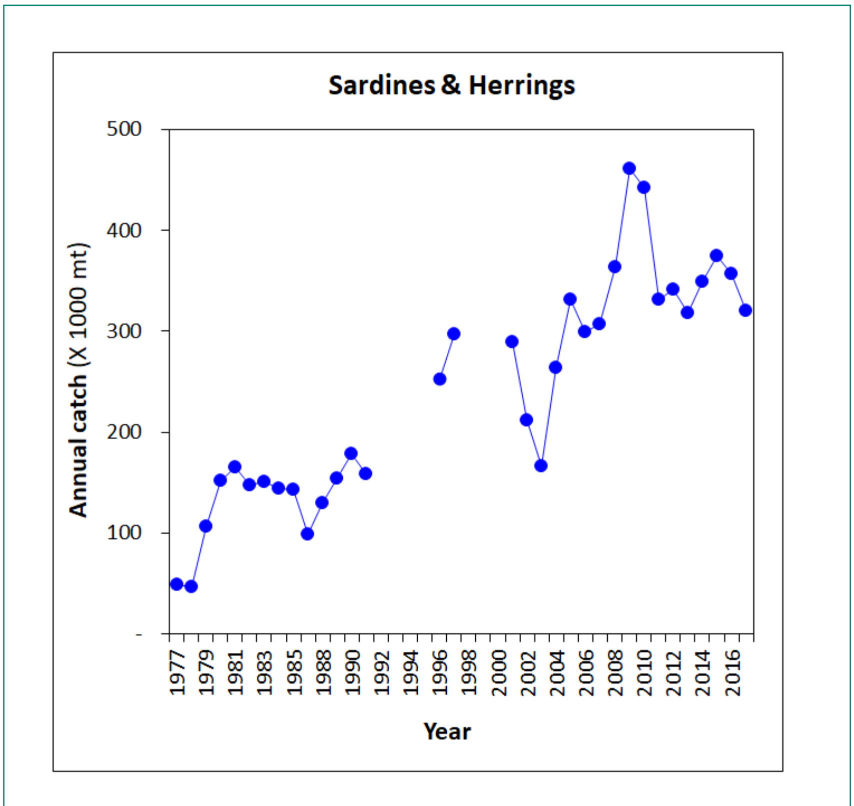

Figure 4. Total annual sardine and herring production in the Philippines from 1977 to 2017 (PSA). Data from 1992 to 1995 was not included because this figure only includes volume of catch from major gear types. The data from 1998 to 2000 is missing because there were no BFAR fisheries profiles published for 1999 and 2000 (the profile for 1998 used 1997 catch by species group but 1998 total landings by sector). During these years, the agency mandated to collect data (Bureau of Agricultural Statistics) was restructuring/revising its survey design.

From 1977 to 1987, estimates were based on the landing site monitoring programme of the Bureau of Fisheries and Agricultural Resources (BFAR) following international protocols. However, in 1988 the mandate to gather fisheries production data nationwide was transferred to another agency, so estimates from 1988 to the present are based on a different but unknown monitoring scheme undertaken by the Bureau of Agricultural Statistics (BAS) and more recently (since 2013) the Philippine Statistics Authority (PSA). Because details of the latter monitoring scheme remain unavailable, the reliability of estimates is questionable. The lack of consensus in monitoring schemes and absence of cooperation in the verification of fisheries statistics result in continued low confidence in the annual catch estimates reported for the Philippines.

A wide range of fishing gears targeting sardines are used in Philippine waters. These include commercial fishing vessels (>3.0 GT) with gears such as purse seines, ring nets, bag nets, drift gill nets and midwater trawls; and municipal fishing vessels (<3.0 GT) with gears such as encircling gill nets, drift gill nets, surface gill nets, lift nets, beach seines and scoop nets. Early juvenile sardines are targeted with fine mesh nets, typically in nearshore coastal waters. Both vessel types use accessory devices such as fish finders, high-powered lamps, fish aggregating devices and hookah compressors (to close nets underwater) to enhance efficiency and increase catches. Some vessels still engage in dynamite fishing. Commercial vessels targeting sardines do not usually target other species; while municipal fishers shift gear types depending on sea conditions (related to monsoons), seasons (lean versus peak months of targets) and other factors like closed seasons. The municipal fishers operate by borrowing money from buyers which they pay back with their catches. The buyers often transport the fresh catches to the local market or to another distributor, depending on how accessible the consumer market is. This municipal fisheries structure is similar all over the country.

The last fisheries-directed census (2002) showed there were a total of 1 614 368 fishers in the Philippines (BFAR, 2018), 85 percent of whom were from the municipal sector, while the rest were from the commercial capture (14 percent) and aquaculture (1 percent) sectors. Using the average annual population growth rate of 1.9 percent from the decade 2000–10, the updated estimate for 2018 was close to 2.2 million fishers directly relying on fisheries as their primary income. If each fisher was head of a household, for an average household size of 4.4 in 2018, the number of individuals indirectly dependent on fisheries for their livelihood was around 9.6 million. The proportion directly involved in sardine fisheries is unknown, but it would likely comprise up to a third of the fishers in the major sardine fishing grounds (i.e. the Zamboanga Peninsula, northern Mindanao and the Visayan Sea).

Most fishing grounds in the Philippines are overfished, including the most productive ones (Green *et al.,* 2003; MERF, 2006). Evidence for this includes: (1) the shift of commercial operations away from Manila and the Visayas to Zamboanga after the decline in the Visayan sardine fishery of the 1970-80s; (2) the decrease in catch per unit effort (CPUE) for small pelagic fish despite an expansion of fishing fleets and effort; and (3) the reduction in size composition (Willette *et al.,* 2011). Moreover, updated information on some aspects of the biology of *S. lemuru* and *S. gibbosa* shows reduced fecundity, smaller size and younger age-at-maturity, and a lack of older individuals (>2 years old) in the population, which are further indications of prolonged overfishing (Campos *et al.,* 2015, 2019; Campos, 2018; Bagarinao, 2018). Reported fishing mortality and exploitation rates for various sardine stocks in the country range from 0.72 to 7.14 and 0.21 to 0.79 respectively (Campos *et al.,* 2017), with sustainable harvest levels having been exceeded as early as the 1970s (Pauly, 2004). Stock assessments have made bold recommendations to reduce fishing pressure by half to maintain the viability of stocks (Zaragoza *et al.,* 2004), yet fishing effort has continued to increase.

Management context

Philippine fisheries are jointly managed by the national government through the Department of Agriculture-Bureau of Fisheries and Aquatic Resources (DA-BFAR) and by local government units (LGUs). The latter have jurisdiction over municipal waters within 15 km of the coast, in conjunction with Fisheries and Aquatic Management Councils (FARMCs) and/or Integrated FARMCs (IFARMCs). The former manages all non-municipal fisheries and aquatic resources.

Philippines fisheries are governed by the Fisheries Code of 1998, which provides for a national policy on the sustainable use of fishery resources to meet the population's growing demand for food. It calls for integrated coastal management of fishery and aquatic resources in specific natural fishery management areas. It addresses the interconnected issues of resource degradation and unrelenting poverty among municipal fishers; and it also promotes and protects their rights, especially in the preferential use of municipal waters (Aquino *et al.,* 2013).

The Philippine Fisheries Code of 1998 (RA 8550) and its amended 2015 version (RA 10654) seek to strengthen the conservation of fisheries resources in the country. A major provision in these codes is the delegation of authority over coastal waters and their resources to municipal LGUs. Under this scheme, adjacent LGUs in the same fishing ground should agree to and eventually adopt a common integrated fisheries management plan. However, most LGUs have been unable to develop the capacity to determine the necessary measures over the past 20 years, and building such local capacity is a long-term goal which cannot address the urgency of the current situation in most fishing grounds. The recently approved Fisheries Administrative Order (FAO) 263 provides a means to address this gap by grouping major fishing grounds in the country into Fisheries Management Areas (FMA) based on information on the distribution of major stocks. Under this FAO, policy and management decisions are made in an integrated manner through the FMA management councils, and technical support and advice are provided by FMA Science Advisory Groups with representatives from academia, research institutes, conservation organizations and BFAR researchers. The current scheme for FMAs is very much in the development stage, with the Visayan Sea in the central Philippines as the initial site.

The current National Stock Assessment Programme (NSAP) – coordinated by BFAR's primary research arm, the National Fisheries Research and Development Institute (NFRDI) – has carried out regular dock-side monitoring of landed catches at strategic locations within major fishing grounds in all regions of the country since the early 2000s. But because of information gaps, this data does not allow estimates of total production by fishing ground. Sardines have been a special focus in the Visayan Sea and northern Mindanao, where growth, mortality and exploitation rates are routinely estimated each year. However, year-round reproductive biology studies and effort monitoring, particularly of the municipal sector, are major gaps in the programme. In some of the FMAs, Science Advisory Groups are making efforts to address these gaps.

A summary of management measures aimed at increasing and protecting the Philippines' sardine fisheries resources – and their effectiveness – is shown in Table 1. This table also includes new measures from the recently drafted National Sardine Management Framework Plan (highlighted blue). The plan received inputs from SAGs, the National Fisheries and Aquatic Resource Management Council (NFARMC) and national representatives of fisher-organizations from both the municipal and commercial sectors. Widespread consultations were scheduled in 2019.

Table 1. Existing and additional management measures aimed at or connected to increasing fish stocks and protecting and conserving Philippine sardine fisheries resources.

Management measures & instruments	Description	Effectiveness
Spatial restrictions (e.g. closed areas, MPAs etc.)		
• RA 8550	• Philippine Fisheries Code. Defines municipal waters as all coastal waters within 15 km of the shore and bans fishing by all commercial vessels (> 3GT) in this area.	• The BFAR (national government) issues licences to fishing vessels above 20GT. The small commercial vessel sector (3-20 GT) is always issued permits by the LGU and is implicitly allowed to fish in municipal waters.
• RA 7160	• Local Government Code establishing jurisdiction of municipalities and cities over coastal waters within 15km of the shore.	• Boundaries not well defined for some areas, particularly those with islands. Difficult for LGUs to implement alone. In some areas only resident fishers are allowed, while in many others there are no restrictions.
• MPAs	• As of 2007, more than 1 300 MPAs had been established nationwide, over 50 percent of which covered areas less than 10 ha (Alino *et al.*, 2007), focusing primarily on coral reefs. More recent MPAs have included adjacent grass beds and mangroves in their no-take zones, but in general do not include substantial portions of sardine fishing grounds.	• As of 2007, only about 10–15 percent of established MPAs showed some level of implementation. The rest were "paper MPAs". With the formulation of the local MPA MEAT in 2011, more MPAs have been actively involved in implementation.
Temporal restrictions (e.g. closed seasons)		
• JAO 1 s. 2011/FAO 255 s. 2014	• Jointly issued by the DA-BFAR and DILG declaring the area of East Sulu Sea, Basilan Strait and Sibuguey Bay (covering 13 978 km^2) closed to fishing specifically for sardines from 15 November to 15 February each year.	• LGU implementation for small-scale sector differs in extent and level, and is also difficult to enforce due to multi-species nature of catches. Largely effective for medium to large commercial vessels, although encroachment into municipal waters is common in all areas.
• FAO 167 (1-3)	• Establishes a closed season for the conservation of sardines, herring and mackerel in the Visayan Sea (15 November to 15 February each year).	• Same as above.
• Coordinated ordinances of 11 municipalities in Balayan Bay, Batangas for a 22-day closed season for commercial fishing	• Designed to conserve bigeye scad and round scad resources, but affects sardines as well because of multi-species nature of catches.	• Jointly enforced by local governments with support from national government agencies (e.g. DSWD) for alternative livelihoods; compliance appears to be widespread.

Table 1. (continued).

Management measures & instruments	Description	Effectiveness
Gear restrictions (e.g. forbidden gears, limits to mesh size etc.)		
• FAO 155 – 1 (1986/1994)	• Regulates the use of fine-meshed nets (< 3cm) in fishing.	• Major gear types used for sardines (purse seines, ring nets and bag nets) are exempted from this FAO until basis for further legislation is available; also exempted is catching fry and small-sized adults of a few named species, but the law uses common names (e.g. dulong) which may include large amounts (up to 60 percent) of early juvenile sardines. Such exemptions make the policy/ law unclear making enforcement weak at best, and conflicts with the need to conserve juveniles. Because implementation of this FAO is largely at the LGU level, enforcement and effectiveness is poor.
• FAO 201	• Ban on use of active fishing gear in municipal waters.	• The level of enforcement varies at LGU level.
Temporal restrictions (e.g. closed seasons)		
• JAO 1 s. 2011/FAO 255 s. 2014	• Jointly issued by the DA-BFAR and DILG declaring the area of East Sulu Sea, Basilan Strait and Sibuguey Bay (covering 13 978 km^2) closed to fishing specifically for sardines from 15 November to 15 February each year.	• LGU implementation for small-scale sector differs in extent and level, and is also difficult to enforce due to multi-species nature of catches. Largely effective for medium to large commercial vessels, although encroachment into municipal waters is common in all areas.
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Participatory restrictions (e.g. licensing, TURFs etc.)		
• FAO 223/BFAR Circ no. 253 (2014)	• Moratorium on issuance of new commercial fishing vessel and gear licences nationwide as part of precautionary approach.	• For a period of three years only; appears to be fully implemented for medium and large commercial vessels.

Table 1. (continued).

Management measures & instruments	Description	Effectiveness
Minimum size		
• Length at first maturity (L_{m50})	• Target sizes determined for three species in various fishing grounds in the country.	• New measure included in National Sardine Management Plan 2019.
• Target minimum spawning potential ratio (SPR): 20 percent	• Target values for at least two species determined for specific fishing grounds.	• Same as above.
Limits to fishing capacity (e.g. max. number of vessels; fleet reduction programme etc.)		
• Target exploitation rate (0.3-0.5)	• Target values determined for multi-species small pelagic fisheries, including sardines; indirect measure limiting fishing effort.	• New measure in National Sardine Management Plan but specific limits to be determined once data on fishing effort, particularly the commercial sector, becomes available.

MPAs: marine protected areas; DA-BFAR: Department of Agriculture – BFAR DILG: Dept. of Interior and Local Governments; MEAT: Management Evaluation and Assessment Tool; DSWD: Dept. of Social Welfare and Development; RA: Republic Act; FAO: Fisheries Administrative Order; JAO: Joint Administrative Order; MC: Memorandum Circular; LGU: Local Government Unit (municipalities and cities); TURFs: territorial use rights for fishing; Lm50: the length at which 50 percent of the fish have reached maturity.

Climate change implications

The Philippines has a tropical climate governed by the monsoon regime, with temperatures averaging between 24–27 °C through the year. The climate is highly influenced by the El Niño Southern Oscillation (ENSO), which is the most important factor affecting interannual rainfall variability. Rainfall patterns are different across the region, with mean annual rainfall varying from 960 mm in SE Mindanao to over 4 000 mm in central Luzon. A cyclonic rainy season starts with the arrival of the southwest monsoon from June to November, which extends up to February with the arrival of the northeast monsoon. Most of the country experiences a dry season from December to May. El Niño events are associated with reduced rainfall and weak cyclone activity, and occur irregularly every two to seven years. La Niña events occur less frequently and are associated with increased heavy rainfall and cyclone activity (USAID, 2017).

Several changes in the marine ecosystems of the Philippines related to climate warming are already evident, and these are expected to increase in the coming decades. The Philippines has experienced temperature spikes which have become more frequent since 1980, along with extreme weather events including deadly typhoons, floods, landslides, severe El Niño and La Niña events, drought, and forest fires (FAO, 2011). Located in the warm waters of the western Pacific Ocean, the Philippines sits in an area known as 'tornado alley,' with about 20 tropical storms entering its area of responsibility each year (Takagi & Esteban, 2015). As the ocean's surface temperature increases over time from the effects of climate change more heat is released into the atmosphere, leading to stronger and more frequent storms or other weather events. The World Risk Index (WRI) ranked the Philippines at number 3 in a list of 171 countries at risk of natural disasters (52.4 percent exposure) (Welle and Brikman, 2015). The country also ranked as the fifth most affected by climate change in terms of extreme weather events, based

Table 2. Philippines' historical climate trends and projected changes by 2050 (USAID 2017).

HISTORICAL CLIMATE TRENDS	CLIMATE PROJECTIONS BY 2050–2100
• An increase in average air temperature of 0.65 °C from 1951–2010, with greatest increases in northern and southern regions (~ 0.1 oC per decade).	• Increase in air temperatures of 1.8–2.2 °C.
• Increased sea surface temperatures of 0.6–1 °C since 1910, with most significant warming occurring after the 1970s. Since 1982, the sea surface temperature has been warming at an average of 0.2 oC per decade with an absolute increase of 0.65 °C in 2017 based on NOAA's OISST. Warming is not homogenous, with offshore areas warming at a faster rate (e.g. Pacific ocean, waters off Ticao and Antique) while other areas such as western Luzon, Sulu Archipelago, Moro Gulf etc. are warming slower than average (Geronimo 2018).	• Increased frequency of extreme weather events, including days exceeding 35 °C, days with less than 2.5 mm of rain, and days exceeding 300 mm of rain.
• Slight decline in the number of tropical cyclones entering PAR but a small increase in the frequency of strong cyclones with maximum sustained wind exceeding 170kph over the period of 1951–2015	• These trends will continue in the future.
• Increased number of strong cyclones during El Niño years and a slight increase of cyclone passage over Visayas since the 1970s.	• Increased heavy and extreme rainfall in Luzon and Visayas during the southwest monsoon, making the wet season wetter, but decreasing rainfall trends for most of Mindanao.
• Increasing trends in annual and seasonal rainfall due to extreme rainfall events.	
• Increased number of "hot days"/decreased number of "cold nights" from 1951–2010.	• Reduced rainfall from March–May in most areas, making the dry season drier.
• Sea level rise of 0.15 m since 1940.	• Sea level rise of 0.48–0.65 m by 2100.

on the Long-Term Climate Risk Index (1998–2017) (Eckstein *et al.,* 2019). Sea level rise in the country is three times higher (60 cm) than the global average of 19 cm. The rise in sea level is attributed to ENSO, the Pacific Decadal Oscillation, land subsidence, groundwater extraction and the melting of glaciers (Rodolfo & Siringan, 2006 in Kahana *et al.,* 2016). Climate warming adversely affects key sectors in the Philippines such as agriculture, fisheries and health (FAO, 2011). The country's historical climate trends and projected changes by 2050 are summarized in Table 2.

Projections of the Earth system models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) in the Philippines also show a decrease in chlorophyll a and primary production of 0.5–11.8 percent of current average values, a decrease in dissolved oxygen and a decline in pH values. Moreover, in terms of marine biodiversity, global models predict relatively high risks of marine species extinction and a low risk of species invasion (Cheung *et al.*, 2009).

Climate change poses a great threat to the productivity and sustainability of sardine fisheries via the associated impacts of increased sea surface temperature, increased rainfall, frequency/intensity of ENSO events, severity and frequency of weather perturbations, sea level rise etc. These changes threaten ecosystem health by altering conditions on which species depend to grow and survive, consequently affecting their distribution and abundance. This further endangers the food security and livelihood of the Filipinos who depend on sardine fisheries.

In the northern Zamboanga Peninsula, upwelling-driven productivity supports a thriving fishery for small pelagics dominated by S. *lemuru* (Villanoy *et al.*, 2011). The intensity of upwelling in the area varies within and between seasons and appears to be modulated by ENSO. Villanoy *et al.* (2011) noted that there seems to be a connection between sardine catch and ENSO, in that landed fish catch is low during La Niña years and high during El Niño years – although a more robust data set is needed to prove this relationship with confidence.

The variability of upwelling in the area has consequences for the early life growth of *S. lemuru*. Bagarinao and Campos (2018) reported significant intra - and interannual variability in early life growth of *S. lemuru* in the northern Zamboanga Peninsula, inferred from otolith microstructure. Moderate winds (4.2 to 4.5 m s-1) in the 2012-2013 'neutral' ENSO year resulted in increased upwelling, elevated food levels and cooler temperatures, favouring faster overall growth in larvae. In contrast, slower growth was observed during weak upwelling conditions in the 2011-2012 La Niña year, characterized by high sea surface temperatures, low chlorophyll a and weak winds (<3.8 m s-1), which may have led to weaker recruitment. Interestingly, sardine production (both juveniles and adults) was also higher during the 2012-2013 year.

The study further shows that peak hatch months with the highest number of survivors varied between seasons, but in both seasons the fish were spawned just prior to periods consistent with upwelling – hence exposure over periods of increased food supply might have enhanced their survival in spite of their slower growth rates. The earliest spawned individuals experienced the highest temperature during the season, accompanied by low food concentrations, which may explain their observed slowest growth rates. In contrast, individuals hatched in the middle of the season, timed with cooler temperatures and peak primary production, exhibited the fastest growth rates. The timing of events and observed growth and survival patterns were strongly correlated to oceanographic conditions, and were consistent for both seasons.

In contrast to the northern Zamboanga Peninsula, there is a decrease in the catch rates of small pelagic fish during El Niño in the Visayan Sea. Sardines, dominated by *S. gibbosa,* form the bulk of the small pelagic fishery in the area. During warm ENSO events, the size at hatching of *S. gibbosa* appears to be smaller (Campos, 2018). These sardine –environment interactions still need to be explored.

Climate stressors and risks for the sardine fishery may vary among the six major fishing grounds in the Philippines, considering their geographical positions and the regional differences in drivers of primary production. Although the effects of climate change on sardine populations and the fishery are still being studied, several consequences can nevertheless be predicted. Table 3 shows a summary of the biophysical changes due to climate change and their expected impacts.

Table 3. Implications of climate change for sardine resources in the Philippines.

Biophysical changes	Expected impacts
Sea surface temperature	• Affects wind systems driving upwelling (northern Zamboanga Peninsula) and dynamics of oceanographic fronts and associated productivity (e.g. Ticao-San Bernardino Strait area) • Changes in hydrography affecting larval transport (David *et al.*, 2017; Cabrera *et al.*, 2011; Villanoy *et al.,* 2011)
Intensification of ENSO	• Increase in sardine production off Zamboanga Peninsula (upwelling region) during El Niño years but decrease during La Niña years (Villanoy *et al.,* 2011). Significant variability in early growth for *S. lemuru* in the area (Bagarinao & Campos, 2018) • Decrease in small pelagic catch rates in Visayan Sea (shallow waters, rivers) (Armada, 1998) and possibly smaller size-at-hatching for *S. gibbosa* in the area (Campos, 2018)
Increase in extreme rainfall (wet season)	• Stronger stratification (density/salinity differences between layers) of the water column requiring stronger than average winds to cause upwelling, hence may decrease sardine production off Zamboanga Peninsula (Villanoy *et al.,* 2011) • Decrease in drying capacity for fish processors (particularly in the Visayan sardine fishery in which primary post-harvest method is drying)
Increased storm frequency and sea level rise	• Relocation of fishers along coast (Cruz *et al.,* 2017) • Vessel safety concerns (Cruz *et al.,* 2017) • Reduction of effective fishing days (MERF, 2006).

Projected impacts of climate change include reduced fish populations and a decrease in catch potential due to changes in habitat suitability (Geronimo, 2019). The area of marine waters suitable for sardines' survival will decrease by approximately 5 percent by 2050, while other small fish (e.g. anchovies and small mackerels) and large pelagic fish will likely suffer a greater loss (~25–80 percent) in suitable habitats.

In a low-emissions scenario (RCP2.6), the maximum catch potential is projected to decrease by 0.2–3.8 percent by 2050–2095. The decrease is not significant, but *S. lemuru* might present changes in size, growth and distribution due to the increase in temperature, the increase in stratification of the water column and the decrease in primary production (Checkley *et al.*, 2009; Cheung *et al.*, 2009; Cheung *et al.*, 2018; Geronimo *et al.*, 2018). Under this optimistic climate scenario, sardines may be able to adapt to 'milder' projected changes as a result of plasticity which allows the stocks to persist in spite of changes in their environment.

In a high-emissions scenario (RCP8.5), Bali sardine production is expected to decrease since the maximum catch potential is projected to reduce significantly by 27.3–83.3 percent by 2050–2095. The average change in maximum catch potential in the Philippines is larger than the average change worldwide, based on the projections and scenarios used (Cheung *et al.*, 2018). Table 4 shows a summary of the projected changes in catch potential worldwide and in the Philippines.

Table 4. Projected changes (percent) in catch potential, in the world and in the Philippines, for all species combined and for *Sardinella lemuru* by 2050 and 2095 relative to 2000. Two emissions scenarios are shown – RCP2.5 and RCP8.5 – based on the results of the dynamic bioclimate envelope (DBEM) model. The table shows the average change in catch potential per EEZ, as well as its range (the difference between the minimum and maximum estimate from the different climate models used in the projections).

Time frame	RCP2.6 (low-emissions scenario)				RCP8.5 (high-emissions scenario)			
	2050		2100		2050		2100	
	average	range	average	range	average	range	average	range
Global catch potential (all spp.)	-2.8	-	-2.8	-	-7.0	-	-16.2	1
PH catch potential (all spp.)	-8.3	19.6	-11.2	15.3	-23.7	35.2	-59.2	25.7
PH catch potential (*S. lemuru*)	-0.2	16	-3.8	19.9	-27.3	52.2	-83.3	26.7

Adaptations and lessons

Mainstreaming climate change adaptation strategies into national and local policies, plans and programmes is one of the objectives of the National Framework Strategy on Climate Change (NFSCC) 2010–2022. This framework takes into consideration and complies with the commitments of the Philippines in multilateral environmental treaties, specifically the United Nations Framework Convention on Climate Change (UNFCCC) that entered into force in 1994. Moreover, the Philippine Congress passed the Agriculture and Fisheries Modernization Act of 1997 (RA 8435), which establishes that the Department of Agriculture, along with other appropriate agencies, should take into account climate change, weather disturbances and annual productivity cycles in forecasting and formulating appropriate agricultural and fisheries programmes.

The government approaches to climate change are seen as reactive and more focused on disaster preparedness and mitigation opportunities than on providing long-term adaptation programmes to reduce vulnerabilities and improve resource sustainability (Nieves *et al.*, 2009). In terms of climate change adaptation to fisheries management, the priority of current efforts is sustainable fisheries management focusing on ensuring stock recovery from overexploitation, thus enhancing the resilience of the stock to climate variability and change.

Although climate change studies in the Philippines are emerging fast, they have so far been mainly focused on different fields of science. The country is still at the level of improving knowledge of fish – environment interactions and relationships in order to understand how climate variability is affecting sardine stocks , although there are already a few studies which provide insights on such dynamics (Villanoy *et al.*, 2011; Bagarinao, 2018; Campos, 2018; Campos *et al.*, 2015). Understanding the dynamics between the life history of sardines and oceanographic conditions, and how sardine populations vary naturally, may enhance the country's forecasting ability and substantially improve management interventions. The development of management models that incorporate environmental factors and trophic relationships is included as one of the goals in the recently drafted National Management Framework for Sustainable Sardine Fisheries in the Philippines. The framework also includes measures to ensure the fishery remains flexible in the face of a changing environment, and to eliminate illegal, unreported and unregulated (IUU) fishing of sardine stocks through a monitoring, control and surveillance (MCS) system. Harvest control indicators include length at first maturity, median length of catches, spawning potential ratio, proportion of juveniles in the catches, catch per unit effort of indicator gear types (i.e. fishing gears that catch the bulk of sardines or primarily target sardines), and exploitation rates. The main sardine-producing regions were identified as priority areas, with small-scale players in the sardine fishing industry the target beneficiaries.

This National Management Framework for Sustainable Sardine Fisheries in the Philippines can be adapted as a specific programme by Fisheries Management Areas (FMA). The creation of FMAs provided a science-based and participatory governance framework for conservation and fisheries management in the Philippines. It can serve as a focus for consensus-building through consultations among interest groups in addressing fisheries issues including climate change. The current scheme for FMAs is very much in the development stage, with the Visayan Sea in the central Philippines as the initial site. The adaption of the proposed management framework within FMAs can be an initial step to address fisheries issues, taking into account the differences in vulnerability of each community.

Tools have been developed to assess the local vulnerability of fishing communities. These include the Tool for Understanding Resilience of Fisheries (VA-TURF) by Mamauag *et al.* (2013) and the Fisheries Vulnerability Assessment Tool (FishVool) by Jacinto *et al.* (2015). The VA-TURF is used to assess the vulnerability of tropical coastal fishery ecosystems to climate change, while FishVool identifies commodities and areas that are highly vulnerable to climate change. The demonstration and validation of FishVool were conducted in General Santos City and Zamboanga City (southern Zamboanga), to assess the vulnerability of the tuna and sardine fishery sectors respectively. Both the tuna and sardine fishery sectors have an overall medium vulnerability (low exposure, medium sensitivity, and low adaptive capacity); however, the sardine sector showed higher sensitivity because of its high dependency (92 percent) on sardine fisheries and the strong exposure of the fishing grounds to typhoons. These findings emphasize the need for continued examination of the issues of climate change and social vulnerability, as subtle differences in coastal communities, their economies, and populations may have implications for their ability to adapt to change (Colburn *et al,* 2016). The VA-TURF can then be used to further understand the resilience of the fishery and to assist coastal communities in planning and preparing for the impacts of climate change. Both the VA-TURF and FishVool tools can provide information to assist local and national government in identifying areas and commodities that are vulnerable to climate change and require urgent measures.

Key recommendations

The evidence of overfishing in major fishing grounds in the country suggests that the Philippine Fisheries Code has not yet succeeded in delivering its main objective – sustainable fisheries. There is enough data to show sardine stocks in the two major sardine fishing grounds (i.e. the Zamboanga Peninsula and the Visayan Sea) are over-exploited. Stocks in the other areas are likely to be in a similar situation. Compounding the issue, there is a lack of management measures that take into account environmental variability: this makes fisheries resources more vulnerable to the impacts of climate change.

Fisheries management interventions are needed to help these sardine stocks recover their biological production potential, so they can continue to support fisheries and become less vulnerable to current and future changes in climate. The following recommendations highlight key management system issues which will support the Philippines' capacity to deal with climate change impacts.

1. Improved governance system to better implement and enforce the current management measures

Enforcement is weak to non-existent in most fishing grounds. While deputized local enforcement teams (Bantay Dagat) are common, their activities are often restricted by a lack of LGU funds to maintain boats and operations, a lack of political will to enforce laws, and a lack of coordination with adjacent municipalities. There are areas, however, where LGU alliances are effective and/or the provincial government plays a proactive central role. Such practices need to be replicated in more areas.

One of the most rampant abuses, which seems to be constantly occurring, is the encroachment of commercial vessels into municipal waters. Under the law, LGUs have jurisdiction over their coastal waters extending to 15 km from the coast, and commercial fishing vessels (>3 GT) are not allowed to fish within this belt. However, about 20 percent of commercial fishing operations still take place in municipal waters. This is because– as mentioned earlier – most LGUs do not have the capacity to police their waters, so compliance is essentially voluntary. The issue is further complicated by unclear policies on small commercial vessels (3–20 GT), which are licensed locally by LGUs. Because many local officials are from influential local families with ties to small commercial operators, there are few if any restrictions on the latter's fishing activities. Given that increasing small commercial vessel capacity will be the focus of future development for the municipal sector, the current lack of policy or a roadmap prevents efforts to provide the support and infrastructure that will be needed. In the case of sardine fisheries, operations requiring development support include vessels deploying encircling gill nets, drift nets, 'small' ring nets and purse seines, and midwater trawls.

A recent issue compounding the challenge is the declining supply of overfished round scads (*Decapterus spp*) in local (primarily Metro-Manila) markets. Because round scads are widely eaten in poorer communities, the short supply has become an important food security issue – this has triggered lobbying by the commercial sector to be allowed to fish closer to shore, where 'fish are still abundant' because small municipal fishers do not have the capacity to catch them all. But the commercial sector would just add more pressure to the already degraded resource. In late 2018, the government opted to import round scads from China, which has in itself stirred up other issues.

2. Improved fisheries monitoring and information systems

While there are ongoing efforts to address this issue under the NSAP, not all of the major sardine fishing grounds are covered adequately; and current protocols need to address gaps in monitoring fishing effort at the municipal level as well as inconsistencies in long-term datasets. All LGUs are required by law to form Fisheries and Aquatic Resources Management Councils (FARMCs) at the municipal and constituent barangay (village) levels. These councils consist of representatives of various stakeholder groups and are tasked with implementing fisheries management plans, if such exist. Most LGUs need assistance in formulating management plans for their FARMCs to implement: this is crucial if the recently formed FMAs are to take effect.

LGUs need the capacity to monitor local fishing catch and effort in order to determine which of the many gear types requires special attention. In the case of small-meshed nets, the absence of data showing their impact is the primary reason why they continue operating. The gaps in historical data have made it difficult to convince stakeholders, especially policymakers, of the real status of fisheries production, thus weakening their determination to formulate and implement effective interventions. Moreover, while harvest control reference points and measures provide clear targets for management plans, these need to be supported by adequate and representative data.

Fisheries monitoring systems also need to incorporate spatial information on vessels. This can provide data on spatial distribution of fishing effort and can deter the intrusion of commercial fishing vessel operators into municipal waters. Recent improvements to the Fisheries Code (RA 10654) include a section providing for a Vessel Monitoring System to monitor commercial fishing operations. However, this has yet to be implemented, and small commercial vessels should also be made part of the system. Having reliable estimates on total annual catch and information on spatial distribution of fishing effort means measures such as allowable catches or 'bag limits' can be put in place at the local level, and protected areas/seasons can be implemented basin-wide or in particular areas of the fishing ground. Lastly, fishery managers should have access to available fishery data: in order to facilitate data-sharing and access to decision-relevant information, data management systems need to be developed.

3. Efficient market chains and adequate support to the industry

The structure of municipal fisheries is similar all over the country, with fishers borrowing money from buyers which they pay back with their catches. The buyers often transport the fresh catches to the local market or to another distributor and so on, depending on how accessible the consumer market is. In island villages, the number of distributors or 'middlemen' is greater, the total cost of transport is more, and the margin of profit becomes smaller, with the smallest amount going to the fisher. While consumer prices have risen substantially in recent years, partly due to the increased cost of transport, the dockside value of catches has not – despite increases in the cost of fuel and other commodities that fishers must buy. The more 'middlemen', the lower profit fishers receive. As a result, faced with increasing costs of living and declining catches, some fishers are forced to use illegal (e.g. fine mesh nets) or destructive (e.g. blast fishing) fishing practices. If the market chain can be made shorter, with more profit going to the fishers (via value-added processing), management interventions might be more acceptable to fishers, making the goal of attaining sustainability in sardine stocks achievable within a shorter time.

Post-harvest practices must be improved to reduce sardine wastage/spoilage, which can reach up to 30 percent during the glut season. Such seasonal oversupply can cause drastic falls in prices, particularly affecting small-scale fishers. Interventions aiming to reduce spoilage and maintain good dockside prices would be helpful, and a general increase in fishery efficiency would help attain long-term sustainability and build up the resilience of coastal communities. But for this to be possible, both local and national government need to support the industry. Viable fisheries translate to productive livelihoods, more local economic activity, and ultimately a higher income for the LGU. This in turn allows the LGU to provide better services to its constituents.

The decision to invest adequately in many small facilities dealing with small-volume landings from municipal and small commercial vessels will always be difficult, but the lack of clear policies to guide decision-making makes it even harder. This is perhaps the root cause of the current lack of support for the industry.

4. Improved research results dissemination

Information from research studies will not reach policymakers unless it is published or disseminated in fora in which relevant national agencies and LGUs participate. This has no doubt contributed to the perennial lack of data mentioned above. The recent establishment of Science Advisory Groups (SAGs) at national and FMA levels – with representatives from academia, conservation organizations and BFAR technical staff – should improve the spread of information. Improved dissemination of research results should also include raising the awareness of coastal communities (the primary stakeholders) on the effects of climate variability, climate change and its projected impacts on their lives.

5. Adaptive management

Today, proactive governance is increasingly necessary to prevent stock collapse. It is crucial to incorporate climate variability into management models and harvest strategy rules, taking a precautionary approach that allows a buffer for uncertainty. Strategic long-term monitoring is essential, particularly for managing fisheries that are already overexploited. Since the necessary large reductions in effort can only be addressed gradually, step-by-step measures need to be evaluated for impact so that the necessary adjustments can be made in a timely manner. Reference points must be flexible, allowing adjustment of fishing effort to levels that are consistent with the yields that can be sustained by resource stocks.

6. Strengthen institutional partnerships

There is a need for improved interaction among all stakeholders, using FMAs as a platform to address fisheries issues and the impacts of climate change. Collaboration with regional and international institutions in pursuing research and management objectives is required.

7. Enhanced understanding of sardine biology, ecological interactions and relationships

Sardines feed on plankton at the base of the food chain, and they thus play a critical role in the transfer of energy to higher trophic levels. This makes them highly sensitive to naturally occurring short- and long-term variability in the environment, and even more so to the unprecedented climate change that is severely upsetting these natural cycles. In the multi-species sardine fishery of the Philippines there is a lack of biological data to project the impacts of climate change on sardine resources, particularly when each species may have different life history strategies and habitat requirements. Importantly, Philippine sardines are very diverse and the literature shows they have been subjected to inconsistent identification or possibly shifts in species composition. For example, *Sardinella melanura* was reported as the dominant species in Butuan Bay and Panguil Bay in the 1990s, while recent monitoring (2012–14) shows *S. lemuru* as the dominant species (90 percent). The sardine stock in Ticao/Burias Pass is in a similar situation, although whether this apparent difference reflects species-shift through the years is uncertain and can no longer be verified. Shifts in species composition are not unlikely in the fishing grounds mentioned above, since both areas are deep and dominated by small pelagic fish which are strongly influenced by hydrographic features, which in turn may fluctuate strongly between years (e.g. ENSO). Nevertheless, misidentifications cannot be discounted.

Shifts in species composition may necessitate a range of strategies to make fisheries sustainable. Flexibility in management measures may be required, because certain interventions designed for a particular sardine species may not necessarily work with another species. This highlights the importance of correctly identifying the species, since biological processes are species-specific and their variability may differ with respect to their environment. Hence it is imperative that monitoring programmes should be set up in major sardine fishing grounds, so that species shifts, if any, can be tracked and the necessary adjustments in management, if known, can be implemented. This also highlights the critical need for BFAR to work with local academic institutions to carry out research on these aspects of the fisheries, as well as sustaining these resources for the long term. It underlines the importance of improving fisheries monitoring and strengthening institutional partnerships (see key recommendations 4 and 6).

Concluding comments

This study provides an overview of the current status of stocks, stressors, threats and measures for sustainability of the Philippines' sardine fisheries. Although we recognize that the synthesis of information presented here may not cover all the data available, it is nonetheless clear that there are significant information gaps on the socio-ecological dynamics of sardine fishing in the Philippines.

This situation makes developing strategies and adaptive measures for future climate conditions very challenging – more so with an overexploited sardine resource. Addressing the overexploitation of these sardine resources should be a priority, to ensure stock recovery and enhance its resilience to climate change. There are management measures/plans already in place to address issues related to overexploitation, but the country needs to radically improve its governance system to better implement and enforce them.

Overfishing and climate change are two distinct but interconnected issues which the Philippine sardine fishery is currently facing. Sometimes the best way to achieve a resilient fishery in the face of climate change is to first put in place a sound and resilient management system.

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Chapter 8: Responses of a small-scale shellfishery to climate change: Foundations for adaptive management

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Summary

The yellow clam *(Mesodesma mactroides)* is a cool-water species that is harvested by artisanal fishers along warm-temperate sandy beaches of the Atlantic coast of South America. This region represents a major global-warming hotspot, where sea surface temperature has been dramatically increasing since the mid-1990s, when a shift in the ocean–climate regime from a cold to a warm period was detected. Yellow clam populations suffered mass mortalities that followed the poleward shift of the warm water front. A long-term decrease in abundance and individual size, as well as increasing signs of deteriorating body condition, have also been documented.

In Uruguay the fishery was reopened 14 years after mass mortalities, when the resource showed signs of recovery, even though abundance never reached pre-mortality levels. A precautionary management approach included a conservative catch quota allocated equally to a reduced number of local fishers. The institutionalization of co-management was a key factor in coping with variations in climate, strengthening collaboration among stakeholders and providing rules and action mechanisms in the face of climate-driven stressors. A shift in the marketing strategy allowed fishers to maximize economic benefits.

Currently, unfavourable weather events and an increase in intensity and frequency of harmful algal blooms restrict the number of fishable days. Weekly phytoplankton and toxin monitoring is being carried out as an adaptive management measure to cope with this stressor and to safeguard seafood health and safety. Imported seafood on local markets also exacerbates the situation by providing an alternative and competing source of clams. Flexible policies and management actions are needed to tackle the challenge of promoting a climate-resilient and adaptable small-scale local fishery.

A) Fishery context

The yellow clam *(Mesodesma mactroides)* is a sedentary infaunal bivalve distributed along warm-temperate intertidal habitats of the Atlantic coast of South America, from Brazil (24°S) to Argentina (41°S). This short-lived species (<4 years: Defeo, Ortiz and Castilla, 1992) is artisanally or recreationally exploited (shovels and hand-picking) along hundreds of kilometres of sandy beaches in Brazil and Argentina. In Uruguay, commercial fishing activity occurs along a 22 km stretch of sandy beach from Barra del Chuy to La Coronilla, at the easternmost part of the oceanic coast (McLachlan and Defeo, 2018).

Reliable fishery statistics started being collected during the fishery expansion phase that began in the early 1980s (Figure 1). Landings increased from 62 tons in 1981 to 219 tons in 1985, drastically decreasing in 1986 (102 tons), and reached only 11 tons in the first quarter of 1987 (Castilla and Defeo, 2001). This declining trend in landings prompted the closure of the fishery from April 1987 to November 1989. An informal co-management system was established in 1987 between the fishery management agency (Dirección Nacional de Recursos Acuáticos – DINARA), coastal authorities and local fishers, who implemented cooperative monitoring, control and surveillance (MCS) procedures (Defeo, 1996). Two years later, fishery-independent surveys carried out as part of MCS procedures showed that adult clam abundance had increased by more than 400 percent, and the fishery was reopened in December 1989 with the co-management system in place and the implementation of a total allowable catch (TAC), distributed as individual quotas allocated to local fishers (Defeo, 1996).

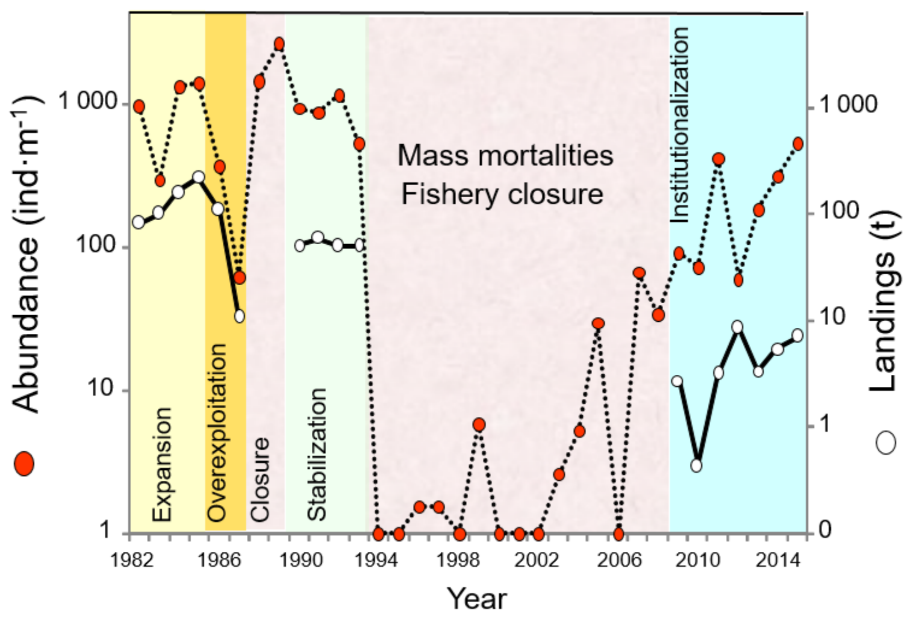

Figure 1. Long-term variations in abundance (individuals per metre) of the harvestable stock estimated through fishery-independent surveys and landings (tons) in the yellow clam fishery, Uruguay. Fishery phases, including the occurrence of mass mortality events, closed seasons and the implementation of high-level policy goals (institutionalization), are also shown. The y-axes are on a logarithmic scale.

The co-management fishery phase lasted until late 1994 and catches varied between 50 and 60 tons per year, but catch per unit effort (CPUE) was twice as high as in pre-closure years (Defeo *et al.*, 2016). In 1994, mass mortalities decimated *M. mactroides* populations throughout the entire distribution range, leading to a full fishery closure between 1994 and 2008 in Uruguay (Ortega *et al.*, 2012, 2016). The fishery was reopened in 2008, once the stock showed signs of partial recovery, under an ecosystem approach to fisheries (EAF) and a formal co-management scheme (Defeo, 2015; Gianelli *et al.*, 2018). Fishery-independent surveys showed that abundance of the harvestable stock was substantially higher than during the fishing closure, but never reached levels like those seen before mass mortality events (Figure 1). During the period 2008–2018, landings remained under 10 tons/year, and the precautionary catch quota (set annually based on abundance estimates) was rarely reached (Gianelli, Ortega and Defeo, 2019).

The yellow clam fishery has gone through different commercialization phases. The product, originally marketed as bait for sport fishing in the 1980s and 1990s, is successfully sold nowadays as a luxury seafood product for human consumption (Gianelli, Martínez and Defeo, 2015; Gianelli *et al.*, 2018). This shift in the marketing strategy was developed jointly by the fishing community and the government. Clam unit price nowadays is USD 4.62/kg, a value several times higher than in previous decades. Only a very small percentage (less than 5 percent) of the final product is sold as bait by independent fishers.

Currently, 36 individual fishing licences are allocated (Gianelli, Martínez and Defeo, 2015). Both men (61 percent) and women (39 percent) have equal tenure rights (i.e. individual fishing licences) and perform the same labour in the fishery. Fishing activity has a strong family tradition and most fishers conduct the activity jointly with family members (Pittman *et al.*, 2019).

B) Management context

A change in the Uruguayan administration in 2005 provided a window of opportunity for policy innovation. The government gave strategic priority to the development of the small-scale fishery sector and developed high-level policy goals that included EAF and consultative co-management as the formal governance mode (Gianelli *et al.*, 2018). The long participatory process towards the institutionalization of these practices was completed in 2013, when the new Fisheries and Aquaculture Law was passed (Defeo, 2015; Gianelli, Martínez and Defeo, 2015; Gianelli *et al.*, 2018).

The political juncture encouraged the conceptualization and development of the project 'Piloting of an Ecosystem-based Approach to Living Aquatic Resources Management,' financed by the Global Environment Facility, implemented by FAO and executed by DINARA for the period 2008–2014 (Gianelli *et al.*, 2018). The yellow clam fishing community wished to engage with the emerging policy and therefore became the first organized group to test the model in Uruguay, taking into account local traditions and the long-term relationship between fishers, the fishery agency and the academic sector. Social processes – including learning and communication about ecosystem dynamics between fishers and scientists – and strong social networks (which had been latent for 14 years) made the fishery a logical candidate for selection (Pittman *et al.*, 2019).

Government initiatives were used in the yellow clam fishery to reconstruct, innovate and apply new institutional and management approaches (Defeo *et al.*, 2018). Critical elements in the transition phase were the recognition of: (1) stock depletion after mass mortalities that prevented opening the fishery; and (2) the successful informal co-management experience developed during pre-mass mortality years, which played a critical role in fostering robust management and governance practices. The local process included initial planning, implementation and feedback loops with stakeholders as the core of a management plan, whose main objectives were to: (1) achieve sustainable exploitation by improving fishing practices following EAF principles; (2) empower the local community through co-management; and (3) improve the livelihood of fishers by securing employment and developing new market opportunities (Gianelli, Martínez and Defeo, 2015). The formal mechanism for stakeholder participation was operationalized by two nested decision-making bodies: the Fishers' Assembly and the Local Fishery Council (LFC), the latter being explicitly recognized in the law as the formal strategy to engage local communities in the decision-making process. Through the Fishers' Assembly, two representatives are elected to participate in the LFC, which is made up of fishers' representatives, DINARA managers, local and departmental government officers, and Coastal Marine Authority officers. The Faculty of Sciences of Uruguay, which played a decisive role during the last three decades by providing scientific information through direct assessment surveys (used as inputs to set the annual TAC) and in catalyzing the co-management process (Defeo 2015; Gianelli *et al.*, 2018), is still invited to the LFC at times. Results of assessment surveys, most of them conducted jointly with fishers, are made available to LFC members and serve as inputs for LFC discussions.

Several operational and spatial management tools are in place, including: (1) a harvest season during summer, coinciding with the highest product demand by tourist resorts; (2) a TAC per fishing season, estimated through fishery-independent surveys; (3) an allocation of a restricted number of fishing licences to local fishers with the longest histories in the fishery; (4) an individual and non-transferable quota, based on an equal share of the TAC among fishers; (5) a minimum landing size limit (50 mm); and (6) a zoning scheme in beach management units with well-defined boundaries, including units allocated solely for recreation and others for commercial harvest (to authorized fishers only) (Gianelli, Martínez and Defeo, 2015). The academic sector played a key role in creating, setting and implementing these management measures and developing the management plan. MCS activities are undertaken jointly by DINARA and the coastal marine authority (Sub-Prefecture), along with the fishers themselves, to prevent illegal fishing and violations of established management tools.

Local traditions and knowledge are also considered in determining and implementing management measures. The management agency shows respect for different local organizations (e.g. elected fishery leaders are formal members of the LFC), and has incorporated traditional local knowledge in management measures discussed at the LFC. A range of market initiatives reflect business ideas from different fisher groups, and new fishing licences always prioritize local families. Fishers also register their activity and report to the management agency via logbooks and a voluntary community-based data collection (CBDC) programme, through which each fisher can provide fishery data on a daily basis (Pittman *et al.*, 2019).

C) Climate change implications

The Uruguay coast is affected by climate change stressors, including warmer sea temperatures and sea-level rise. These have been accompanied by an increase in the frequency and intensity of onshore winds and in the frequency of storms and other extreme weather events, like flooding and droughts (Ortega *et al.*, 2013, 2016; Barreiro, 2017). This coast is located in a major global-warming hotspot in the Southwest Atlantic Ocean, where sea surface temperature (SST) is increasing at several times the average global rate (Hobday *et al.*, 2016). This increase in SST has resulted in a higher frequency of positive anomalies along the Uruguay coast, particularly since the mid-1990s, when a regional shift in the ocean–climate regime from a cold to a warm period was detected (Ortega *et al.*, 2013). The position of the warm water front (represented by the 20ºC isotherm, a proxy for the front of tropical waters) showed a consistent long-term poleward shift at a rate of ca. 9 km/year (Ortega *et al.*, 2016). This shift was accompanied by an increase in speed and frequency of onshore southern winds, particularly from the south-southeast (Escobar, Vargas and Bischoff, 2004; Ortega *et al.*, 2013). These winds enhance the advection of warm waters from the Brazil Current, especially for Uruguayan sandy beaches exposed to the swell coming from the southeast. A significant increase in frequency and height of the waves propagating from the east and east-southeast has also been observed (Codignotto *et al*., 2012), along with an increase in the frequency and duration of southeasterly storm surges (Escobar, Vargas and Bischoff, 2004; D'Onofrio, Fiore and Pousa, 2008). The Uruguay coast is also affected by a long-term rise in sea level (Orlando, Ortega and Defeo, 2019).

Increased ocean warming, onshore winds and storm intensity have affected the physical components of the social-ecological system (SES, Figure 2). Beach morphodynamics have been altered in the long-term, with an increase in swash width and wave height/period, and a decrease in the beach face slope, augmenting erosion rates and accentuating dissipative characteristics (Ortega *et al.*, 2013). These changes were positively correlated with the long-term increase in wind speed anomalies, suggesting that climate forcing is shaping beach morphodynamics.

Changes in climate observed during the last three decades on the Uruguay coast and the related changes in the physical habitat detailed above have gradually eroded the environmental quality, the target species (yellow clam), associated fauna and the social component of the fishery system (Figure 2). The yellow clam, a cool-water species of Antarctic origin, suffered mass mortalities that followed the poleward shift of the warm water front, first in 1993 in southern Brazil, and then reaching Uruguay in 1994 and Argentina from 1995 to 2002 (Ortega *et al.*, 2016). Mortalities began to occur concurrently with the ocean–climate regime shift mentioned above, particularly in late spring and early summer, when high sea temperatures increased the susceptibility of these cool-water clams to disease. These events also occurred concurrently with low phytoplankton biomass, which constitutes the main food source for clams (Lercari *et al.*, 2018). Mass mortalities, together with the long-term decrease in abundance and individual size, and increasing signs of deteriorating body condition of *M. mactroides,* have been correlated with the increase in SST (Ortega *et al.*, 2012, 2016).

These effects of climate change have elicited opposite responses in other species with different biogeographic origins. The decline in yellow clam abundance promoted an increase of warm-water species, such as the wedge clam *(Donax hanleyanus)* and the sand crab *(Emerita brasiliensis)* (Celentano and Defeo, 2016), which are subordinate competitors for space and food. The increasing prevalence of species with a tropical biogeographic origin in response to increasing SST suggests a 'tropicalization' (*sensu* Cheung *et al.*, 2013) of the ecosystem. These trends caused sweeping changes in ecosystem structure and functioning, including a simplification of the food web. Biomass distribution across trophic levels and ecosystem attributes showed marked long-term fluctuations, primarily related to changes in system productivity that resulted from the effects of increasing SST and more intense onshore winds. Ecosystem indicators reflected a fragile state, characterized by a greater organization and a lower adaptive potential to address unexpected disturbances (Lercari *et al.*, 2018; Jorge-Romero *et al.*, 2019).

The fishery has been dramatically affected by these stressors. It was closed for 14 years in Uruguay and is still closed in Argentina and Brazil, influencing economic revenues and the livelihoods of local communities (Gianelli, Martínez and Defeo, 2015). The target species did not display a short-term capacity to adapt to changes generated by the mass mortality event. This lack of resilience to the detrimental impacts of mass mortalities was evident, even under the fishery closure from 1994 to 2008. Further, although some signs of recovery were observed in almost 15 years (i.e. four clam generation times) after mass mortalities, yellow clam abundance never reached pre-mortality levels throughout the species distribution range (Defeo *et al.*, 2018). This indicates a high vulnerability to climate change, in particular a high sensitivity to increasing SST and a low adaptive capacity to respond to these changes (Schoeman, Schlacher and Defeo, 2014).

The governance and social components of the SES were not prepared to cope with the unusual changes caused by mass mortalities, showing a low collective capacity to adapt to these perturbations and to minimize welfare losses in the short-term. The governance system did not respond fast to the problem at hand, with no contingency plans in place, and no options provided to fishers to mitigate the economic impact of the fishery failure on their livelihoods, causing income losses and unemployment (Defeo *et al.*, 2018). Fishers immediately responded through autonomous adaptation actions, by diversifying their livelihoods in other sectors of the economy (e.g. construction, agriculture and selling firewood), but it was very difficult to ensure work continuity under adverse fishery conditions (Gianelli *et al.*, 2018).

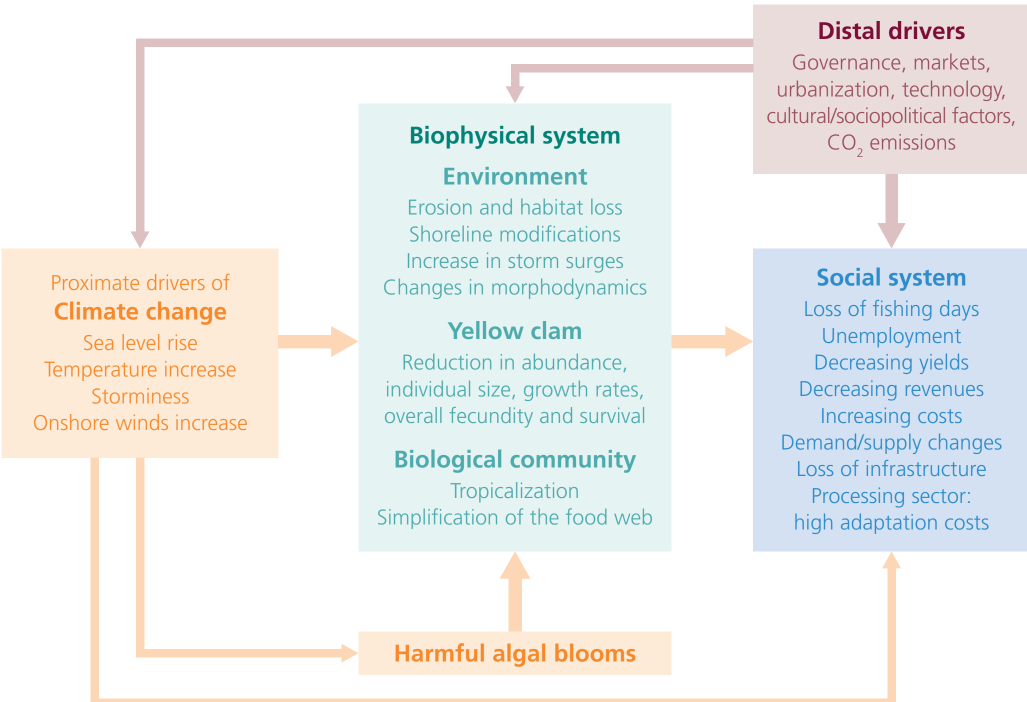

Figure 2. Conceptual diagram of the main drivers affecting the social-ecological yellow clam fishery system, with emphasis on the effects of climatic drivers on the biophysical and social components.

[1] See also https://www.washingtonpost.com/graphics/2019/national/climate-environment/climate-change-world/.

The long-term trend of increasing sea level, onshore winds and storm intensity caused beach erosion and a reduced capacity for recovery of the subaerial profile, generating habitat loss for the clam (Ortega *et al.*, 2013). These morphological beach changes limited the accessibility of the resource to fishers (Defeo *et al.*, 2013). Thus, economic income from fishing diminished due to a decrease in catch rates and in the number of fishable days over time (Defeo *et al.*, 2013; Gianelli, Ortega and Defeo, 2019), which negatively affected fishery livelihoods.

Another climate change related stressor of critical importance in this system has been the increasing occurrence of harmful algal blooms (HABs), which are most noticeable during the austral summer. The increase in HABs occurs particularly after the shift from a cold to a warm ocean climate period. These events have also produced a long-term shift in the phytoplankton community structure, with an increasing predominance of warm-water species (Martínez *et al.*, 2017). Intensification of HAB events strongly affected the fishery due to the immediate fishing bans imposed by DINARA. The number of ban (closure) days due to HABs increased from 30 days in 2014 to 33 days in 2015, and extended to the entire fishing season in 2017 (almost four months) (Pittman *et al.*, 2019). This has led to several problems for the fishery today, including: (1) loss of revenue for fishers and processors; (2) increasing economic uncertainty; (3) unmatched demand for the local market (loss of clients); and (4) if HAB events persist over several days, fishers must look for another job in localities where economic opportunities are already scarce (Gianelli, Martínez and Defeo, 2015; Gianelli *et al.*, 2019).

D) Adaptations and lessons

After the fishery reopened, specific solutions to the challenges imposed by long-lasting climate-driven stressors were identified and implemented. To this end, some elements of the management cycle were adapted in response to demonstrated climate signals (Figure 3).

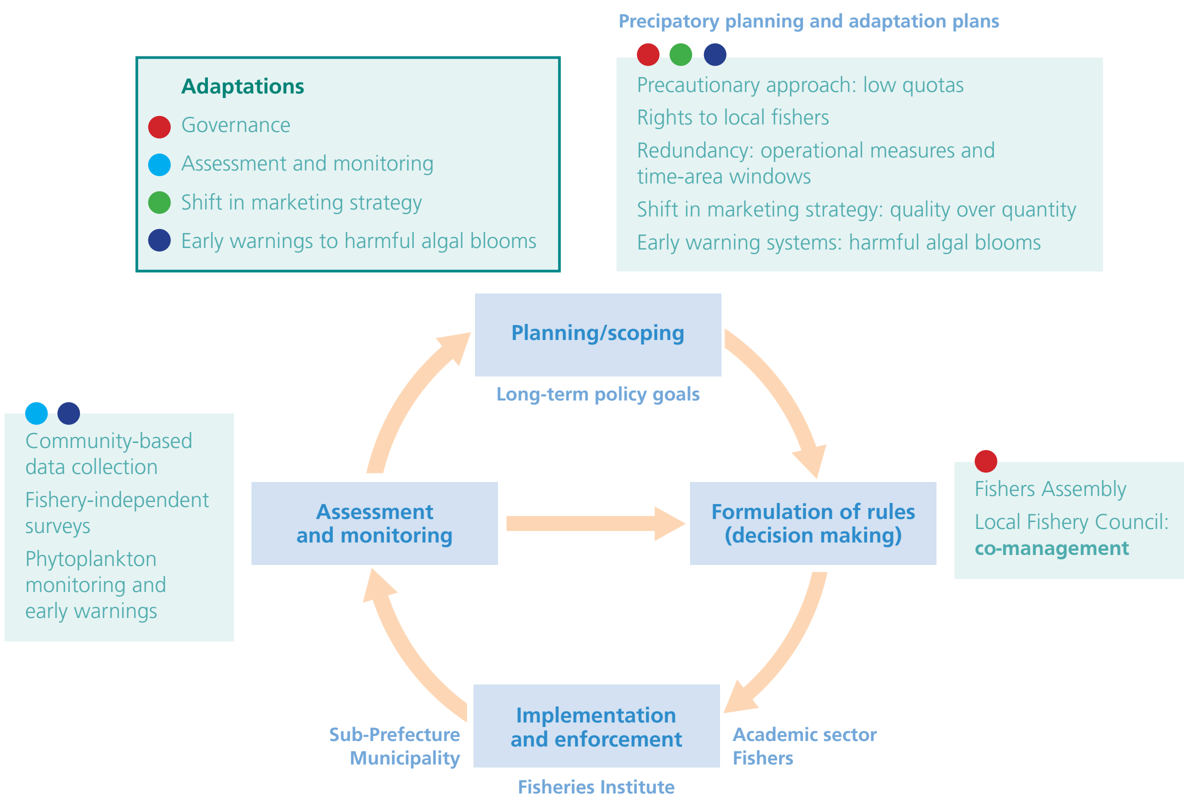

Figure 3. The management cycle for the yellow clam fishery in Uruguay, including specific adaptations and solutions to the challenges imposed by long-lasting climate-driven stressors (see text for details).

1) Governance

Governance has been perceived as an acute problem in coastal shellfisheries, particularly in developing countries (Defeo and Castilla, 2012). The nature and rate of ecological change currently being experienced because of the increasing influence of climate-driven stressors requires a significant amount of flexibility in institutional arrangements to deliver a timely response to these challenges. In this context, the implementation of high-level policy goals in the yellow clam fishery (planning/scoping process, Figure 3) was useful to empower fishers in the governance process. The participatory governance approach has played a critical role in all four steps in the management cycle for the yellow clam fishery (Figure 3). The formalization of community participation in the LFC was critical in strengthening local cohesion and empowerment. This is reflected, for example, in the way clam unit prices are regulated by the local community (Gianelli, Martínez and Defeo, 2015), and notably through the formulation of rules in the decision-making process (Figure 3). LFC meetings, which are held before and after each fishing season, foster a participatory assessment of the performance of the SES through ecological (the stock and the surrounding physical environment), socioeconomic (pre- and post-harvest activities) and institutional (norms to regulate harvest and access to resources according to established objectives) indicators, thus providing an integrated view of the three sustainability pillars.

Fishers are highly satisfied with the participatory governance structure in place, which has facilitated participation in decision-making processes and provided a platform to share their opinions about the fishery (Pittman *et al.*, 2019). Collaborative actions and adaptive responses at the community and government (i.e. co-governance bodies) levels have also provided capacity to deal with climate change. For example, fishing seasons have been adjusted to accommodate the occurrence of HABs (see below in #4), which has included closing the fishery for numerous consecutive months. LFC meetings incorporate the perspectives of local fishers, who are supportive of the closures and changes to the harvesting season, thus strengthening the implementation and enforcement processes of the management cycle (Figure 3). Similarly, the weekly monitoring of phytoplankton composition and toxin monitoring – discussed at the LFC meetings – provided advanced warning to the community's yellow clam processing and storage facility. This monitoring strategy was perceived as a specific adaptation and partial solution to the challenges of HABs (Figure 3). The information flow and transparency enhanced the capacity of the governance system to provide timely responses to changing conditions.

2) Assessment and monitoring

The long-term stock monitoring performed by the Faculty of Sciences and the management agency demonstrated that the yellow clam was not resilient to the effects of mass mortalities, reaching only a modest recovery after more than four generation times. To increase the monitoring of the fragile biophysical system threatened by climate-driven stressors, fishery-independent information gathered to assess the status of the stock and the surrounding environment was complemented by a CBDC programme developed after fishery reopening (Figure 3). This programme consisted of recording each fishing event in individual logbooks, including daily landings, fishing effort, fishing grounds visited, selling price and the final destination of landings (e.g. processing plants, intermediaries, own consumption) (Gianelli, Ortega and Defeo, 2019). Fisher participation was critical in assuring unbiased reporting of results and implementation of an up-to-date information flow from fishers to scientists.

As well as substantially increasing the flow and exchange of high-quality information, the active participation of the fishers in the CBDC programme strengthened the relationship between resource users and managers (Pittman *et al.*, 2019). The information was useful to increase understanding of system functioning, and was critical for setting a precautionary management approach based on low TACs and a restricted fishing season only during summer (when demand for the product is high). The precautionary TAC was distributed equally among local fishers, who were the only ones authorized to harvest clams. This approach was geared to achieve positive bio-socioeconomic outcomes (Gianelli, Martínez and Defeo, 2015; Gianelli *et al.*, 2018), fostering economic, social and environmental sustainability. A zoning scheme was also implemented, with portions of the beach allocated solely for tourism activities and serving as buffers for resource restocking.

Employing both spatial and temporal operational management tools helped to consolidate a sustainable management framework in the context of management redundancy, and hence safety, in fishery regulations through specific 'area-season windows' (Caddy and Defeo, 2003). The simultaneous application of these management tools has proved to be an effective precautionary strategy, diminishing the risks of overexploitation (Gutiérrez, Hilborn and Defeo, 2011). Nevertheless, MCS activities still represent a huge challenge: it is not easy to control illegal and recreational fishers, and enforcement costs are beyond the finances of the management agencies.

3) Post-harvesting sector: shifts in marketing strategy

The 14-year fishery closure caused a long-term interruption in the supply of the product for market consumption, leaving the commercial channels open to the importation of frozen products – such as the congeneric surf clam *(Mesodesma donacium)* from Chile – to fulfil the demand. When the fishery was reopened in 2008, fishers were sponsored technically and economically by the government and the Faculty of Sciences, and responded adaptively by diversifying their market to cater for restaurants' preferences for specific product attributes, such as freshness and quality.

Once clams are harvested, most of the catch goes to a certified local processing plant, and is then marketed as fresh clams for the restaurant market. The transition away from 'bait' towards 'high-quality seafood product' for human consumption is reflected in the higher price paid to fishers, as well as the greater value society now places on the product – it is also a source of local pride and social identity to the communities involved (Gianelli, Martínez and Defeo, 2015). Moreover, unit prices are now fixed during the local Fishers' Assembly before each fishing season (through 'letters of agreement'; Defeo, 2015) to avoid conflicts and rent-seeking behaviour from external intermediaries. These decisions have also been supported by the LFC. This strategy has raised clam unit prices over time, reaching USD 4.62/kg in 2018, a value five times higher than in the 1980s and three times higher than in the 1990s. The percentage of the total catch destined for human consumption has also increased, reaching almost 95 percent in recent years (Gianelli *et al.*, 2018).

This shift in the marketing strategy has maximized economic benefits for the local community, particularly under an adverse scenario of low standing stocks and a short fishing season (Defeo *et al.*, 2018). Chefs are playing an increasing role as strategic stakeholders, helping fishers to promote the product and to find new market initiatives and developments. The emerging interaction among fishers, chefs and the academic sector is also helping fishers to be more competitive in the domestic market and to increase the profitability of the value chain (Proverbio *et al.*, 2019). In this context, it would be helpful to promote initiatives to increase the perceived value of the local product, either through a tourism initiative package including seafood stalls, gastronomy and recreational fishing, or through a domestic traceability label that endorses climate change adaptation practices while supporting local culture.

The successful shift in marketing strategy is being threatened, however, by increasing seafood imports, which are displacing domestic products including the yellow clam from the national market (Gianelli and Defeo, 2017). In recent years, demand for yellow clams has dropped as retailers and consumers have opted for a constant supply of cheaper seafood imports. Even though the local community has responded by diversifying products and markets (Gianelli, Martínez and Defeo, 2015), this external driver still represents a threat to local livelihoods. However, to date, no measures have been identified that could help lessen the increasing impact of foreign seafood imports. Ideally, the governance system should provide enough flexibility to deal with the complexity and uncertainty of globalized seafood markets that affect the fishery. Collaborative actions and adaptive responses at the community and institutional (i.e. co-governance bodies) levels could help to prevent or mitigate the negative effects of external drivers on the social-ecological system, thus promoting more sustainable pathways (Defeo *et al.*, 2018).

4) Early warnings of harmful algal blooms (HABs)

A critical proximate driver threatening the productivity of the yellow clam fishery is the increasing occurrence, periodicity and duration of HABs (Figure 2), which have been associated with climate-driven changes (Martínez *et al.*, 2017). Clam harvesting is often constrained by the accumulation of toxins associated with HABs, and DINARA has been forced to forbid yellow clam harvesting, particularly during the peak summer demand, because of health concerns (Gianelli, Ortega and Defeo, 2019). The adverse effects of HABs and unfavourable weather conditions have led to a significant under-utilization of individual fishing quotas, and therefore to economic inefficiency in some years (Gianelli, Ortega and Defeo, 2019). Fishers and processors confirm this, stating that fishing bans can lead to loss of revenues and clients (due to unmatched demand by restaurants in seaside resorts) and high economic uncertainty (Pittman *et al.*, 2019).

Yellow clam fishers are particularly vulnerable to the detrimental socioeconomic effects of HABs due to their limited capacities and options for adaptation. In response to this situation, DINARA has implemented a weekly monitoring programme to provide timely estimates of phytoplankton composition and toxin concentration so they can provide early warnings to the local community and ensure healthy seafood for consumers (Figure 3). These early warnings are useful for fishers, who can store catches in the certified processing plant to allow them still to commercialize the product during harvest bans. DINARA provides strict inspections of any product stored (testing concentration of toxins and organoleptic quality) so its sale can be authorized.

In addition, when HABs occur during the fishing season, DINARA can choose to extend or re-open the fishery in autumn/winter to mitigate the fishing days lost earlier. This has been a partially successful adaptive approach to counteract the detrimental effects of HABs.

Nevertheless, despite the adaptation measures in place to address the impact of HABs on the fishery, further work is needed to provide an early warning system, in parallel with the development of infrastructure to store the product following strict protocols and quality standards. An early warning system of this kind could provide fishers and processors with systematic information on potential HAB events, and could be useful in reducing the uncertainty associated with fishing bans.

5) Other potential options

Early clam extraction and long-term maintenance of clam culture tanks are other potential areas to be explored and improved (Proverbio *et al.*, 2019). Diversified products (e.g. frozen, smoked or canned clams) could also help counteract the detrimental effect of fishery bans, but to fill this gap capacity-building and technology transfer initiatives must be developed (Gianelli, Ortega and Defeo, 2019). Adaptation pathways should be co-developed to effectively maintain human wellbeing. Augmenting these adaptive capacities will also require effort by LFC to: (1) adapt fishery management decisions in line with the demands of changing contexts; and (2) ensure existing norms and decrees are flexible and responsive enough to accommodate change, while supporting livelihood security.

E) Conclusions and key recommendations

Different lines of evidence suggest that the yellow clam population, its fishery and the wider ecosystem are being threatened by a changing climate. This is reflected in high species sensitivity to increasing SST, sea level rise and erosion of the physical habitat, as well as changes in system productivity and a trend towards tropicalization of the intertidal community. Mass mortalities resulting from increases in SST have had devastating socioeconomic impacts in the past.

The implementation of EAF and the institutionalization of co-management have been key factors in coping with variations in climate and market conditions. The adaptive and precautionary approach to management promoted fishery recovery and enhanced community wellbeing. It also strengthened collaboration among stakeholders and provided some rules and action mechanisms in the face of climate-driven stressors and market globalization. The governance structure, with two nested decision-making bodies, promoted fishers' participation and generated a sense of ownership. The interaction among stakeholders has fostered participatory data collection through the CBDC programme – including ecological, social and economic data – which has allowed for: (1) uncertainty reduction in stock estimates; (2) assessment of the relative contribution of different predictors to the short- and long-term dynamics of the fishery; and, therefore, (3) an integration of this knowledge into decision-making processes.

The adverse effects of HABs and unfavourable weather conditions bring another degree of uncertainty to the fishery, and have led to a significant under-utilization of individual quotas and economic inefficiency. As HABs are becoming an increasing threat, adaptive responses to cope with bioeconomic losses should be integrated in decision-making processes to mitigate the effect of losing fishing days within a limited season. Transdisciplinary capacity development projects are still needed to allow the local community to build resilience and adaptive capacity in the face of the increasing and pervasive influence of climate change and HABs. These capacity-building initiatives, in partnership with fishers, should be useful to provide flexible learning pathways to meet community needs (Pittman *et al.*, 2019). The preliminary system of early warnings built to cope with HABs must be improved to provide fishers and processors with greater certainty and systematic information on potential events. An updated early warning system could be integrated with a decision support tool and dashboards to foster the information systems required to inform adaptive management of the fishery in the face of climate change. Augmenting these adaptive capacities will require multi-level efforts to: (1) ensure existing norms and decrees are flexible enough to accommodate change, while supporting livelihood security; (2) adapt fishery management decisions to the demands of changing contexts; and (3) develop fishery practices that are climate-smart, ecologically-appropriate and socially-salient. The co-production of actionable pathways should be aligned with the fishers' and managers' existing priorities and initiatives to tackle the climate and economic changes threatening the fishery.

Achieving fishery transformation is more complex than simply changing legislation or introducing new restrictions on resource use. Despite the significant improvements that have been made in governance, it is not clear which government measures and policies could help deal with the increasing impacts of climate change, price shocks or seafood importation. Fishers have negative perceptions of these issues, highlighting their immediacy – more institutional flexibility is needed to cope with the complexity and uncertainty of the environment and the market. Robust guidelines should be developed to improve the adaptive capacity of institutions and the local fishing community to respond to the socio-ecological impacts of climate change and market globalization. This strategy should be accompanied by the development of flexible policies and management actions to tackle the challenge of promoting a climate-resilient and adaptable small-scale fishery, capable of sustaining ecosystem services and human wellbeing into the future.

The yellow clam example provides lessons for other small-scale fisheries, especially shellfisheries. In particular, the adoption of governance systems with effective participation from the fishers themselves has facilitated meaningful interaction with management agencies, which has in turn improved relational aspects within the fishery (e.g. CBDC, participatory stock assessments) and information flow regarding tools and interventions that can help address the negative effects of climate (e.g. HABs).

The empowerment of the fishers has increased their willingness to collaborate in resource and ecosystem monitoring, implementation and management. The sense of belonging and collaboration demonstrated by the fishing community has contributed to the accumulation of social capital and the development of diversified small businesses and livelihoods – the results of which are difficult to capture in a traditional cost-benefit analysis.

As a result of this rewarding experience, LFCs have scaled up rapidly at the national level. There are currently 12 decentralized governance bodies spread across Uruguay, to engage local communities in fisheries management but also to address challenges related to the impacts of the rapidly changing climate on the coast. Indeed, the new National Adaptation Plan for the agricultural and fisheries sector identifies strengthening LFCs as a way to enhance the adaptive capacity of fishing communities dealing with this situation.

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Chapter 9: Management responses to non-indigenous species in the Mediterranean and the Black Sea in the face of climate change

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Summary

The Mediterranean Sea is a biodiversity hotspot and is also one of the most highly invaded regions on the planet. Invasions are continuously increasing, especially by species of Indo-Pacific origin arriving through the Suez Canal. With climate change and the associated warming of the seas, Indo-Pacific species in particular will survive more easily in the Mediterranean and the Black Sea basins. Not all non-indigenous species (NIS) are deemed invasive: this is only the case when they pose a threat to either economic, ecological or human health. Once a NIS becomes established in a marine realm, eradication is often impossible, and the best management strategy is to try to control the population.

Here we discuss the management responses to two very different invasive NIS, the Rapa whelk (*Rapana venosa*) gastropod in the Black Sea, and the silver-cheeked toadfish (*Lagocephalus sceleratus*), a pufferfish in the Mediterranean basin. Although the Rapa whelk is an invasive species which has negatively impacted native molluscs through high predation, it has become a very important export commodity for Black Sea countries, and this offers a route to some control of its population. However, management of the species can be seen as controversial. Should it be managed to be a sustainable fishery, or should it be fished at higher rates to try to counteract its negative ecological impacts? And what is the best fishing method for this species – beam trawls which have negative ecological impacts, or scuba with its associated dangers to human health? Pufferfish, on the other hand, are deemed invasive due to their negative impacts on economic, ecological and human health resulting from their tetradotoxin (TTX) poison concentrations. Owing to their negative impacts, new commercial solutions for alternative uses of these two species should be sought, with a view to shifting their net impacts from negative to positive.

Unless creative engineering is undertaken to deter new migrants into the Mediterranean, for example in the Suez Canal, the influx of NIS will continue to increase. With global warming and its associated warming seas, more Lessepsian migrants will continue to alter the biodiversity in the Mediterranean and the Black Sea by 'tropicalization' from lower latitudes and 'Meridionalization' through the northward expansion of species' ranges. The best science can do is to try to measure their impacts and find creative ways to control their populations.

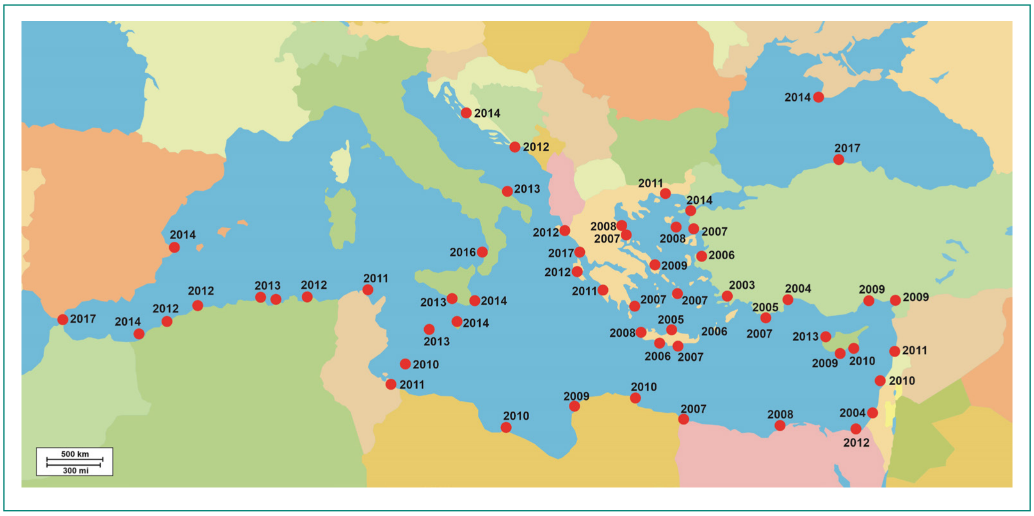

Figure 1. Map of the Mediterranean and the Black Sea, and expansion of *L. sceleratus* shown using years of first record (2003–2018) along the Med. & Black Seas (modified and updated from Galanidi, M and Zenetos, A., 2019; Bilecenoglu and Öztürk, 2018)

Fishery context

The Mediterranean and the Black Sea (Med. & Black Seas hereafter) are semi-enclosed seas, connected to each other by a series of narrow straits (the Bosporus and the Dardanelles Straits); with limited exchange with the Atlantic Ocean through the Strait of Gibraltar and with the Red Sea through the Suez Canal (Figure 1). The Mediterranean Sea is a hotspot for marine biodiversity, containing an estimated 4–18 percent of the world's marine species while only representing about 0.3 percent of total ocean volume (Bianchi & Morri, 2000). Conversely, the Black Sea is particularly low in biodiversity, owing to its peculiar oceanography and to the existence of an anoxic area encompassing waters deeper than around 150 m (corresponding with the pycnocline; Stanev *et al.*, 2013) or about 87 percent of the water mass (Zaitsev & Manev, 2000). The semi-enclosed nature, geography and dynamics of both seas, as well as their location in a transition zone between mid-latitude and sub-tropical climatic zones, makes them particularly sensitive to direct and indirect climate change impacts (see for example Coll *et al.*, 2012)

Med. & Black Seas fisheries are an important source of food, employment and income for coastal states. They are characterized by a predominance of small-scale fisheries (up to 84 percent of all fisheries), with the large majority targeting multiple species which in most cases are distributed across several neighbouring countries (FAO, 2018b). More than 100 000 vessels are currently thought to be operating in the area, based on official statistics and estimates of small boat numbers. These vessels combined capture a total of 1 220 000 tonnes of fish and shellfish annually, providing direct employment for at least 250 000 people and an estimated economic revenue of USD 2.8 billion (FAO, 2018b).

Management context

Fisheries management in the Med. & Black Seas is fraught with complexity, with national, supranational (e.g. European Union) and regional management frameworks all coexisting and interacting. This involves different stakeholders operating at different geographical and institutional levels, and includes diverse mechanisms for decision-making, monitoring and control. The General Fisheries Commission for the Mediterranean (GFCM) of the Food and Agriculture Organization of the United

Nations (FAO) is the Regional Fisheries Management Organization (RFMO) active in both the Med. & Black Seas, playing a critical role in fisheries governance in its area of application and having the authority to adopt binding recommendations for fisheries conservation and management. It thus offers both riparian states and distant fleets from other countries operating in the area a legal framework to manage their fisheries. Such recommendations can relate, among other things, to the regulation of fishing methods, fishing gear and minimum landing size, as well as the establishment of spatial protection measures, fishing effort control and of multiannual management plans for selected fisheries. Compliance with GFCM decisions is regularly assessed and ensured by a Compliance Committee.

The activities of the GFCM are currently guided by the mid-term strategy (2017–2020) towards the sustainability of Med. & Black Sea fisheries. The strategy acknowledges the need to create an adaptation strategy for coping with the potential effects of invasive species and climate change on fisheries. This strategy should be based on an evaluation of the potential ecological and socio-economic effects of climate change and of the introduction of NIS on Med. & Black Sea fisheries.

Under the GFCM mid-term strategy, fisheries management focuses on (but is not exclusive to) a set of priority species identified by GFCM contracting parties, cooperating non-contracting parties, partner organizations and scientific experts from the region. Rapa whelk is a priority species in the Black Sea, while pufferfish is considered a priority invasive species in the Mediterranean. Management of Rapa whelk in in the Black Sea is guided in particular by Recommendation GFCM/42/2018/9 on a regional research programme for Rapa whelk fisheries in the Black Sea (geographical subarea 29). This recommendation has the specific objective of collecting data on Rapa whelk in order to improve research and scientific knowledge on the sustainable exploitation of the stock, aiming to maintain it at maximum sustainable yield (MSY) as well as keeping it socio-economically viable.

A Memorandum of Understanding on NIS exists between the United Nations Environment Programme Mediterranean Action Plan (UN Environment/MAP) and the GFCM. Since 2017 this has framed a series of important initiatives, specifically towards establishing a joint NIS pilot programme in relation to fisheries in different subregions of the Mediterranean, notably the eastern Mediterranean. This includes the development of a sub-regional integrated monitoring and assessment programme (IMAP) and a GFCM monitoring programme.

Climate change implications in the Mediterranean and Black Sea

Direct and indirect climate change impacts are already obvious in both seas, with temperatures in the region rising faster than the global average, and an increase in frequency and intensity of heatwaves and droughts (Cramer *et al.*, 2018). These impacts are also affecting the marine ecosystem, with an observed increase of sea surface temperatures, changes in thermohaline structure and circulation, and sea level rise (Hidalgo *et al.*, 2018). Changes in the distribution of species are also apparent, with both 'Meridionalization' (occurrence of warm water species in northern regions) and 'tropicalization' (expansion of non-indigenous tropical species) being obvious in the Mediterranean, as well as 'Mediterranization' (spreading of Mediterranean species) to the Black Sea (Puzanov, 1967).

The appearance of NIS in the area is of particular concern, due to their potential impact on both existing ecosystems and on the fisheries operating there. During recent decades an increasing number of NIS have entered the Mediterranean Sea (Galil *et al.*, 2015): this makes it currently the most invaded sea on the planet, playing host to between 700–1 000 marine NIS (Katsanevakis *et al.*, 2014). Although the appearance of NIS can occur due to a number of different reasons, the most common vectors of transfer are from ballast water, biofouling, aquaculture-associated migrations, and transfers facilitated by the Suez Canal. Their successful expansion has been enhanced by warming sea temperatures, making the Eastern Mediterranean increasingly similar to the Red Sea in terms of species composition (Raitsos *et al.*, 2010).

On the basis of existing projections for the area, the impacts briefly described above are expected to continue and intensify, eventually affecting the overall productivity and carrying capacity of Med. & Black Sea ecosystems (Hidalgo *et al.*, 2018). Given the high levels of consumption of fish protein and the dependency on fish products in the region (FAO 2018b,c), along with the environmental impacts that are predicted, the vulnerability of Med. & Black Seas fisheries to climate change is high (Hidalgo *et al.*, 2018). Vulnerability is anticipated to be higher in developing countries in the south and southeast given their higher exposure to warming, their overall lower adaptive capacity (Hidalgo *et al.*, 2018), and their proximity to the Suez Canal (Ulman *et al.*, 2019). In the Black Sea dependency on fisheries is lower (FAO 2018b, c), but its loss of biodiversity, especially the removal of top predators, has made the system much less stable and simplified the food web, thus increasing its vulnerability to impacts from NIS (Zaitsev, 2008; Ulman *et al.*, 2020).

Management responses and lessons

In this section, we will use two contrasting examples to investigate the existing and potential future impacts of NIS on fisheries, and the management measures that have been adopted and implemented in response – as well as lessons learnt from these measures. These are Rapa whelk in the Black Sea, and pufferfish (*Lagocephalus sceleratus*) in the Eastern Mediterranean Sea. With respect to their impact on biological diversity and/or human activities, the Rapa whelk is considered the 52nd worst invasive species in Europe (Nentwig *et al.*, 2018), and the IUCN considers *L. sceleratus* to be one of the worst invasive marine fish (Otero *et al.*, 2013).

Rapa whelk in the Black Sea

In the 1940s, almost the entirety of the landlocked Black Sea ecosystem was considered pristine. The Black Sea continental shelf, particularly the much broader shelf area in the northwest, was enriched by nutrients carried by the big rivers such as the Danube, which provided fertile habitats for the rich mollusc fauna as well as many fish species.

In 1946, a large gastropod species, Rapa whelk, appeared in Novorossiysk Bay (Russia) – one of the busiest commercial harbours of the Black Sea. This species, native to the Pacific Northwest, is thought to have been transported via biofouling. Its abundance increased rapidly as it easily adapted to Black Sea conditions and spread over the entire basin within a decade. It is thought that its predatory nature, a lack of competition from other predatory gastropods, lack of predators, and an abundance of potential prey species facilitated this successful establishment (ICES, 2004). Concurrent to its increase, a sharp decrease in other mollusc species on which Rapa whelk was feeding was noted. In fact, Rapa whelk has a penchant for the total destruction of food items in its area of habitat (Chuhchin, 1984).

Oyster (*Ostrea edulis*) and scallop (*Flexopecten glaber*) populations along the Caucasus and Crimean coasts disappeared (Chuhchin,1961; Drapkin, 1963), the bivalve *Chamelea gallina* declined in the north-eastern Black Sea (Chikina and Kucheruk, 2005) and south-eastern Black Sea (Dalgıç and Karayücel, 2007), and mussel beds in the entire basin deteriorated (Chuhchin, 1984; Zaitsev and Ozturk, 2001), allegedly as a result of Rapa whelk predation pressure.

The Rapa whelk has high fecundity, a fast growth rate, and broad tolerance to salinity, temperature, water pollution and oxygen deficiency. The gradual worsening of the ecological condition of the Black Sea ecosystem – due mainly to eutrophication since the 1940s – adversely affected many benthic species, and gave Rapa whelk a competitive advantage. This allowed the Rapa whelk population to increase even during the most critical period experienced by this marine ecosystem in the 1980s, when extreme eutrophication-driven hypoxic (and even anoxic) conditions were reported along the coasts of the Black Sea.

Being a small enclosed basin, the Black Sea responds to changes in climate faster and more significantly than oceans do. Warming has already been catalysing the 'Mediterranization' of its biota elements, favouring species with an affinity for warm climates. With this in mind, Rapa whelk – with its high resilience in adverse environmental conditions – is likely to further enhance its place in the ecosystem. Indeed, recent observations indicate that the reproductive period of the species is extending, as the thermal window in which the species is reproductively active is being expanded due to temperature rise (Basusta, N., 2020, pers. comm., 14 April).

When it first appeared in Black Sea Rapa whelk was not locally appreciated as seafood, and was thus regarded as a marine pest for the following three decades (ISSG, 2007). In the early 1980s, however, a profitable market for the species was found in the Far East, with South Korea, Japan and China among others paying high prices for frozen and processed Rapa whelk meat. Turkey was the first country to harvest, process and export the species to the Far East. Ten years later, Bulgaria entered the market, followed by Romania and Ukraine. According to GFCM statistics, Rapa whelk landed by Black Sea countries reached 23 000 tonnes in 2017; Turkey alone received USD 12.5 million in revenue from exports of the commodity in 2018 (Figure 2).

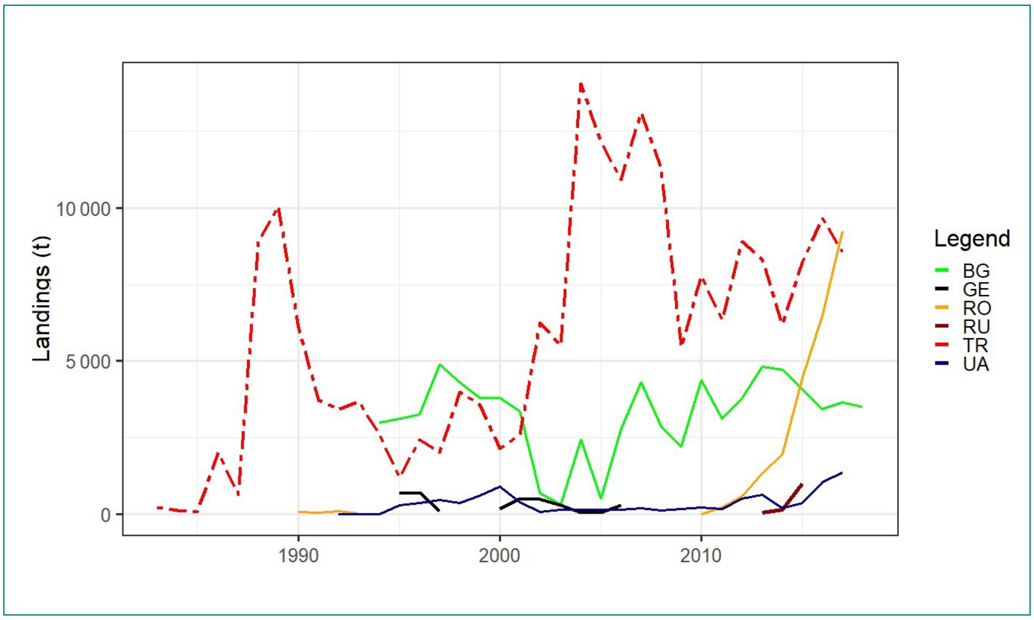

Figure 2. Rapa whelk landings in the Black Sea (GSA 29). Landings (t) by countries.

Different fishing methods have been trialled to harvest Rapa whelk: dredging, beam trawling and scuba diving are the main methods employed in the region at present. There have been several attempts to promote non-destructive gear such as pots and traps (Sahin, 2004; Saglam and Duzgunes, 2014), however, these were not profitable enough. Currently beam trawl is the most commonly used fishing gear, catching 95 percent of the Rapa whelk in Turkey and Bulgaria, and 90 percent and 74 percent in Ukraine and Romania respectively. While removal of the species by beam trawl helps control its spread, the significant damage the gear causes to benthic habitats and other commercial species in coastal areas (Zengin *et al.*, 2014) jeopardizes any benefits of this NIS fishery to the ecosystem.

This situation has led to the first fisheries management conflict for the species. While it is possible to control the growth of a non-indigenous invasive species by using beam trawls, the method creates extra pressure on other species, especially on bycaught juvenile turbot (*Scopthalmus maximus*), whose biomass is already below safe biological limits (FAO, 2019). On the other hand, banning mobile bottom fishing gear, such as beam trawls and dredges, would force fishers to resort to diving – a dangerous practice which has claimed many lives. This conflict, experienced in almost every Black Sea country, resulted in the liberalization of the use of beam trawls to generate more revenue from the highly valuable stock, which is now being fished close to its maximum sustainable yield (FAO, 2019).

In an attempt to reduce the impacts of the gear on other species, restrictions have been enforced on beam trawling. For example, in Turkey, the beam trawl fishery is not allowed to operate during the summer season (15 April–31 August), when juveniles of many fish species, especially turbot, settle in nearshore nursery grounds. This has reduced discard rates by half (to 1.22 percent), while turbot and other commercial species are no longer observed in the bycatch (Erya-ar *et al.*, 2018). However, it should be noted that the highest catches per unit effort (CPUE) for Rapa whelk – almost double – have always been recorded in July during their spawning season.

Exploitation was initially seen as an opportunity to control the invasion of this NIS in the Black Sea, and regulations enforced by the riparian countries for Rapa whelk fisheries mainly addressed the side effects of the fishing gears used. However, the perception of the species changed in parallel with the increasing revenue it generated – and that, in turn, triggered a change in fisheries regulations, which shifted to maintaining the species for its monetary value. For example, in Romania, Rapa whelk was initially fished by scuba diving and beam trawls were only permitted later, in 2013, provided that the fishery was not carried out within marine protected areas (MPAs) and used a minimum landing size of 4 cm shell length. Following the liberalization of beam trawling, Romanian catches of the species increased exponentially: in 2018, Rapa whelk accounted for 94.65 percent of national landings (Anon, 2019). Similarly, in Bulgaria, Rapa whelk fisheries started in 1994 using scuba diving, and beam trawling was legalized in 2012. Since 1995, this species has been the most valued commercial species in this country, ahead of sprat.

Until the 2000s, the density of Rapa whelk along the Ukrainian coast was not high enough to stimulate commercial interest, and the species was exploited by divers only. Since 2016, a limited number (35–40) of artisanal vessels have been authorized for beam trawling. As a result, Ukrainian landings have increased up to five times, and the total catch of the species has exceeded 1 000 tonnes in recent years. The proportion of divers exploiting the catch has decreased by about 25 percent. Aside from a licensing limitation, no additional regulations are applied to the Rapa whelk fishery in Ukraine (STECF, 2017).

From the perspective of the GFCM, which is the RFMO coordinating governmental efforts to manage fisheries in the Black Sea effectively, Rapa whelk is a priority commercial species. Since 2018, with Recommendation GFCM/42/2018/9, the GFCM has started working towards a regional Rapa whelk fisheries management plan aimed at maintaining the stock within safe biological limits, to be implemented in 2022.

The situation of Rapa whelk in the Black Sea is a remarkable example illustrating some of the challenges in the management of NIS. Controlling the adverse effects of a NIS on the ecosystem through a fishery may be considered an appropriate ecological approach. However, if the species in question occupies the nursery habitats of commercial fish whose biomass has already fallen below safe biological limits (e.g. Black Sea turbot), the fishery could also create extra pressure on the stocks of the native species.

Replacing mobile bottom gears with habitat-friendly but less efficient (and dangerous) fishing methods, such as diving and trapping, can be beneficial to the ecosystem but may lead to losses in both the fishing and processing industries. The consequences of this approach have socio-economic risks, especially considering that in the Black Sea Rapa whelk fishing is practised mainly by small-scale fishers with low incomes.

Besides, a problem arises when the income from the NIS fishery reaches an important percentage of the total revenue from fishing: should the biomass of the species be kept as low as possible to reduce damage to the ecosystem, or should it be kept at a level that can achieve maximum sustainable yield of an economically valuable resource? The latter would require the protection of the NIS through the introduction of management measures – in other words, this would mean supporting the invasion.

A possible solution might be to impose seasonal restrictions to reduce damage to nursery habitats and other species, thus minimizing the impact of the Rapa whelk fishery on the ecosystem, as is the case in Turkey. However, as the CPUE during the restricted period is significantly higher than during the rest of the year, such a regulation would be prone to illegal, unreported, and unregulated (IUU) fishing. On the other hand, a management strategy similar to that adopted by Romania – in which sensitive and essential habitats (such as nursery grounds) that are most likely to suffer from the fishery are identified and protected – could be more rational in terms of feasibility.

Pufferfish (*Lagocephalus sceleratus*) in the Eastern Mediterranean

L. sceleratus belongs to the Tetraodontidae family of pufferfishes, named with a Greek term for four teeth, due to their two fused upper and lower teeth. This group of fishes is currently represented by 12 species in the Mediterranean Sea. Among these species, *L. sceleratus* is native to the Indo-West Pacific Ocean, and is a highly opportunistic predator. It also has a high concentration of TTX, which is the strongest known paralytic toxin and can be fatal to humans (Sabrah *et al.*, 2006). Noguchi and Ebesu (2001) were the first to report 2 mg of TTX to be a standard lethal dose for an adult, which has been widely used as the standard quote ever since. In Japan, there is a gastronomic culture dedicated to eating *'fugu'* whereby eating certain species of pufferfish in small quantities can lead to a tingling effect and slight dizziness. However, due to the very high TTX concentrations found in *L. sceleratus,* its consumption is banned in Japan, even as a *fugu* item (Arakawa, 2010).

L. sceleratus was first reported in the Mediterranean in Gökova Bay on Turkey's southwestern coast in 2003 (Akyol *et al*. 2005). A decade on, it had expanded its Mediterranean range to the other side of the basin into Spanish waters (Izguerdo-Munoz and Izguerdo-Gomez, 2014) and at its most westward point to Algeria (Kara *et al*., 2015), after which it was reported in Turkey's Marmara Sea (Irmak and Altınagac, 2015), in 2017 in Gibraltar (Azzuro *et al.*, 2020), and in 2018, surprisingly, in the Black Sea (Bilecenoglu and Öztürk, 2018). Since it was first recorded in the Mediterranean, this species has spread throughout most of the region aside from France (Figure 1), showing exceptionally high concentrations along the Eastern Mediterranean, particularly on Turkey's Levantine coast (Coro *et al*. 2018) and in Cypriot waters. Another pufferfish species, the yellow spotted puffer (*Torquigener flavimaculosus*), is also becoming increasingly abundant in the region, particularly in Turkey and Cyprus where its catches nearly rival those of *L. sceleratus* (Pers. comm., Cicek, B.A., PhD, Biological Sciences, Eastern Mediterranean University, Cyprus).

L. sceleratus is characterized by rapid growth and high reproduction rates, a wide ecological niche, a scarcity of natural predators, and avid carnivorous feeding habits (Bilecenoglu, 2010; Otero *et al.*, 2013; Kalogirou, 2013; Ünal *et al.*, 2015; Ünal and Göncüoglu, 2017; Biecenoglu and Öztürk, 2018; Coro *et al*., 2018). It is frequently found in waters shallower than 70 m, and it spawns from April to June in the Mediterranean Sea (Sabrah *et al.*, 2006; Aydin, 2011). It can reach very large sizes (specimens up to 7 kg have been documented, and several fishers in Turkey's Mugla province report catching larger specimens of between 10–12 kg). Interestingly, no predators were known for this species in the Mediterranean until 2017, when a 3 cm juvenile *L. sceleratus* was found inside a dolphinfish (*Coryphaena hippurus*) in Cretan waters (Kleitou *et al.*, 2018), and then in November 2019 when social media documented loggerhead turtles and garfish (*Belone belone*) consuming *L. sceleratus* in Turkey and Greece respectively. Its favoured prey items tend to be crustaceans when the fish are juveniles, and a combination of cephalopods, crustaceans and fish as adults (Kalogirou, 2013).

Information from fishers indicates that *L. sceleratus's* abundance continues to increase in southern Turkey, as damage from the species to nets and longlines continues to worsen. *L. sceleratus* is notorious for biting off longline hooks and biting holes in fishing nets, then consuming the catch of both. Since it is not commercially targeted no large-scale stock assessments have yet been carried out for the species, however a few localized studies indicating relevant population numbers have been carried out along the Egyptian coast (Farrag *et al.*, 2015), in the Gulf of Suez (El-Ganainy, 2017) and in Antlaya Bay, Turkey (Deval *et al.*, 2017). In Cyprus, since 2012, L. sceleratus has been contributing some 50 percent of total marine fishery catches by weight (Ulman *et al.*, 2015). Since this species usually prefers medium-high water temperatures as in its native range, the ongoing warming of the Mediterranean Sea due to climate change is likely to be beneficial to its expansion success as an invasive species (Nader *et al.*, 2012).

Despite a scarcity of research on the topic, there are indications that this species may pose a significant threat in the Mediterranean, resulting in negative impacts on the native biodiversity, ecosystem and fisheries (Zenetos *et al.*, 2005; Peristeraki *et al.*, 2006; Streftaris and Zenetos, 2006; Öztürk, 2010; Nader *et al.*, 2012; Ünal *et al.*, 2015). Threats from *L. sceleratus* can be classified into three different aspects: i) socio-economic impacts, in particular on fisheries, ii) consumption risks to human life, and iii) ecological impacts on native biodiversity.

Fisheries impacts

It is well reported that *L. sceleratus* causes significant negative economic impacts to gillnet, trammel net and longline fisheries, from damaging the nets and the catch to consuming catch and hooks (Katsanevakis, 2009; Michailidis, 2010; Kalogirou, 2013; Ünal *et al.*, 2015; Ünal and Göncüoglu, 2017; Öndes *et al.*, 2018; Ünal and Göncüoglu-Bodur, 2018). As an illustration, prior to this invasion a new gillnet would last a fisher about five years – but recently, due to the increasing abundance of *L. sceleratus* and the associated damage, fishers in southern Turkey have had to replace these nets every two to three months. In some regions *L. sceleratus* also break off and sometimes ingest 20–30 percent of longline hooks and consume their catch (Bishop, 2016). A recent assessment showed that the economic losses the species causes to Turkey's small-scale fisheries are between EUR 2–5 million annually (Ünal *et al.*, 2015; Ünal and Göncüoglu-Bodur, 2017; Öndes *et al.*, 2018) – and this may even be an underestimate.

Consumption risks to human life

The consumption of *L. sceleratus* is also a threat to public health, and as such it is considered a high-risk invasive species by the European Union (Galanidi and Zenetos, 2019), where the consumption of Tetraodontidae species is prohibited, as it is in other Mediterranean countries. Consumption of TTX can be fatal if over 2 mg is ingested (Noguchi and Ebesu, 2001; Rambla-Alegre *et al.*, 2017): several human fatalities have been reported in Lebanon, Egypt and Palestine (Bane *et al.*, 2014). TTX is present in all organs of *L. sceleratus* including its muscle, with the highest concentrations found in its liver and gonads. One recent Cypriot study found half of the tissues sampled to be over the safe consumption limit, with higher TTX concentrations found in fish caught in summer (Akbora *et al.*, 2020).

Ecological impacts to native biodiversity

Due to its extremely high abundances in some localities, and high predation rate, it can be hypothesized that *L. sceleratus* is taking a toll on native biodiversity. However, this is rather difficult to prove scientifically, as it would require controlled experiments in the natural realm. Since *L. sceleratus* is shy of humans, designing such an experiment would take much ingenuity. In Rhodes, Greece, Kalogirou (2013) did report a marked decline in squid populations which he linked to pufferfish increases. Ünal and Kızılkaya (2019) reported a decline in shrimp populations in Gokova Bay just five years after its first recorded appearance there, which may be attributable to *L. sceleratus.* Additionally, Ulman (unpublished data) found several cases of *L. sceleratus* cannibalism in late 2019, along with its consumption of several other NIS in the region. Cannibalism was known in this species in its native Indo-Pacific region, but had not yet been confirmed in the Mediterranean. Its potential control of other NIS is a very interesting topic which should be further investigated.

Due to its toxicity, the consumption and sale of pufferfish is prohibited across the entire Mediterranean. However, managing the invasion is a major concern and even a priority issue for some affected countries. At the national level, the fishing, landing and sale of *L. sceleratus* have been banned in Egypt, Lebanon, Turkey and European Union countries with a European law (854/2004/EC) prohibiting the sale of any pufferfish. In 2009, both North and South Cyprus initiated a bounty system for pufferfish which is still ongoing; North Cyprus pays USD 0.67 (4 Turkish Lira; TL) per pufferfish tail to fishers, which has resulted in over USD 16 500 (TL 100 000) in government compensation for 2018 and 2019. South Cyprus pays USD 3.34 per kg of pufferfish to fishers, resulting in over USD 334 000 in government compensation each year (Çiçek, B.A. and Petrou, A., pers. comm.). However, after more than a decade of the bounty system in Cyprus, scientists have not yet noticed a decrease in catches, suggesting its limited effectiveness in reducing populations. Currently, fisheries managers and policymakers in Turkey are under pressure to formulate and implement an effective management tool to inhibit the pufferfish problem (particularly *L. sceleratus*) (Ünal and Göncüoglu-Bodur, 2018). The Directorate General of Fisheries and Aquaculture (DG-Fish) in Turkey is planning a new policy initiative to create a bounty system paying USD 1 for each landed pufferfish, to support both fishers and a healthier marine ecosystem (Pers. comm., M. Kanyılmaz, Head of Resource Management, DG-Fish, Turkey). In addition to bounties, commercializing this abundant invasive species has recently become a hot topic in the region. For example, there are plans to exploit some of the Eastern Mediterranean population for its TTX for use in extreme pain medicine, to make wallets from its skin, and even to use its powerful teeth as dental implants.

At a regional level, the GFCM added *L. sceleratus* to the priority list of seven NIS to be monitored in the Eastern Mediterranean Sea (FAO, 2018a), and a sub-regional monitoring plan has been prepared in collaboration with the UN Environment/MAP. The sub-regional monitoring plan will provide information in support of both UN Environment/MAP and GFCM objectives, reinforcing their cooperation towards the achievement of common objectives. Specifically, the sub-regional monitoring plan will provide information on NIS, including *L. sceleratus,* and ensure the collection of data to support the Mediterranean Quality Status Report 2023 in relation to the NIS indicator of UN Environment/MAP, as well as the Recommendation GFCM/41/2017/6 in relation to the submission of information on NIS (FAO, 2018d).

Key conclusions and recommendations

- Climate change impacts in the Mediterranean Sea include 'Meridionalization' (the occurrence of warm-water species in northern regions) and 'tropicalization' (the expansion of non-indigenous tropical species); while 'Mediterranization' (the spread of Mediterranean species) is taking place in the Black Sea (Puzanov, 1967). Although these trends are also occurring in other regions, in the case of the Med. & Black Seas the impact on biodiversity and fisheries is particularly high, due to the semi-enclosed nature of the area and the cumulative impacts inflicted on its ecosystems by pollution, eutrophication, overexploitation etc.
- NIS may have both positive and negative impacts on ecosystems (e.g. on biodiversity or the state of native species) and fisheries (e.g. on economic revenue). The NIS described in these two case studies were initially solely perceived as pest species, but then it was realized that commercial opportunities could, to differing extents, be created to help offset some of their negative economic or ecological impacts. This is a crucial aspect of facilitating successful adaptive management.
- Based on the premise that once a NIS becomes established in a marine environment its eradication is often impossible, hence the best management strategy is to try to control the population, the specific cases of commercialization of invasive species discussed here could be applied to all NIS. Creative commercial or biomedical opportunities should be sought wherever possible, to offer some control over NIS populations.
- Small-scale fishers should be at the forefront of adaptive management of this kind of resource. They should be encouraged and supported in pursuing new commercial NIS initiatives, since their sector is highly marginalized in the Mediterranean, but also heavily impacted by NIS.

- Lacking sufficient scientific research and advice or the adoption of adequate measures, fisheries often adapt autonomously to the appearance and increase in abundance of NIS. They do this in various ways, including through the modification of fishing activities (e.g. gear, period, etc.) and the development of new fisheries. However, these adaptations are not always optimal, and may be maladaptive with unplanned or unexpected effects (e.g. impacts on other components of the ecosystem). They may also not achieve their desired objectives to minimize the impacts of the NIS on ecosystems, fisheries or human health.
- The Med. & Black Seas NIS experience points to the importance of continued monitoring of NIS through routine systems especially in NIS hotspot areas, the provision of scientific advice, and the adoption of management measures, including fisheries management measures. Planned adaptation, when agreed upon by experts, can lead to better results than autonomous adaptation which may not take into account all possible costs and benefits of the invasion. Early implementation of the above measures can facilitate the avoidance of maladaptation as well as help achieve agreed objectives (e.g. minimizing impacts or increasing profits from NIS).

In conclusion, climate change is expected to exacerbate the appearance and increase in abundance and spread in distribution of NIS in the marine environment. The combination and interaction between the two is expected to reshape ecosystems, in particular in semi-enclosed areas/seas such as the Mediterranean and Black Seas. The resilience of ecosystems as well as that of the fisheries sector in the face of these impacts and changes is closely related to the ability of the holistic system to adapt to them (Barange *et al.*, 2018). The only remedy is thus to concede the reality of the situation and focus on maximizing economic benefits from the use of NIS while minimizing the impact they inflict on ecosystems. This is only possible through monitoring-based adaptive, agile management plans. Sound scientific knowledge of the NIS in question and of the impacted ecological systems, as well as an in-depth understanding of the socio-economic context and the institutional limitations and tools available, are all important components required to achieve a flexible adaptive response of this kind (Barange *et al.*, 2018). Continued data collection and monitoring are thus at the basis of this approach, which needs to be complemented with informative advice and with the involvement of the fishing sector in implementing measures that could address the objectives of economic sustainability and minimal ecological impact. In order to become effective, these elements need to be implemented and the approach pursued not just in the short term, but also over longer time periods.

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Chapter 10: Adapting to climate change in the South African small pelagic fishery

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Summary

The small pelagic fishery in South Africa is the country's largest in terms of annual catch (ca 380 000 tonnes on average) and the second most valuable. Sardine (*Sardinops sagax*) and anchovy (*Engraulis encrasicolus*) combined make up an average of 80 percent of annual catches by this fishery, with West Coast round herring (*Etrumeus whiteheadi*) of lesser importance. The sardines are canned or frozen, while anchovy and round herring are reduced to fish meal and oil.

This fishery has been identified as one of South Africa's most vulnerable to climate change impacts, primarily because of the economic value of the catch and the large number of people involved in catching and processing. Some changes in the oceanography, and in distribution patterns and abundance trends of these three small pelagic fishes have been observed, and may be attributable to climate change. Both anchovy and sardine have shown shifts in their relative distributions (from the West to the South Coast) that are significantly correlated with cross-shelf sea surface temperature gradients off the South Coast: this has had negative impacts on the sardine but not the anchovy fishery.

Since 2000 the population sizes of anchovy and round herring have been higher than before, possibly due to increased upwelling – anchovy recruitment strength has been shown to be significantly correlated with cumulative summer upwelling. In contrast, the sardine population size has been low since the mid-2000s and is presently very low, possibly as a result of deleterious impacts on sardine (but not on anchovy or round herring) of recent harmful algal blooms off the South Coast: these may be driven by climate change.

The decline in the sardine population and its present depleted status has had substantial impacts on the small pelagic fishery, and is a critical and immediate concern. The fishery must adapt to this change and prepare for further change in future by better utilization of current and new resources, at least in the short term. Adaptation measures that have been implemented include importing frozen sardines to keep factories operational and meet local demand, and the development of an experimental fishery for the mesopelagic lanternfish (*Lampanyctodes hectoris*). Other potential adaptation measures include rebuilding the sardine population; developing anchovy products (fillets, dried, etc.) for human consumption, including developing markets; investigating the use of larger vessels with different fishing gear (i.e. pelagic and midwater trawls instead of purse-seiners) to harvest anchovy and round herring; fishing off the South Coast for anchovy and developing processing infrastructure there; increasing present low exploitation levels on round herring and developing canned products for human consumption; and developing an integrated research response to improve forecasting of likely climate change impacts on these species and the fisheries they support.

Overview of fishery

The South African fishery for small pelagic fish is an industrial-scale fishery that was initiated off the West Coast in the late 1940s using purse-seine nets to target adult sardine, horse mackerel (*Trachurus capensis*) and chub mackerel (*Scomber japonicus*) (Beckley and van der Lingen, 1999). Declining catches of these species during the mid-1960s (Figure 1) resulted in the fishery switching to smaller meshed nets to target juvenile anchovy that recruit off the West Coast. These have dominated landings since, and to a lesser extent adult West Coast round herring have also been targeted. Because both sardine and round herring juveniles form mixed schools with anchovy juveniles, the former two species are taken as bycatch in anchovy fishing operations. Negligible quantities of the two mackerel species have been taken since their catches declined, and while sardine catches remained low for three decades the fishery began to target this species off the South Coast in the 1990s and catches increased to a second peak in the mid-2000s, before declining again to very low levels in recent years (Figure 1). Mesopelagic fish (almost entirely Hector's lanternfish) are taken as bycatch on occasion, sometimes in large quantities. The small pelagic fishery is the country's largest in terms of catch, with a combined annual catch of all species of 377 000 (± 113 000) tonnes over the period 1950–2019. Sardine (directed and bycatch combined) and anchovy together have comprised 79 ± 12 percent on average of the annual catch taken by the small pelagic fishery during this time.

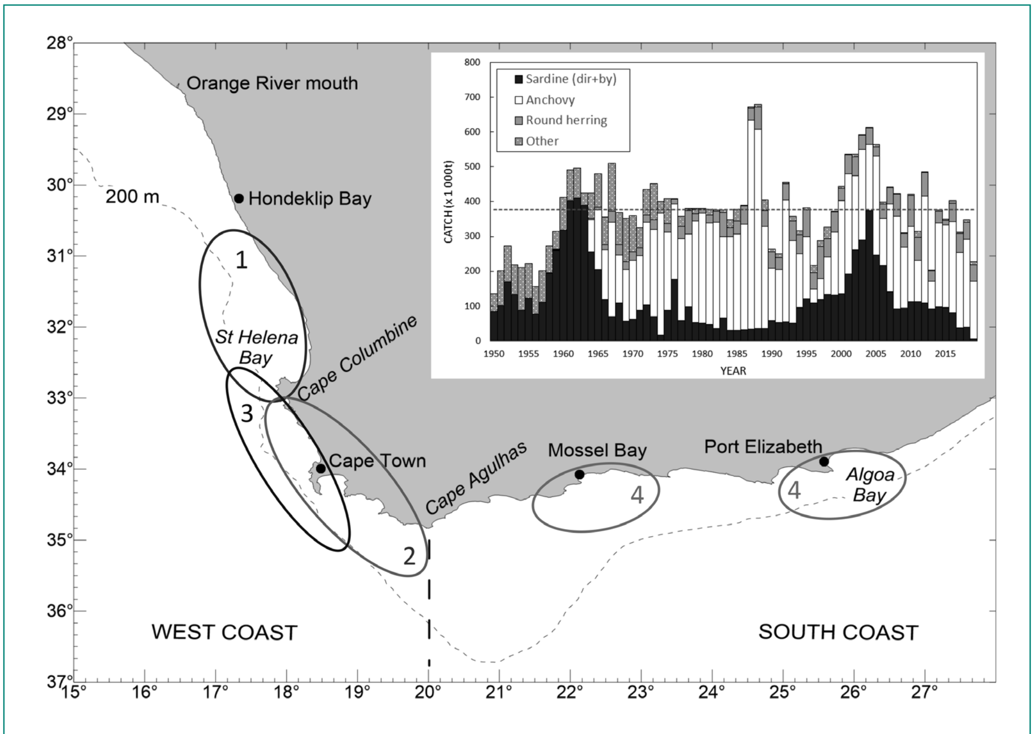

Figure 1. Map showing the main fishing areas of the South African small pelagic fishery (1 = historical catches of sardine, horse mackerel and chub mackerel and present catches of juvenile anchovy; 2 = present catches of juvenile and adult anchovy and adult sardine; 3 = present catches of West Coast round herring; and 4 = present catches of adult sardine off the South Coast. The dotted line indicates the 200m depth isobath and some coastal towns and features are labelled. The insert shows annual catches of sardine (directed and bycatch combined), anchovy, West Coast round herring and other species (horse mackerel, chub mackerel and lanternfish) landed by the South African small pelagic fishery from 1950–2019, with the average annual catch indicated by the black dotted line.

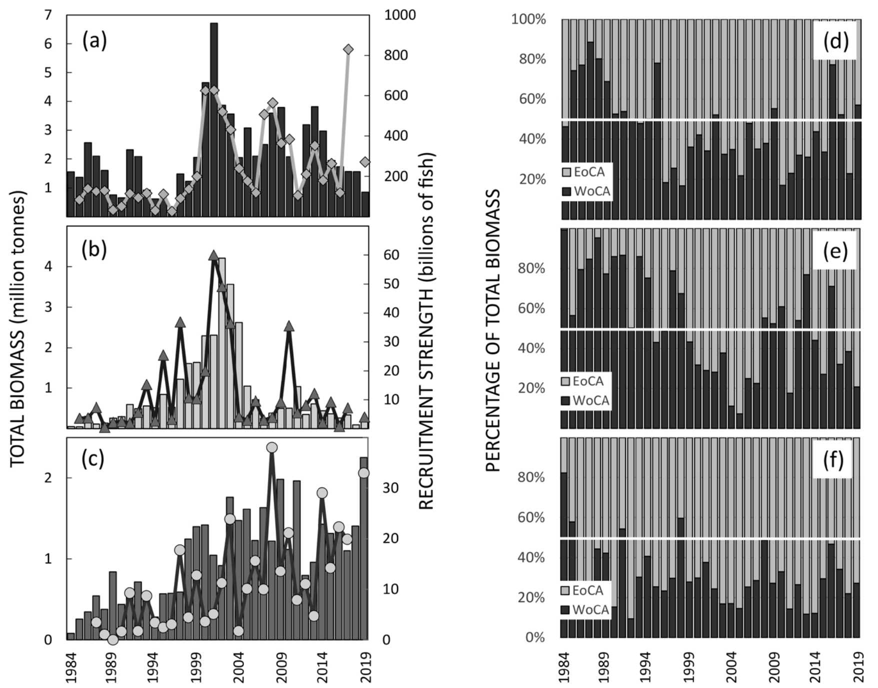

Figure 2. Time series of (left panel) survey-estimated total biomass (histograms) and recruitment strength (symbols and lines; note that there was no recruit survey in 2018) of (a) anchovy, (b) sardine, and (c) West Coast round herring, 1984–2019; and of (right panel) the percentage of total biomass observed to the west of Cape Agulhas (WoCA) and East of Cape Agulhas (EoCA) during biomass surveys of (d) anchovy, (e) sardine, and (f) West Coast round herring, 1984–2019; the white dotted lines indicate the 50 percent level.

Most of the processing infrastructure is located on the West Coast. Sardine is canned or frozen for human consumption, pet food and bait; while anchovy and round herring are reduced to fishmeal and oil – sardine is approximately five times as valuable per unit landed mass than the other two species. This fishery is South Africa's second-most valuable, with a wholesale value in 2013 estimated at R 1.6 billion (Brick and Hasson, 2016; equivalent to around USD 160 million) and employing more than 5,000 staff in 2008 (Brick and Hasson, 2016), including full-time sea-going and factory processing staff as well as seasonal workers. The South African purse-seine fleet currently consists of 75 vessels ranging from 14 to 39 m in length and fitted with fish pumps (for anchovy and round herring) or ice and/or refrigerated seawater (for sardine).

At present, the South African sardine population is depleted (Figure 2b), with the biomasses estimated by pelagic survey (see below) in recent years being very low. In contrast, anchovy and round herring populations are presently abundant, although anchovy biomass is substantially lower than in the peak years of the early 2000s (Figures 2a, c; DAFF, 2016).

Management context

Management of the South African small pelagic fishery has been undertaken by the relevant national government department (presently the Department of Environment, Forestry and Fisheries): this sets annual catch levels, which are allocated to individual rights-holders within the fishery. Separate annual total allowable catch (TAC) levels for sardine and horse mackerel were set during the 1950s and 1960s, but a national TAC for all species combined that ranged between 360 000 and 450 000 tonnes per annum was applied during the 1970s. Species-specific TACs for sardine and anchovy were introduced in 1983 and formal mechanisms for determining TAC levels developed during that decade, with an overall aim of implementing a conservative approach to facilitate rebuilding of the sardine population (Cochrane *et al.*, 1998). However, the bycatch of juvenile sardine in anchovy fishing operations means that catches of the two species cannot be simultaneously maximized, since high anchovy catches will negatively impact sardine recruitment and high sardine catches can only be sustained by limiting juvenile sardine bycatch – and hence limiting anchovy catches. For this reason, whereas historically they had been managed separately, a joint operational management procedure (OMP) for the two fisheries that provided a framework for quantifying the trade-off between sardine and anchovy TACs was developed by the Department's Small Pelagic Scientific Working Group (SP-SWG) and implemented in 1994 (De Oliveira and Butterworth, 2004).

OMPs are adaptive management approaches that use a simulation-tested set of rules and pre-specified data, stock assessment methods and harvest control rules to determine and implement management actions. They can be designed to satisfy pre-agreed management objectives (Kell *et al.*, 2006). Objectives of the initial joint sardine/anchovy OMP were to maximize the average sardine-directed and anchovy catches in the medium term subject to constraints on inter-annual variability in TAC levels so as to enhance industrial stability. The OMP's formulae were conditioned on low probabilities of the abundances of these two resources dropping below agreed threshold levels that might compromise successful future recruitment.

Pre-agreed OMP formulae are developed in consultation with stakeholders including fishing industry representatives and various NGOs, and the plans are typically revised every four to five years to include additional data and new information. The current small pelagic OMP (OMP-18; de Moor, 2018) recommends annual TACs for both anchovy and directed-sardine, total allowable bycatches (TABs) for juvenile sardine caught with anchovy and for juvenile and adult sardine caught with West Coast round herring, and precautionary upper catch limits (PUCLs) for West Coast round herring and mesopelagic fish. These are set at the start of the year and are based on results from the previous total biomass survey. Because the anchovy fishery primarily catches recruits, the anchovy TAC and juvenile sardine TAB for anchovy-directed fishing are revised mid-year following the completion of the recruitment strength survey (see below).

Stock assessments for sardine and anchovy incorporated in the OMP (note that a stock assessment model for West Coast round herring is not presently incorporated into the OMP) are age-structured production models. These stock assessments use data (see Figure 2a-c) from annual hydro-acoustic surveys conducted since the mid-1980s that estimate total biomass (austral spring) and recruitment strength (autumn), as well as annual catches of anchovy and directed- and bycatch sardine. Fish length frequency data from both surveys and commercial catches are also included in the assessments. Whereas previous OMPs assumed panmictic populations of both sardine and anchovy, recent research has indicated the presence of multiple sardine stocks off the South African coast (van der Lingen *et al.*, 2015) and OMP-18 uses a two-mixing stock assessment model for sardine, modelling western and southern stocks targeted by the purse-seine fishery (de Moor *et al.*, 2017). OMP-18 also includes threshold levels for western stock biomass and the spatial distribution of directed-sardine catches, which if passed trigger explicit spatial management measures aimed at maintaining a relatively low exploitation rate of sardine off the West Coast (de Moor, 2018).

OMPs for the small pelagic fishery are simulation tested to ensure an acceptable level of risk of the sardine and anchovy populations falling below specified thresholds over a range of harvest control strategies. As part of an ecosystem approach to management of the small pelagic fishery, simulations were also run using parameters denoting risk to the African penguin (*Spheniscus demersus*) population. Penguins were selected as an ecosystem representative because of their conservation concern (currently listed as Endangered) and the fact that they are highly dependent on small pelagic fishes (particularly sardine) as forage. A model of penguin population dynamics, coupled with candidate OMPs, allowed assessment of the impact on penguins of predicted future pelagic fish population trajectories under alternative harvest strategies, but analyses to date have suggested that even large reductions in pelagic catches would be of little benefit to penguins (DAFF, 2016). Additionally, the impact of closing areas to purse-seining around islands containing penguin breeding colonies has also been examined, with Sherley *et al*. (2018) reporting that such closures were beneficial in terms of chick survival and condition in some but not all instances.

Climate change implications

The complexity and inherent variability in the marine ecosystems around South Africa, particularly of physical mesoscale processes which directly impact small pelagic fish habitat, results in a low signal-to-noise ratio that makes the detection of climate change signals difficult (van der Lingen and Hampton, 2018). This is exacerbated by a limited ability to disentangle the multiple drivers of ecosystem change, specifically fishing and climate change. Observations of physical changes in the marine environment off the West Coast that are considered likely to be due to climate change include a cooling of coastal waters over the past four decades by around 0.2 °C per decade (Blamey *et al*., 2015): this is possibly in response to stronger, unseasonal upwelling-favourable winds and a southward (poleward) expansion of the South Atlantic Subtropical Anticyclone (also known as the South Atlantic High Pressure; Sousa *et al.*, 2018). In addition, the West Coast has shown a tendency, albeit non-significant, for increased upwelling over the period 1979–2014 (Lamont *et al.*, 2018). Upwelling on the South Coast overall has shown a significant increase over the past 35 years (Lamont *et al.*, 2018); localized intermittent upwelling intensity in that region has also increased (Duncan *et al*., 2019), and coastal waters there have also shown some cooling (around 0.1 °C per decade; Blamey *et al.*, 2015). In contrast, the Agulhas Current – positioned at the shelf edge and an important driver of oceanic variability in the region (Augustyn *et al.*, 2018) – has warmed by up to 0.6 °C per decade (Rouault *et al.*, 2010; Blamey *et al.*, 2015), with this region identified as one of 23 global marine hotspots where the ocean is warming more rapidly than elsewhere (Hobday and Pecl, 2014). Thermal gradients across the South Coast shelf (known as the Agulhas Bank) have therefore increased in recent decades.

Under the high-emission representative concentration pathway (RCP) 8.5 scenario and using the CMIP5 ensemble (Scott *et al.*, 2016), sea surface temperatures in the southern Benguela are projected to increase by around 1 °C by 2050 and by up to 2.5 °C by 2100; pH is predicted to decrease by 0.08–0.1 by 2050 and by 0.2 by 2100; dissolved oxygen at the surface is predicted to decrease by around $3.E^{-3}$ $mol.m^{-3}$ by 2050 and by $4–8.E^{-3}$ $mol.m^{-3}$ by 2100; and primary production off the West Coast is predicted to increase by $20–40.E^{-9}$ $mol.m^{-2}.s^{-1}$ by 2050 and by $40–80.E^{-9}$ $mol.m^{-2}.s^{-1}$ by 2100, but not to increase elsewhere (NOAA's Climate Change Web Portal https://www.esrl.noaa.gov/psd/ipcc/).

Because of their responsiveness to environmental forcing, small pelagic fish have been characterized as 'excellent bio-indicators of climate-driven changes in marine systems' (Peck *et al.*, 2013). Predicted effects of climate change on ecosystems dominated by these species include changes in distributions, changes in productivity and the composition of lower trophic levels, and changes in circulation patterns, which may impact small pelagic fish recruitment success (Fréon *et al.*, 2009).

Both anchovy and sardine have shown changes in their relative (*i.e.* percentage of total biomass) distributions off South Africa in recent decades. Anchovy spawners showed an abrupt shift from being located predominantly (>50 percent of observed biomass) to the west of Cape Agulhas (WoCA) from 1984–1995 to being located predominantly east of Cape Agulhas (EoCA) in 1996, and this shift has mostly persisted since (Figure 2d). Roy *et al.* (2007) documented coastal cooling EoCA in 1996 and reported a significant positive correlation between the cross-shelf sea surface temperature gradient EoCA and the percentage of anchovy spawner biomass EoCA over the period 1984–2005. Roy *et al.* (2007) hypothesized that the shift was environmentally mediated, and updating the analysis to 2011 supported this hypothesis (Augustyn *et al.*, 2018). However, changes in sea surface temperature gradients EoCA appear to be linked to multi-decadal variability in wind, specifically a north-south migration in the large-scale wind belts (Malan *et al.*, 2019), and hence may not be a response to climate change.

Sardine have also shown an eastward shift in their relative distribution (Figure 2e), but that occurred more gradually than was observed for anchovy (van der Lingen *et al.*, 2011) and appears to have been reversing in recent years. Whereas cross-shelf sea surface temperature gradient EoCA and the percentage of sardine biomass EoCA for the period 1984–2011 are significantly correlated (Augustyn *et al.*, 2018), the relationship is weaker than that for anchovy. The changed sardine relative distribution may also have been driven by fishing pressure, which is historically higher for sardine off the West compared to the South Coast (Coetzee *et al*., 2008).

The shift in anchovy relative biomass had little impact on the small pelagic fishery because it targets primarily juvenile anchovy off the West Coast, whereas the sardine shift had substantial impacts. The centre of gravity of directed-sardine catches showed a progressive eastward movement from the mid-1990s to the mid-2000s, with >50 percent of the total directed-sardine catch being taken off the South Coast in 2005 (and much of that having to be trucked to the processing facilities on the West Coast, which increased transport costs) (Augustyn *et al.*, 2018). The relative distribution of round herring has remained roughly constant over the same time period (Figure 2f).

Increasing water temperatures and stratification arising from climate change have the potential to alter the productivity and species composition of the plankton on which small pelagic fish feed, but the trophic dissimilarity between sardine and anchovy (van der Lingen *et al.*, 2006) suggests that changed plankton compositions will impact these two species differently. Sardine feed primarily on smaller zooplankton whereas anchovy (and round herring) feed predominantly on larger zooplankton and smaller fish, hence an increase in zooplankton size will likely favour anchovy and round herring whereas a decrease may favour sardine. In the southern Benguela, larger zooplankton are hypothesized to be more abundant when upwelling is stronger and smaller zooplankton more abundant when upwelling is weaker (van der Lingen *et al.*, 2006). Observations from the Humboldt Current ecosystem are that temporal patterns of euphausiid (larger zooplankton) dominance are in phase with anchovy biomass patterns, whereas temporal patterns of small zooplankton dominance are in phase with sardine biomass patterns (Ayon *et al.*, 2011), which supports the trophic dissimilarity hypothesis. The fact that recruitment strength and total biomass of anchovy in particular, but also round herring, have been higher after 2000 than before, whereas sardine has not shown this pattern (Figure 2a-c), could be considered as evidence for a climate change-driven enhancement of the trophic environment for anchovy and round herring that has led to a positive population response by the two species. However, given the relatively short (35 years) period of the time series and the fact that small pelagic fish populations fluctuate on a variety of time scales (Field *et al.*, 2009), this should be interpreted cautiously.

Another possible indication of climate-induced changes in plankton composition is the anomalous and spatially and temporally extensive harmful algal blooms (HABs) that have occurred on the South African South Coast during the past decade, particularly in 2011 and 2015 (van der Lingen *et al.*, 2018). These HABs appear to have a deleterious impact on sardine but not on anchovy or round herring, since sardine within the HAB area show a substantial reduction in body condition compared to those outside. This was interpreted as a consequence of the sardine ceasing to feed because of hypothesized chemical irritation arising from entrapment of the small (50µm) bloom-causing dinoflagellates on fish gill rakers; the larger gill raker spacing of anchovy and round herring means that these species cannot entrap the dinoflagellates (van der Lingen *et al.*, 2016). The poor condition of sardine has negative implications for their spawning success and subsequent recruitment, given the dependence of clupeoids on stored energy for successful reproduction (Ganias *et al.*, 2014). In addition to these biological impacts, HABs appeared to be responsible for a reduction in sardine availability off the South Coast, with catches taken off Port Elizabeth and Mossel Bay declining substantially following the bloom events. HABs have been predicted to increase as a consequence of climate change, and there is some evidence for increases in their frequency, severity and geographical domain (Wells *et al.*, 2015). Understanding to date suggests that should these events continue off the South Coast, they will have significant negative impacts on sardine, the small pelagic fishery, and the ecosystem, given the importance of sardine as forage for a variety of fish, mammal and seabird predators (see e.g. Crawford *et al.*, 2019).

The present depleted status of the sardine population may be a result of persistent poor conditions off the South Coast. The sardine biomasses estimated by the 2018 and 2019 pelagic biomass surveys were the third- and sixth-lowest, respectively, of the time series and well below the levels predicted during simulation testing of OMP-18. Given this, the SP-SWG declared 'Exceptional Circumstances', under which it would be irresponsible to recommend a directed-sardine TAC and associated TABs for 2019 and 2020 as specified by OMP-18. Instead, the SP-SWG recommended a conservative directed-sardine TAC of 12 250 tonnes for the 2019 fishing season (compared to 65 000 tonnes for 2018), of which only 2 145 tonnes were taken, providing a stark signal of low sardine availability and/or abundance at present. Similarly, a conservative interim directed-sardine TAC of 10 000 tonnes (with a maximum of 30 percent to be caught off the West Coast) has been recommended for 2020.

Adaptations and lessons

The vulnerabilities to climate change of 16 South African marine fishery sectors were recently assessed in order to determine priorities for climate change adaptation (Hampton *et al.*, 2017a). Fishery scientists and managers used three indices in the vulnerability assessments: (i) the sensitivity of the resource and fishery to climate change; (ii) the potential adverse impacts of climate change on human livelihoods; and (iii) the ability of those involved in the sector to adapt to such impacts. The small pelagic fishery was considered to be highly sensitive to climate-induced changes that would cause moderate socio-economic impacts, and to have low to moderate adaptive capacity. This fishery was considered one of the more vulnerable sectors, primarily because of its economic value and the large number of people involved. This is despite indications from a trait-based assessment of likely sensitivity to climate change of important South African marine species that suggested that sardine and anchovy had low likelihoods of being negatively impacted (Ortega-Cisneros *et al.*, 2018a). A more recent analysis characterized the South African small pelagic fishery as being moderately vulnerable to climate change via direct climate threats, the exposure and sensitivity of the sector, and some aspects of the national governance and economic environments (Cochrane *et al.*, 2019).

Potential adaptation to climate change for the small pelagic and other fishery sectors was discussed at a multi-stakeholder workshop (Hampton *et al.*, 2017b) in response to five threat categories: (i) decreased and/or more variable resource abundances; (ii) changes in resource distributions; (iii) changes in fish behaviour; (iv) deterioration in weather including more frequent and/or severe storms; and (v) the introduction of pathogens. Suggested adaptation measures were prioritized, and the feasibility and time-scale of high-priority measures was identified at the workshop and subsequently elaborated in further discussions (listed in Table 1 and discussed below). So far, only a few of these measures have been implemented or attempted.

Diversify value chain/increase product value

Most high-priority adaptation measures suggested were to address changes in resource abundances. They included importing frozen sardine in order to keep canning factories operational and staff employed, and to meet local demand; canning round herring for human consumption; processing anchovy for bait and human consumption; and developing/expanding the fishery for other small pelagic and mesopelagic fish species for reduction to fish meal and oil. Management responses that should be considered included allowing for increased variability in resource abundance in OMPs (possibly by strengthening the resilience of small rights-holders in particular to deal with interannual variability in TACs), and allowing a less conservative approach in allocation of the initial anchovy TAC. Future climate scenarios are not presently considered in OMP development, although a useful approach appears to be to modify basic population parameters such as natural mortality and growth rate in stock assessment models depending on the climatic state of the ecosystem and documented fish responses to different states (as applied in the Peruvian anchoveta fishery; see Oliveros-Ramos *et al.*, this volume. In addition, the four- to five-year period between OMP revisions may need to be reduced given the potential for climate change-induced impacts to act over shorter time scales.

One of these measures has been implemented for some time and others have been further discussed with some limited attempts at implementation. Frozen sardine have been imported into South Africa for over a decade but concerns about the potential for the introduction of pathogens such as pilchard herpesvirus (PHV) have been raised. PHV caused mass mortalities of Australian sardine following the importation of sardine to feed sea-caged southern bluefin tuna, and an examination of sardine off South Africa showed them to be naïve (i.e. not previously exposed) to this virus and hence at risk of infection from imported fish (Macey *et al.*, 2016). Between 56 000 and 71 000 tonnes of frozen sardine were imported each year over the period 2010–2014 from countries where *Sardinops sagax* occurs, indicating a realistic risk of infection of local stocks and identifying the need for an expanded pathogen-import-risk assessment (Macey *et al.*, 2016). Despite this risk, however, the importation allowed canning factories to remain operational in the face of reduced and/or more variable local catches.

Round herring is presently being canned but only in limited quantities because demand is not high and it costs 15 percent more than canned sardine, which is recognized as a basic food item and hence is zero-rated in terms of value-added tax (Benguela Current Commission, 2019). The potential for producing anchovy for human consumption in South Africa has been discussed for several years, and while some products were produced in the 1980s these were not developed or expanded. Local and labour-intensive (i.e. by hand) production of anchovy fillets is considered feasible (Backteman, 2010; Anonymous, 2013) and the cost of imports of anchovy products for human consumption was estimated at around USD 1.7 million in 2013 (Anonymous, 2013), but despite these positive indications and continued interest (Benguela Current Commission, 2019) there has been no further development.

Establish developmental fisheries (diversify livelihoods)

Mesopelagic fish (primarily Hector's lanternfish) were first documented in South African purse-seine catches in the mid-1960s when the fishery switched to smaller-meshed nets to target anchovy, with occasional high catches of lanternfish taken in the 1960s and 1970s, principally during summer and autumn (Figure 3). Catches were used to produce fish meal and oil but their high oil content meant that lanternfish had to be mixed with other species (e.g. anchovy) in order to avoid clogging the machinery (Centurier-Harris, 1974). This characteristic, combined with good anchovy catches during the 1980s in particular, led to decreased targeting of the mesopelagic species. More recently, experimental midwater trawling for small pelagic and mesopelagic fishes in 2010 and 2011 resulted in good catches of lanternfish in the West Coast shelf break region during winter (Figure 3), and successful processing of this species into export-quality fish meal and oil has been achieved (M. van den Heever, Pioneer Fishing, pers. comm). This has led to a recommendation for the formal development of a commercial mesopelagic fishery for the production of fish meal and oil, with an annual precautionary upper catch level of 50 000 tonnes (Coetzee, 2016). Midwater trawlers fishing under experimental permits until this fishery is formally declared caught almost 6 000 tonnes in 2018 and 3 500 tonnes in 2019. Immediate implementation of this recommendation is hampered, however, by the need for large pelagic and midwater trawlers – these have high operational costs, which makes them unavailable to smaller rights-holders, and they can only berth in large harbours such as in Cape Town and Saldanha Bay (Benguela Current Commission, 2019). These factors unfortunately led to a cessation of experimental mesopelagic fishing by the single company that had invested in the experiment at the end of 2019, but mid-term implementation appears feasible.

Table 1. Suggested high priority adaptation measures for the small pelagic fishery identified at the fisheries adaptation workshop (Hampton *et al.*, 2017b), and in subsequent discussions with fishery scientists, managers and sector representatives (indicated by *). Timescale: short = immediate; medium = 3–5 years.

Threat	High-priority possible adaptation measures	Species	Feasibility	Timescale
Decreased and/or more variable small pelagic fish abundance	Can round herring and develop a market for the product; apply for VAT zero-rating for canned round herring	Round herring	High	Medium
	Revise/extend existing Operational Management Procedures (OMPs) to allow for increased variability in abundance	All	High	Short
	Import fish (e.g. cutlets) for local canning/processing but need to screen for pathogens as local *S. sagax* naïve to pilchard herpes virus (PHV) found in Australian sardine (Macey *et al.*, 2016)	Sardine	High	Short
	Develop an anchovy fishery for bait and high-quality products for human consumption (South Coast)	Anchovy	Medium	Medium
	Increase ability of industry to handle variations in TAC/make better use of TAC. (e.g. more/better catch arrangements between rights-holders)	All	High	Short
	Introduce measures to protect small rights-holders from large TAC reductions and associated negative socio-economic impacts	All	High	Short
	Consider allowing larger proportion of the TAC to be taken in the first allocation (cf. anchovy quota seldom filled under present rules)	Anchovy (sardine bycatch)	High	Short
	Develop/expand reduction fisheries for other small pelagic and mesopelagic fish species*	Anchovy, round herring, mesopelagics	High	Medium
Changes in small pelagic fish distributions	Expand canning and off-loading facilities on the South and East Coasts (e.g. Mossel Bay and Port Elizabeth)	Sardine	High	Short
	Differentiate between West, South and East Coast sub-populations in management	Sardine	High	Short
	Use larger vessels and more efficient gear (e.g. pelagic trawls) to fish on the South Coast	Anchovy and round herring	High	Short
Changes in small pelagic fish behaviour	Use larger vessels and more efficient gear (e.g. pelagic trawls) to fish on the South Coast*	Anchovy	High	Short
Deterioration in weather including more frequent and/or severe storms	Deepen fishing harbours to accommodate larger fishing vessels	All	High	Medium
Introduction of pathogens	Screen all imported fish products for pathogens which could infect local wild stocks	Sardine	Medium	Short
	Perform expanded PHV pathogen import risk assessment*	Sardine	Medium	Short

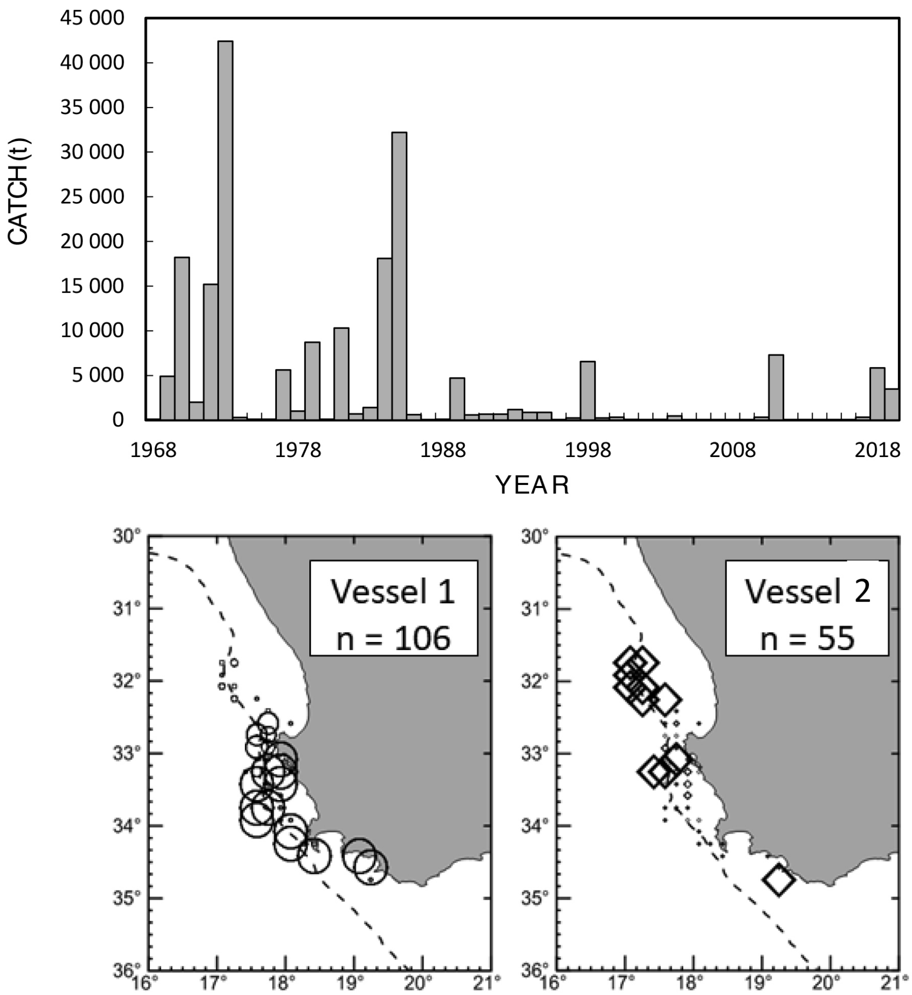

Figure 3. Time series (upper) of annual catches of lanternfish off South Africa from 1968–2019; and catch locations (lower) of experimental midwater trawls by two vessels during 2011 (symbol size is proportional to catch and the number of fishing trips in that year is shown).

Relocate on-shore infrastructure and/or fishing effort

Adaptation measures in response to changes in resource distributions and behaviour included the need to expand sardine offloading and canning facilities on the South Coast; incorporating sardine population structure into stock assessment models; and using larger vessels and more efficient gear (e.g. pelagic trawls) to fish for anchovy and round herring on the South Coast. The need for development of infrastructure on the South Coast to process adult anchovy for human consumption has also been identified (Benguela Current Commission, 2019). Sardine population structure has been taken into account with the development of an assessment model for western and southern stocks as described above. Although the impact of likely catches off Port Elizabeth of sardine from the eastern stock warrants investigation, perceptions are that catches by the purse-seine fishery have a negative impact on the beach-seine fishery and substantially more valuable ecotourism activities associated with the annual winter migration of this stock known as the sardine run (van der Lingen, 2015).

Additionally, OMP-18 includes spatial management rules to balance the exploitation rates of western and southern stocks and avoid overexploitation of the more productive western stock. Experimental fishing targeting round herring and anchovy off the South Coast using pelagic and midwater trawls deployed from larger vessels has been initiated and has shown some initial success.

Improve predictive capacity

An increase in long-term research and monitoring, and an improvement in predictive capacity in terms of the likely responses to climate change of exploited fish off South Africa, have been identified as a critically-needed adaptation for fisheries management (Hampton *et al.*, 2017b; Augustyn *et al.*, 2018; Benguela Current Commission, 2019). Similarly, Lombard *et al.* (2019) identified six multi-disciplinary projects to support ecosystem-based approaches to marine spatial planning in order to facilitate a government initiative to fast-track the South African ocean economy (known as Operation Phakisa – www.operationphakisa.gov.za), including the need to develop models to better understand the potential impacts of climate change on food webs and fisheries. Some studies relevant to the small pelagic fishery have begun to address this; for example Raybaud *et al.* (2017) who used an ecological niche model comprising only two abiotic variables (sea surface temperature and bathymetry) to evaluate possible climate change effects on the distribution of European (Cape) anchovy (*Engraulis encrasicolus*). That study reported that all warming scenarios applied in their simulations – from +2 °C to +4–5 °C – projected a reduction in the probability of occurrence of this species in all regions south of 48°N, with the greatest difference (up to 50 percent) between the present and 2090–2099 being off South Africa. Similarly, by using an end-to-end model (Atlantis) and climate projections to evaluate the cumulative impacts of climate change (warming and horizontal and vertical mixing) and fishing on the structure and function of the southern Benguela ecosystem, it was shown that warming had the greatest effect on the biomass of most species, almost always negative, with anchovy in particular being severely impacted (Ortega-Cisneros *et al.*, 2018b). Hence, increasing temperatures appear likely to have negative impacts on small pelagic fish off South Africa, in particular anchovy.

However, the predicted increase in upwelling in eastern boundary ecosystems in general (Wang *et al.*, 2015), and particularly in their poleward portions (Rykaczewski *et al.*, 2015), may have beneficial effects on small pelagic fishes off South Africa. A recent study demonstrated that South African anchovy recruitment is positively correlated with cumulative upwelling from December to March (austral summer), with van der Sleen *et al.* (2018) developing a threshold-generalized additive model that included two linear relationships between cumulative upwelling and recruitment strength for low and high categories of anchovy spawner biomass WoCA. The slope of the regression for the high biomass category (>0.74 M tonnes) was substantially higher than that for the low biomass category, and the model was able to account for 82 percent of the variability in observed anchovy recruitment over the period 1985–2014. van der Sleen *et al.* (2018) suggested that their findings could be used in management of the anchovy fishery, specifically in setting the initial anchovy TAC, by anticipating higher/lower recruitment when the anchovy spawner biomass WoCA was above/below the threshold level. Similarly, Lockerbie and Shannon (2019) used a trophic model (Ecopath with Ecosim) of the Southern Benguela that was fitted to catch and biomass data for the period 1979–2015 and assessed ecosystem changes under different possible future scenarios, including one where increased upwelling was modelled as increased (by a factor of two) primary production. Compared to the baseline scenario, where future ecosystem state was simulated under the present climate, increased primary production had strong positive impacts on the entire ecosystem, particularly on lower trophic level species such as small pelagic fish. Positive impacts of increased primary production persisted even when fishing pressure on lower trophic level species increased, suggesting that expansion of the small pelagic fishery might be possible under a scenario of increased upwelling.

The contrasting projections of these models, however, shows that comprehensive understanding of climate change impacts on small pelagic fish off South Africa, and the fisheries and ecosystems that they support, has yet to be achieved. A concerted and multi-disciplinary national research response needs to be developed as an adaptation to climate change in South African marine fisheries: some progress in this has been made through a multi-stakeholder workshop that aimed to identify and co-ordinate such research (Hampton *et al.*, 2017c).

Key recommendations

The present depleted state of the South African sardine population and recent low to very low catches of this species have seriously impacted and are of major concern to the small pelagic fishing industry (Benguela Current Commission, 2019). Given the ecological importance of sardine, their depletion will almost certainly also negatively impact the ecosystem. Whether this decline can be attributed to climate change is as yet uncertain, but a recovery of the sardine population in the short- to mid-term seems unlikely: the fishery must adapt to this change and prepare for climate change impacts by better utilization of other pelagic and mesopelagic resources. The importation of sardine to keep factories operational and maintain local market share, the inclusion of sardine population structure into stock assessment models, and the initiation of a fishery for mesopelagic species are adaptation measures that have been implemented to date. The first of these carries a disease risk and may not be a viable long-term option given its dependency on a steady supply of sardine from elsewhere. The identification of two semi-discrete sardine stocks that have different productivity characteristics has changed perceptions regarding the population structure of this species off South Africa. These changes have resulted in the inclusion of spatial management options in OMP-18 that give greater protection to the more productive western sardine stock at low biomass levels, which should lead to improved utilization of this resource.

The adaptive capacity for better utilization of other pelagic and mesopelagic resources differs between rights-holders in the small pelagic fishery, with small rights-holders on the South Coast being the most vulnerable and needing to increase their flexibility and ability to diversify (Benguela Current Commission, 2019). Some avenues for better utilization could include:

- ***Rebuild the sardine population*** (particularly the more productive western stock) via precautionary management; maintain sardine population structure to promote genetic and phenotypic diversity and resilience to climate change; implement expanded risk assessment for PHV in imported frozen sardine.
- ***Develop anchovy products for human consumption*** and develop markets for them; use larger vessels and different fishing gear to target adult anchovy off the South Coast (which will likely have a low juvenile sardine bycatch) and build anchovy processing infrastructure there.

- ***Increase exploitation of West Coast round herring***, presently managed via an annual precautionary upper catch limit of 100 000 tonnes but with average annual catches of 48 000 tonnes compared to an average annual population biomass of 1.4 million tonnes over the period 2000–2019; determine sustainable harvest levels with consideration for ecosystem needs (e.g. predation by Cape hakes *Merluccius capensis* and *M. paradoxus*) and develop and incorporate a round herring stock assessment model into the OMP for the small pelagic fishery; apply for VAT zero-rating for canned round herring.
- ***Increase exploitation of lanternfish***, presently managed via an annual precautionary upper catch limit of 50 000 tonnes and with an average annual observed biomass in shelf waters off the West Coast of around 450 000 tonnes over the period 2009–2019; determine sustainable harvest levels based on survey-derived estimates (and noting that surveys likely do not cover the full distribution of the resource, which precludes comprehensive population assessment) and with consideration for ecosystem needs (e.g. predation by Cape hakes).
- ***Develop an integrated, concerted and multi-disciplinary national research response*** to support adaptation to climate change in South African marine fisheries. Such research should aim toward or include, inter alia: (i) identification of plausible scenarios of future ocean states likely to arise under climate change; (ii) characterizing the resilience of exploited species to climate change; (iii) development of bioclimatic envelope models to predict future distributions of exploited species; (iv) improved understanding of physiological responses of exploited species to increasing temperature and acidification, and the likely impacts on their productivity and distribution; (v) development of early-warning systems for extreme events including HABs, low oxygen water and marine heat waves; and (vi) measures to mitigate climate change impacts on local communities and develop alternative livelihoods. While these are over-arching issues that will be useful for all of South Africa's marine fishery sectors, such research will also inform and improve management of the small pelagic fishery.

The South African small pelagic fishery has a moderate adaptive capacity, and some of the implemented or proposed adaptation options here could be usefully applied to small pelagic fisheries elsewhere, notably increasing product value (i.e. products for human consumption) and targeting new resources (e.g. mesopelagics).

It is important to note that adaptation options for the South African small pelagic fishery were identified following broad stakeholder participation that included industry associations, fishery scientists and managers, parastatals and non-governmental organizations, and tertiary education institutions, and continued development of these options will require a co-ordinated and integrated approach. However, further strengthening the adaptive capacity of the small pelagic fishery is considered difficult without inputs from or changes in the national economy and governance, including streamlined bureaucratic processes and regulatory requirements, improved availability of finances for adaptation and development, and general improvements in the national economy (Cochrane *et al.*, 2019).

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Chapter 11: Transboundary fish stocks in the Northeast Atlantic: reflections on climate change and management[1]

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Abstract

Management and allocation of quotas of straddling and transboundary stocks is complicated. Changes in stock distribution due to climate change make it more so. Climate change is influencing a non-uniform poleward shift of stocks across many species in the Northeast Atlantic. Norwegian experiences in joint management of shared stocks gained over 40 years provide a useful basis for future management.

In the development of management regimes for transboundary or straddling fish stocks, quota-sharing is key. The Law of the Sea Convention does not prescribe how quotas of transboundary stocks should be allocated between states. Even though there might be mutual agreement on the relevant factors to be considered, including the actual distribution of the stock, the negotiated result will rarely follow any template or model. However, there may be reason to check whether the starting point for such negotiations has been situation-specific, and/or has changed over time. Increased scientific knowledge about zonal distribution has become a key point in negotiations.

Variation in stock distribution may be caused by changes in stock size or demography, by natural variability and/or by climate change. This paper uses Northeast Arctic cod *(Gadus morhua)*, North Sea cod *(Gadus morhua)*, Norwegian spring-spawning herring *(Clupea harengus L)* and Northeast Atlantic mackerel *(Scombrus scombrus)* as examples. We draw conclusions on general principles related to improved management of transboundary stocks while at the same time illustrating that these are multifaceted in nature. Northeast Atlantic mackerel and Norwegian spring-spawning herring represent widely distributed stocks where previously agreed allocation keys no longer apply. On the other hand the bilateral allocation keys for Northeast Arctic and North Sea cod remain stable after 40 years, despite shifts in stock distributions.

[1] This case study is based on a draft version of the open access article **Gullestad, P., Sundby, S., Kjesbu, O.** 2020; 21:1008-1026, [Management of transboundary and straddling fish stocks in the Northeast Atlantic in view of climate-induced shifts in spatial distribution - Gullestad - 2020 - Fish and Fisheries - Wiley Online Library]. The text relies fully on the information on biology and oceanography in the article written by Svein Sundby and Olav Kjesbu, both affiliated to the Institute of Marine Research, Bergen Norway (Gullestad, Sundby and Kjesbu, 2020). All editings of this case study are, however, the sole responsibility of Peter Gullestad and Gunnstein Bakke, both affiliated to the Directorate of Fisheries, Bergen Norway. Readers are invited to consult the article for a more in depth description of the issues. This applies in particular to information on biology and oceanography. The article also provides information related to another fish stock whose area of distribution is influenced by climate change with consequences for management. The Directorate of Fisheries would not have been in a position to contribute with a unique case study to this valuable work of FAO if the article had not been in preparation when the authors were asked by FAO to contribute.

Progress in the understanding of Northeast Atlantic fisheries oceanography

Increasing understanding of fish stock fluctuations has been a continuous task for fisheries research for the last century, and development of long time series on fish stocks and the environment has become crucial to this. As early as the 1940s, ICES arranged a conference to address the impacts of warming in the North Atlantic during the first half of the twentieth century (Rollefsen and Tåning 1949). During the warming of the North Atlantic from the 1920s to 1940s marine organisms were displaced northward. Drinkwater (2006) made a comprehensive summary of the literature on the impacts of this warming event. In contrast, the long-term cooling that occurred from the 1950s towards the last cool period of the 1960s to the early 1980s was paid much less attention by the scientific community. However, in retrospect it became apparent that fish stocks of the North Atlantic retreated southward again before the most recent long-term warming that began in the mid-1980s caused them to extend northward once more (Sundby and Nakken 2008; Drinkwater *et al.* 2014). These long-term climate fluctuations are known as the Atlantic Multidecadal Oscillation (AMO), and they have a periodicity of 60 to 80 years (Sutton and Hodson 2005).

The development of the AMO during the twentieth century – with a cool phase going into the 1920s, a warm phase from the 1930s to the 1950s, a new cool phase from the 1960s to the 1980s, and finally the recent warm phase beginning in the 1990s – corresponds to large-scale oscillating northward and southward shifts of North Atlantic fish stocks, as well as changes in stock biomass. International negotiations on quotas of shared stocks in response to the extensions of EEZs to 200 n.m. during the late 1970s were thus conducted at the end of the last cool AMO period, when North Atlantic fish stocks in general were distributed in a southerly mode. Since then, the positive phase of the AMO – in addition to increasing anthropogenic climate change – has led to a greater temperature increase than during the previous warming from the 1920s to the 1940s.

Allocation in the Barents Sea

The Barents Sea is dominated by demersal fish species. It is influenced in the north by winter ice cover and Arctic species, while the southern part has an inflow of warmer Atlantic water and boreal species of zooplankton and fish.

In 1975 Norway and the Soviet Union signed an agreement to cooperate on fisheries management in the Barents Sea and established the Joint Norwegian-Soviet Fisheries Commission in 1976. One of the Commission's first tasks was to agree on the total allowable catch (TAC) for Northeast Arctic cod and haddock for 1977. The parties also agreed to allocate the TACs of cod and haddock evenly between them, after deduction of an allocation to cater for third parties continuing to fish in the area. Another important element of the agreement was the opportunity to fish in each other's waters. With younger year-classes of cod distributed to the east in Soviet waters, fishing could take place on older year-classes further west in Norwegian waters. In addition to increasing the economic efficiency of the Soviet Union fishery, the resulting improvement in exploitation patterns increased long-term yield, to the benefit of both parties (Gullestad *et al.* 2018).

There were several reasons why the parties swiftly decided to share cod and haddock TACs (Engesæter 1993). There was a lack of reliable data on stock distribution; the parties disagreed on the delimitation line between their zones (agreement was only reached in 2010); and importantly, due to overfishing, the parties agreed on the urgent need to establish a coherent coastal state management regime for the entire Barents Sea. The equal sharing of cod and haddock between Norway and Russia has remained unchanged since 1977. In addition, in bilateral agreements with third parties (the European Union and the Faroe Islands), Norway and Russia have annually exchanged quotas of cod and haddock on a reciprocal basis since the 1970s.

In the early 1990s, the Northeast Arctic (NEA) cod stock was increasing due to management measures combined with heightened stock productivity (Kjesbu *et al.* 2014), and cod became available in international waters in the northeastern part of the Barents Sea. This was known as 'the Loophole', (Figure 1) and unregulated fishing developed there. Several measures were introduced to deal with this issue, including blacklisting of vessels and cooperation with several European port states to deny vessels permission to land unregulated catches from the Barents Sea. With Greenland and Iceland as newcomers to fishing in the Barents Sea, Norway and Russia agreed to give vessels from these countries quotas of cod in Norwegian and Russian waters, in exchange for fishing opportunities in their waters and an end to unregulated activity in 'the Loophole'. An agreement with Iceland was finally concluded in 1999, and since 2000 the total annual allocation of cod to third parties in the Barents Sea has remained stable at 14.15 percent of TAC.

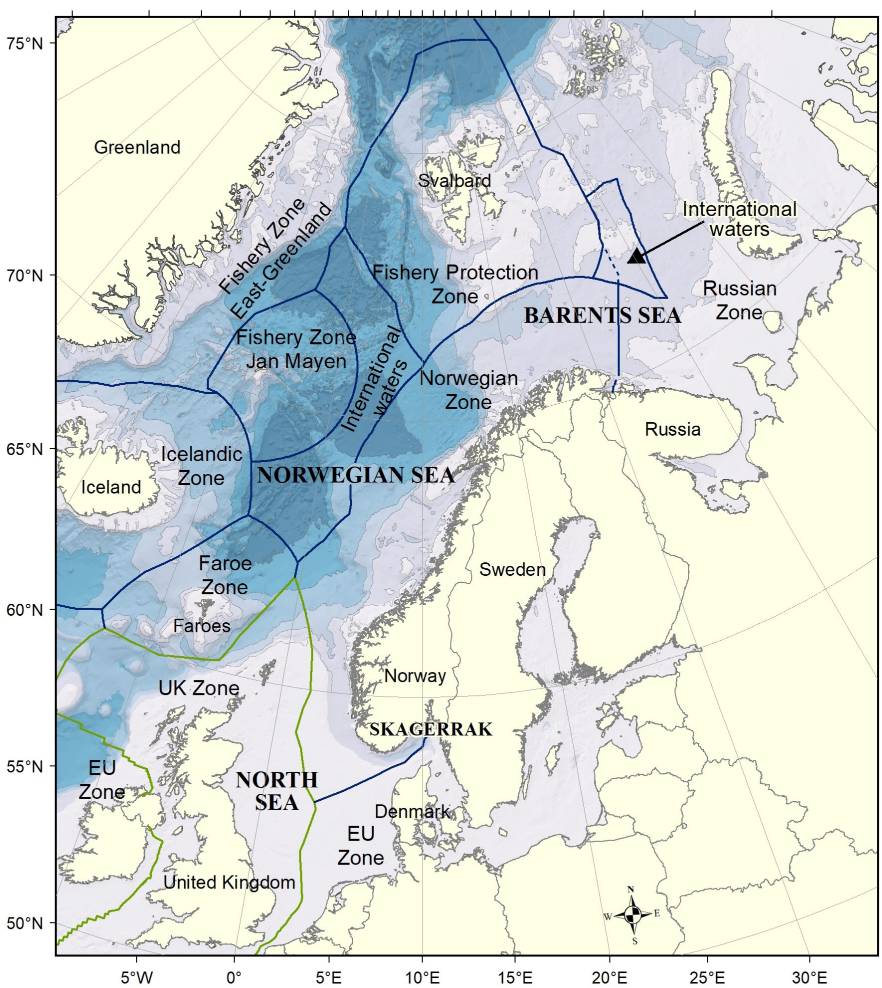

Figure 1. Exclusive economic zones (EEZs) in the Northeast Atlantic associated with the three large marine ecosystems of the Barents Sea, the Norwegian Sea, and the North Sea including Skagerrak and Kattegat.

Northeast Arctic cod

Northeast Arctic cod is a highly seasonal migratory stock with spawning areas along the Norwegian coast during spring, and summer feeding grounds stretching northward to the ice edge in the Barents Sea. During the last decade the biomass has increased considerably. The record-high situation is thought to be due to a combination of higher ocean temperatures and good management (Kjesbu *et al.* 2014). Behind these two overarching factors there are, however, additional large-scale climate processes and also management decisions taken by the Norwegian-Russian Fisheries Commission.

The recent increase in stock size had already started in 1983, following the interdecadal cooling during the 1960s and 1970s (Sætersdal and Loeng 1987; Ellertsen *et al.* 1989). Improved recruitment (year-class formation) from 1983 was ascribed to higher temperatures that provided better food conditions for young cod and hence increased their survival rates (Ellertsen *et al.* 1989). However, increased spawning stock biomass was also found to contribute equally to year-class formation (Ottersen and Sundby 1995).

As the temperature increased in the Barents Sea the adult part of the stock was displaced towards the northeast (Ottersen *et al.* 1998). Along with the temperature increase the ice cover in the northern part of the Barents Sea retreated. This resulted in cod moving to higher and higher latitudes to feed during summer. Generally, the habitat of the cod has increased in size and has moved north and east with the retreating ice edge (Kjesbu *et al.* 2014). As Northeast Arctic cod migrate a long way to spawn, it appears that spawning areas have also been displaced northeast along the Norwegian coast (Sundby and Nakken 2008). Since the millennium, ice cover in the northernmost parts of the Barents Sea has been very low during summer (Årtun *et al.* 2018), and this has enabled cod to feed all the way to the shelf edge in the Arctic Ocean north of Svalbard (Fossheim *et al.* 2015). The extraordinary recent 10-year increase in the size of the stock is most likely due to the considerable increase in suitable habitat area (Kjesbu *et al.* 2014). However, this remarkable increase would not have been possible without the sound harvest controls that have been in place since the late 1990s.

Poleward displacement combined with increased stock size is not a unique event in the history of Northeast Arctic cod. The time series of stock abundance, spawning areas and climate conditions show that the stock abundance has varied in parallel with the multidecadal climate oscillations (i.e. AMO) throughout the twentieth century (Hollowed and Sundby 2014; Drinkwater and Kristiansen 2018), and that spawning habitats have shifted accordingly northward and southward along the coast (Sundby and Nakken 2008). During the previous warm phase of AMO from the 1930s to the 1950s, North Atlantic marine species including Atlantic cod were displaced poleward (Tåning 1949; 1953; Drinkwater 2006), and spawning areas of Northeast Arctic cod were even identified in the ocean area between Bear Island and West Spitsbergen (Iversen 1934). The present warming phase has, however, exceeded the previous warming of the 1930s to the 1950s due to the additional influence of steadily increasing anthropogenic climate change.

Allocation in the North Sea

The North Sea is influenced by the inflow of Atlantic water from its northern entrance, by freshwater runoff along its southeastern coasts, and by brackish water outflow from the Baltic Sea.

In 1977, Norway and the European Community (EC) negotiated a Framework Agreement on future cooperation on fisheries management. In 1978 the International

Council for the Exploration of the Sea (ICES), on the request of the North East Atlantic Fisheries Commission (NEAFC), submitted a report (ICES 1978) on possible relevant factors to be considered for establishing allocation keys (i.e. the division of the TAC for each fish stock into national quotas) of shared resources in the Northeast Atlantic. These factors were: (i) the occurrence and migrations of the fishable part of the stock; (ii) the occurrence of juvenile and pre-recruit fish; (iii) the spawning areas and the distribution of eggs and larvae; (iv) the history of the fishery including the distribution of catch, rate of exploitation and fishery regulations; and (v) the state of exploitation of the stock. The report did not, however, advise on how these factors could be weighted to reach an agreed allocation key.

Taking the report as a starting point, a working group of EC and Norwegian research scientists and managers analysed the situation for several transboundary North Sea stocks. The experts proposed that – given the lack of comprehensive and reliable data for several of these factors, and the problems of weighting factors together – negotiations should focus on the distribution of the fishable part of the stock, including the zonal distribution of catches. On this basis in 1979 the EC and Norway agreed on allocation keys for five groundfish stocks (Norwegian shares ranged from 7 to 52 percent), and these allocation keys have remained unchanged to date.

North Sea herring

The North Sea herring stock was depleted in the 1970s, and Norway and the EC agreed a moratorium from 1978. By the early 1980s the stock was gradually recovering, and reopening the fishery came back on the agenda. Based on stock distribution data from the period of depletion, the EC would only agree to allocate a marginal share to Norway. The Norwegian position was that the stock had started to rebuild and, consequently, was already increasing its eastward distribution. Following unsuccessful negotiations, Norway opened a fishery in the latter half of 1984 in the Norwegian part of the North Sea. A catch of 96,000 tonnes appeared to justify the Norwegians' position. In 1987, the parties finally agreed on a three-step allocation key, depending on small, medium or large stock size – Norway's share would be 25, 29 and 32 percent respectively. This arrangement was replaced in 1997 with a fixed Norwegian share of 29 percent, which is still in place.

North Sea cod

The allocation key for North Sea cod is one of the five that has remained unchanged. Norway holds a share of 17 percent. However, despite the unchanged allocation key, this stock is being affected by changes related to climate. North Sea cod is found at the upper range for temperature habitats of this species (Sundby 2000). The biomass of North Sea cod was at its peak abundance during the last cool period of the 1960s and 1970s – the 'Gadoid Outburst' in the North Sea (Cushing 1984), which influenced not only cod, but also haddock *(Melanogrammus aeglefinus)*, whiting *(Merlangius merlangus)*, saithe *(Pollachius virens)*, and Norway pout (Trisopterus esmarkii). After the 1980s, the North Sea cod stock steadily decreased (Hislop 1996) until around 2005 (Hislop *et al.* 2015). This decline coincided with the combined warming phase of the AMO and the global anthropogenic increase of temperature – the latter may have amplified the effects of the former. Sundby *et al.* (2017) pointed out that the distribution of the adult stock, as well as the spawning areas, had been displaced towards the northeast during the same period. Prior to the 1990s cod spawning areas were spread over most of the North Sea (Brander 1994), while the major spawning areas are now found at the shelf near the western slope of the Norwegian Trench and in the northernmost part of the North Sea in the waters off Scotland and Shetland (Sundby *et al.* 2017). This displacement might be an indirect effect of higher temperatures as the main abundance of *Calanus finmarchicus*, the main prey for the cod larvae, now appears in the same region of the North Sea (Sundby 2000). From 2006 until 2015 spawning stock biomass was continuously rising, but only in the northern half of the North Sea that is influenced by inflow of Atlantic water masses from the northern entrance to the North Sea. In the southern half of the North Sea spawning stock biomass has seen a continuous decreasing trend. From 2017, the trend has also been negative for the northern North Sea (ICES 2019).

Allocation in the Norwegian Sea and adjacent seas

Now we move on to information related to Norwegian spring-spawning herring, blue whiting and Northeast Atlantic mackerel – i.e. 'the Norwegian Sea Pelagic Complex'. The fact that all these stocks are widely distributed implies that their habitats are significantly larger than the Norwegian Sea per se, but this area is important for fishing during the summer feeding season.

The Norwegian Sea ecosystem is constrained by the inflow of warm Atlantic water in the southeast and by Arctic water masses in the northwestern parts. This deep oceanic area (Figure 1) is dominated by pelagic and deep-water species, except along the shelf region of the Norwegian coast where demersal species occur.

A model for zonal attachment – the Iceland-Greenland-Jan Mayen capelin stock

Zonal attachment is defined by stock distribution during life cycle. Capelin *(Mallotus villosus)* is a short-lived species that dies after spawning at age three to five. Icelandic fishers had exploited this stock since the mid 1960s. In the late 1970s, Norwegian fishers started a summer fishery when capelin were feeding in the Fishery Zone around the Norwegian island of Jan Mayen. In the 1980s the stock was regulated unilaterally or bilaterally by Iceland and Norway on an ad hoc basis, Greenland being at the time a non-fishing coastal state to the stock. In 1989, the three parties managed to agree on an allocation key. The agreement gave Iceland, as the major shareholder, the final word with regard to the decision on TAC. Provisions for access to waters were important elements in reaching the agreement. Results from a model, developed by Johannes Hamre at the Norwegian Institute of Marine Research, were used as starting point for agreeing allocation. The model compiles quarterly trawl-acoustic data on the zonal distribution of the biomass of a representative year class throughout its lifetime (Hamre 1993), thus summarizing the distribution of biomass across zones in all life stages. A revised allocation key was agreed in 1998, and again in 2018, based on updated information on stock distribution.

Norwegian spring-spawning herring

Norwegian spring-spawning herring is the largest herring stock in the world, with spawning stock biomass estimated at 16 million tons in 1945 (Toresen and Østvedt 2000). The adults spawn at coastal banks off the Norwegian coast, and the pelagic offspring drift with the Norwegian Coastal Current to the main nursery areas in the Barents Sea. After spawning in spring, they migrate to feed in the Norwegian Sea. They then assemble in wintering areas until the next spawning season (Dragesund *et al.* 1997; Gullestad *et al.* 2018).

Norwegian spring-spawning herring has also undergone major multidecadal-scale changes in spawning stock biomass (Toresen and Østvedt 2000). However, unlike most of the other stocks in the Northeast Atlantic, this stock does not display poleward shift in distribution in parallel with the positive phases of multidecadal climate oscillations like the AMO. The most apparent link with changes in distribution is related to the stock abundance per se rather than coupled to temperature. Abrupt changes in overwintering areas seems closely linked to the proportion of young to older individuals, i.e. when the former category dominates (cf. strong year classes) and thereby defines where to go (Huse *et al.* 2010). Subsequent to the stock collapse during the 1960s the summer feeding habitat area in the Norwegian Sea also collapsed back to a small area along the Norwegian coast in the vicinity of the spawning areas (Dragesund *et al.* 1997), apparently because the coastal areas had sufficient amounts of copepods to feed the small herring stock. Moreover, overwintering areas were also confined to minor Norwegian coastal regions adjacent to spawning areas. When the stock started recovering during late 1980s the stock needed larger feeding areas, and summer feeding throughout the Norwegian Sea was resumed (Dalpadado *et al.* 2000). Today the science community is increasingly becoming aware of another factor that complicates the dynamics of summer feeding distribution in the Norwegian Sea, the density-dependent interaction with the blue whiting and the Northeast Atlantic mackerel (Huse *et al.* 2012; Utne and Huse 2012).

Overfishing, in combination with reduced stock productivity due to a period of colder ocean climate, caused the stock to collapse to near extinction in the late 1960s. Recovery started with the strong year class in 1983. During depletion, the stock was confined to limited areas of Norwegian coastal waters; a characteristic feature of this stock is extensive, flexible and varying migration patterns. The migration may be relatively stable for periods while larger changes occur at varying time intervals.

Starting with the 1983 year class, the stock again extended its habitat range at the juvenile stage into the Barents Sea, including Soviet Union waters. The Soviet Union claimed coastal state rights, and when Norway showed reluctance, the Soviet Union in 1984–85 fished 82,000 tons of juveniles in their own EEZ to make their point. In 1986 an agreement was reached according to which Norway would grant the Soviet Union an annual quota of adult herring in Norwegian waters. The parties at the same time agreed to a minimum catch size for herring of 25 cm in total length. This in practice closed the Barents Sea, including Soviet waters, for any fishing of herring. The partnership between Norway and Russia in the management of herring is still viable. By 1990, the 1983 year class had left the Barents Sea and started to take up some of the stock's previous migration pattern. This suggests that the stock gradually became available for fishing in summer in international waters of the Norwegian Sea (Figure 1), and possibly in the EEZs of several coastal states of the Norwegian Sea.

In 1996, the five coastal states – Norway, Russia, Iceland, the Faroe Islands and the European Union – agreed on an allocation key, which lasted until 2002. The Hamre model was used in analysing the zonal attachment as a starting point for the negotiations. As part of the overall agreement, bilateral agreements on access to waters were concluded. The allocation key was again discussed during the period 2002–2006, and a new key agreed from 2007 until 2013, since which time the coastal states have not reached consensus. In 2013 and 2014, four of the five coastal states managed to reach an agreement on TAC and allocation. For 2015 and 2016 no agreement was reached. For 2017 and 2018 all five coastal states agreed on a TAC, but not on allocation (Norwegian Government 2019).

The parties jointly decided on a management/harvest strategy in 1999, including a harvest control rule (HCR) for determining the TAC. In November 2018, all five coastal states adopted a revised management strategy and a 2019 TAC. In the absence of an agreed allocation key the parties set their national quotas unilaterally, yet related these to the agreed TAC. In all years without a full five-party agreement, the sum of unilaterally set quotas has been higher than the advised TAC. In 2018 and 2019, the sum of unilateral quotas amounted to 132 percent of the advised/agreed TAC. Established schemes, agreed both through the coastal states agreements and NEAFC, on technical regulations, electronic reporting systems, control etc, have not been affected by disagreement on the allocation key. Some management measures on which parties cooperate thus remain in place, and this limits the level of overfishing relative to the advised TAC. This also applies to blue whiting and Northeast Atlantic mackerel, discussed below.

Blue whiting

Blue whiting has an extensive distribution, from Morocco in the south to Svalbard in the north, inside coastal state waters and straddling into international waters west of the British Isles and in the Norwegian Sea. The species' distribution is not affected by climate change to the same extent as the Norwegian spring-spawning herring and the Northeast Atlantic mackerel. The fishery for blue whiting was begun by the Soviet Union in the late 1960s, followed by Norway in the mid 1970s. The fishery is now also important for European Union member countries as well as the Faroe Islands and Iceland. A peak spawning biomass of around 7 million tons was estimated for 2003 (ICES 2018a).

From 1977 to 2005, no comprehensive quota regulation of blue whiting fisheries existed. Fisheries were regulated unilaterally or bilaterally, or were carried out without quantitative restrictions. In 2005, four coastal states – the European Union, the Faroe Islands, Iceland and Norway – entered into a framework agreement on the management of the stock. After deduction of a quota to third parties (Russia and Greenland) in international waters, to be managed through NEAFC, the remainder was shared between the coastal states. This agreement on allocation lasted until 2014. By 2019, a new allocation key had not yet been agreed. Negotiations have zonal attachment considerations as a starting point, although some parties place particular emphasis on the distribution of the fishable part of the stock.

From 2009, revised in 2017, the coastal states have agreed on a management/harvest strategy including a HCR. In accordance with the HCR, the parties agreed on a TAC for 2018 and 2019. This was a basis for their unilateral decisions on national quotas, and limited them to an extent. These decisions are taken based on the share each individual country holds as a position in the negotiations on allocation. As a result, the sum of unilateral quotas in 2018 and 2019 amounted to 130 percent of the agreed TAC. The countries thus adhere to the management strategy, including the HCR, but disagree on the allocation – the same approach that they take to the management of Norwegian spring-spawning herring and Northeast Atlantic mackerel, species that are more affected by climate change than the blue whiting.

Northeast Atlantic mackerel

Northeast Atlantic mackerel comprises – together with Norwegian spring-spawning herring and blue whiting – the third part of the 'Pelagic Complex' summer feeding in the Norwegian Sea. The recent advancement of mackerel far into the Nordic Sea is not a novel phenomenon; the northward-southward shifts in distributions appear in concert with the AMO oscillations of the North Atlantic region (Astthorsson *et al.* 2012).

The Northeast Atlantic mackerel stock spawns in spring/early summer in the North Sea, west of Ireland and in Portuguese waters. Since the mid-1990s, summer and autumn feeding have extended substantially. Prior to this time, the northernmost migration was limited to the North Sea and the southernmost part of the Norwegian Sea (Uriarte and Lucio 2001). Subsequently, the feeding migration expanded to East Greenland and Svalbard.

Until 1999, no comprehensive quota regulation existed. The fisheries were regulated unilaterally or bilaterally, or were carried out without quantitative restrictions. Bilateral arrangements existed between the (at the time) recognized coastal states – the European Union, Norway and the Faroe Islands. In the period 1999–2009, these three parties entered into ad-hoc trilateral annual agreements on TAC and on allocation. A share was allocated to third parties in international waters to be managed through NEAFC. From 2006, the stock gradually increased and became available in fishable concentrations during summer in Icelandic waters, and later in Greenlandic waters.

For 2010, the three parties were unable to reach agreement. The Faroe Island claimed a bigger share, and Iceland also claimed a share as a coastal state. Against this background, the European Union and Norway entered into a ten-year bilateral framework agreement on the management of the stock, including allocation and mutual access to each other's waters. During the period 2010–2013 the four parties negotiated extensively, without success. Consequently, the European Union and Norway entered into bilateral annual agreements. In 2014, the European Union, Norway and the Faroe Islands managed to agree on a trilateral five-year framework agreement, later extended until 2020. On this basis, the three parties have annually agreed on TAC and allocation, including mutual access to each other's waters. Several attempts have been made to include Iceland in the agreement. Greenland has also participated in these consultations, which have been based on zonal attachment considerations. For 2018 the sum of unilateral quotas amounted to 122 percent of the TAC agreed by the European Union, Norway and the Faroe Islands. In 2015, the three parties to the framework agreement embraced a management strategy and a HCR for the mackerel stock. The management strategy was revised in 2017, following a technical revision of method by ICES.

Over the last ten years, eco-labelling has become widespread in economically important European fisheries, including the fisheries for mackerel. However, in March 2019 the Marine Stewardship Council (MSC) suspended all its Northeast Atlantic mackerel fishery certificates. The reason for the suspension was an observed decline in stock biomass and a lack of effective control of total exploitation. The MSC noted 'The North East Atlantic mackerel stock had faced overfishing due to increased activity from fishing vessels outside of MSC certification. International agreements aimed at managing the stock had broken down and all MSC certificates were suspended' (MSC 2019). However, the assessment of the Northeast Atlantic mackerel stock was highly uncertain, and in March 2019 ICES conducted a new revision of the assessment method. Based on this revision, the stock situation has been assessed to be more positive than was previously assumed (ICES 2019 special request).

Efforts in the Northeast Atlantic Fisheries Commission (NEAFC) to solve the allocation problems for the three major pelagic stocks

NEAFC was subject to a performance review in 2014 (NEAFC 2014), and one of the major concerns expressed was the issue of non-agreement by NEAFC parties on allocation of key fish stocks. As a follow-up to the report, NEAFC established a working group (WG) to address allocation at the annual meeting in 2015. The WG commenced its work in 2016 under the following terms of reference: 'Define, analyse and recommend: (i) the criteria for quota allocations on stocks occurring in the North-East Atlantic, both discrete stocks in the Regulatory Area (i.e. areas beyond national jurisdiction) and straddling stocks occurring both in the waters of the Coastal States and the Regulatory Area; (ii) the appropriate reference period; (iii) the weighting to be given to each of those criteria; and (iv) the minimum time period for which the allocation criteria should apply and the consequent timing of any review.' The WG was unable to finalize its work in 2016, and the Commission instructed the WG to continue in 2017. Although the WG would operate under the same mandate as in 2016, the Commission requested the WG in 2017 to prioritize the three main pelagic stocks that are the most relevant for NEAFC: blue whiting, Norwegian spring-spawning herring and Northeast Atlantic mackerel.

The WG established a sub-group composed of research scientists in order to respond to a suite of specific questions and create an improved basis for discussions on how 'stock distribution during life cycle' (zonal attachment) should be applied in practice. The sub-group suggested guidelines for zonal attachment analysis. In 2017 the WG put its work on hold, mainly because the United Kingdom of Great Britain and Northern Ireland was about to leave the European Union, and the consequences for allocation among coastal states were unclear. However, prior to that decision some progress had been made. The WG continued on a proposal for 'Criteria for the allocation of fishing opportunities in the North East Atlantic', which included elements such as scope/application, basis for allocation, and criteria to be used. The latter element was difficult, both in terms on agreeing on which criteria are relevant, and their possible weighting (or ranging). The draft contained six different criteria (not in order of importance): (i) zonal attachment, (ii) biomass conversion, (iii) historic fishing, (iv) national dependency, (v) local/regional dependency, and (vi) conservation and management of the stock. The document has no formal status. Following the report by the WG to the Commission in 2017, it was decided that the WG should temporarily suspend its work.

Conclusions

The United Nations Convention on the Law of the Sea (UNCLOS) does not deliver a clear answer to how quotas of transboundary stocks should be allocated between states. The negotiation processes on allocation keys can be complicated, and it can take years before any agreement is concluded. Although there might be some sort of mutual understanding on the relevant factors to be considered, the negotiation result will rarely follow any existing template or model. There are certainly many additional circumstances which could have an impact on the negotiated agreement, a few of which have been discussed in this Chapter. The development of sustainable and successful fisheries management of transboundary stocks nevertheless involves more than allocation keys; and a comprehensive management regime, once established, may have a mitigating effect on potential future disagreement on the subject. In general, however, stock distribution or zonal attachment should play an important role in agreements on allocation keys. It is apparent that negotiations involving only two main parties and where there is relatively little variation in stock migration dynamics over the years (cf. cod in the North Sea and in the Barents Sea) have given rise to agreements that have been much more stable than those for widely-distributed, highly dynamic pelagic stocks (cf. Norwegian spring-spawning herring and Northeast Atlantic mackerel).

A wide range of measures to support sustainable management have been developed since the 1970s, and the process is still ongoing. To support this development scientific cooperation has been extended bilaterally and through ICES as the primary scientific adviser to coastal states in the Northeast Atlantic. Technical regulations on issues such as gear, selectivity, protection of juveniles, and discarding practices have been improved and harmonized bilaterally or through NEAFC. Starting in the late 1990s, the precautionary approach has been embedded in management strategies and in HCRs. Most Northeast Atlantic transboundary stocks are now managed according to agreed management strategies and HCRs. Standards and protocols for the collection and exchange of data from fisheries (satellite tracking and electronic logbooks) have been introduced and harmonized throughout the region, including through NEAFC for the high seas areas. In addition, numerous bilateral agreements on cooperation on control have been concluded between coastal, flag and port states. Most coastal states in the region reach annual bilateral quota agreements, including the exchange of fishing opportunities in each other's waters. This network of diverse measures and agreements developed over the past 40 years is little affected by present disagreements on certain allocation keys. It could be argued that this mutual dependence has a dampening effect on conflicts regarding allocation and on their consequences. The latter point is illustrated in the fact that for both herring and mackerel the parties adhere to the agreed HCRs/management strategies although they disagree on allocation. This puts a cap on how much more than the recommended TAC is actually fished.

Improved knowledge of stock distribution has increased over time, strengthening the role of zonal attachment as the starting point for negotiations on allocation keys. Stocks change their distributions for a series of intrinsic reasons (e.g. stock size, demography and physiology), due to interspecific competition, climate fluctuations, and now also climate change. The consequences of the latter driver are likely to be amplified long-term changes in distribution for many fish stocks, increasing the complexity in reaching solutions on management, and in particular reaching compromises on allocation keys for straddling and transboundary fish stocks. However, as scientific expertise (i.e. model projections and predictions) on how natural variability and climate change are influencing fish stocks' abundances and distributions is rapidly improving, this new knowledge could have the potential to clear out premises for negotiations and facilitate reaching agreements.

Agreements are, however, the result of political compromises, not a copy of results from scientific modelling. Nor are they copies of previous agreements related to other species, or agreements between other parties related to the same species. Access to waters is often an important element in reaching agreement. Flexible access to waters may, for a fixed quota, contribute to reducing the cost of catching or increase the value of the catch. Flexible access may also improve exploitation patterns, increasing the long-term yield from the stock, to the mutual benefit of all parties. It seems unlikely that states will agree in advance of any change in stock distribution, no matter what causes it, on the principles guiding how agreements on allocation should be drafted or how existing agreements should be amended.

A comprehensive set of management measures and agreements may help mitigate the most negative effects of the lack of consensus on allocation keys. For example, with or without an agreement on a management strategy and HCR, it is difficult to imagine that responsible coastal states would allow their own vessels to open up an unregulated fishery today, as they are all bound by agreements preventing that. In the Northeast Atlantic, cooperation between the states on measures related to control secures transparency among them on the quantities caught. It can be argued that this increases the trust between the parties and encourages individual states to limit overfishing in relation to the advised TAC for the pelagic species.

In conclusion, bilateral allocation keys once agreed have shown resilience over time. Allocation keys for widely distributed pelagic stocks have been much more difficult to agree on, not only because such stocks migrate across several zones, but also because they have highly variable habitat extents, a trait that will be even more noticeable in the future under continued climate change. Therefore agreements for such stocks have been of a temporary nature. Bilateral agreements, on the other hand, tend to include more stocks and areas of cooperation , which may contribute to mutually beneficial long-term partnerships.

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Chapter 12: The Parties to the Nauru Agreement (PNA) 'Vessel Day Scheme': A cooperative fishery management mechanism assisting member countries to adapt to climate variability and change

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Summary

The eight Pacific Island countries that are the Parties to the Nauru Agreement,[1] together with Tokelau, manage the largest tuna fishery in the world. As a group, these Small Island Developing States have developed a system to manage fishing effort, known as the Vessel Day Scheme (VDS). The system is an effective adaptation to the profound impacts of climate variability, i.e. the El Niño Southern Oscillation (ENSO), on the distribution and abundance of tuna within their combined exclusive economic zones (EEZs).

The VDS limits purse-seine fishing effort, defined in terms of fishing days, to an annual Total Allowable Effort (TAE). The TAE is allocated among the eight sovereign PNA members as a set of Party Allowable Effort limits (PAEs), based largely on recent effort history. Tokelau has a separate TAE/PAE that is adjusted in relation to changes to the PNA TAE. Parties can trade PAE days, and use a range of other VDS provisions, to adapt to the effects of ENSO. For example, during La Niña events, when most fleets prefer to fish in the west of the region, PNA members located there can buy days from those in the east. The converse occurs during El Niño episodes. The VDS ensures that the benefits of this fishery, which underpin the economies of many of the PNA members, can be distributed equitably, regardless of where the fish are caught within their EEZs.

The allocation of PAE is also a non-confrontational adaptation to climate change because it matches the climate-driven redistribution of tuna. However, adaptations to climate change-driven redistribution of tuna from the EEZs of PNA members into high-seas areas are also needed.

[1] Federated States of Micronesia, Kiribati, Marshall Islands, Nauru, Palau, Papua New Guinea, Solomon Islands and Tuvalu.

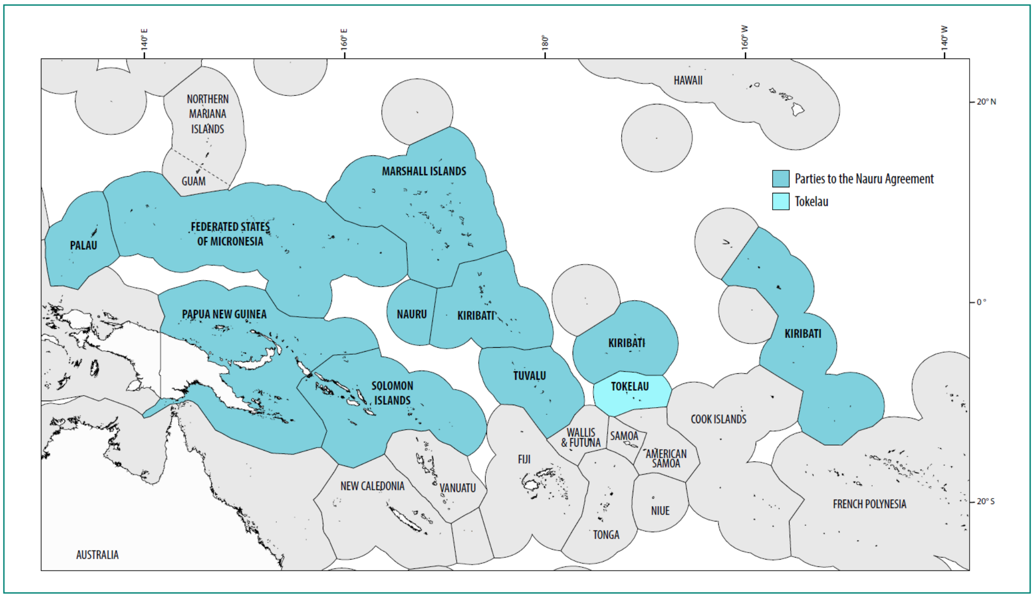

Figure 1. Map of the Pacific Islands region, showing the EEZs of the eight countries that are the Parties to the Nauru Agreement (PNA), and Tokelau.

A. Fishery context

This case study is based on the industrial purse-seine fishery targeting tropical tuna species in the combined EEZs of the eight Pacific Island countries that are the Parties to the Nauru Agreement (PNA) and Tokelau (Figure 1), an area of almost 13 million km^2. For the purpose of this paper, reference to PNA includes Tokelau. In 2018, approximately 250 purse-seine vessels participated in this fishery, with ~35 percent of the vessels flagged in Pacific Island countries and ~65 percent from other member countries of the Western and Central Pacific Fisheries Commission (WCPFC) (Williams and Reid, 2019; Clark, 2019)

Between 2014 and 2018, the annual landed value of tuna caught by the PNA purse-seine fishery averaged USD 2.2 billion.3 However, because many of the PNA members do not have the opportunity to harness this value by participating in all parts of the supply chain, the economic benefits for these countries are derived mainly from fishing access revenue. This revenue makes extraordinary contributions to the economies of PNA members. In 2016, the total fishing access fees received by PNA members exceeded USD 450 million, providing between 28 percent and 98 percent of all government revenue for six4 of the nine PNA countries and approximately 5 to 10 percent for the other three5 members (FFA, 2018a, b). Across the region, the fishery also supports the employment of more than 20,000 people on fishing vessels, in fish-processing operations and fisheries management roles, including as onboard observers (FFA, 2018a).

The PNA purse-seine fishery targets skipjack tuna (which averaged 76 percent of the catch between 2014 and 2018), but also harvests smaller yellowfin and bigeye tuna (which comprised 20 percent and 4 percent of the average catch during that period, respectively). The total annual average catch from the PNA purse-seine fishery is 1.4 million tonnes (Table 1), and represents more than 50 percent of the recent (2014–2018) average tuna catch from the entire western and central Pacific Ocean (WCPO) of 2.7 million tonnes. This equates to almost 30 percent of the total global tuna supply (SPC, 2019a; Clark, 2019).

[2] Nauru Agreement Concerning Cooperation in the Management of Fisheries of Common Interest, https://www.pnatuna.com/content/nauru-agreement.

[3] WCPFC Area Catch Value Estimates, https://www.ffa.int/node/425.

[4] Federated States of Micronesia, Kiribati, Marshall Islands, Nauru, Tokelau and Tuvalu.

[5] Palau, Papua New Guinea and Solomon Islands.

Table 1. Total annual tuna catches (tonnes) between 2014 and 2018 from the EEZs of the Parties to the Nauru Agreement. FSM = Federated States of Micronesia, RMI = Republic of Marshall Islands, PNG = Papua New Guinea (Source: Pacific Community).

Year	FSM	Kiribati	RMI	Nauru	PNG	Palau	Solomon Is	Tuvalu	Tokelau	Total
2014	134 732	705 944	78 383	179 480	337 408	2 704	57 894	95 882	27 194	**1 619 621**
2015	160 645	613 357	31 657	67 107	189 007	185	100 174	76 783	44 134	**1 283 049**
2016	192 474	390 151	85 291	115 702	335 429	3 809	151 118	113 544	5 010	**1 392 527**
2017	191 165	377 258	27 880	82 295	377 397	12 698	158 726	53 328	33 546	**1 314 294**
2018	282 886	398 414	31 321	177 668	372 101	4 845	70 867	88 183	37 854	**1 464 138**
Average	**192 380**	**497 025**	**50 907**	**124 450**	**322 268**	**4 848**	**107 756**	**85 544**	**29 547**	**1 414 726**

The stocks of all three tropical tuna species caught by purse-seine in the WCPO are assessed to be in a healthy condition – none of the species are overfished, and none of them are currently subject to overfishing (Brouwer *et al.*, 2019). The healthy status of tuna stocks in the WCPO is due to the sound management arrangements implemented by PNA members (Section B), the Pacific Islands Forum Fisheries Agency (FFA) and WCPFC. The Oceanic Fisheries Programme at the Pacific Community (SPC) provides the science needed to assess the status of the tuna stocks, and the impacts of industrial tuna fishing on the ecosystem. The scientific advice provided by SPC that underpins the work of the tuna management agencies is evaluated annually by the WCPFC Scientific Committee.

Due to the comprehensive management arrangements implemented by PNA, FFA and WCPFC, levels of illegal, unreported and unregulated (IUU) fishing are low in PNA waters (MRAG, 2016).

B. Management context

PNA members manage purse-seine fishing in their EEZs through the 'Vessel Day Scheme'[6] (VDS) (Aqorau, 2009). The VDS was designed to enable PNA members to maximize their net economic returns from the sustainable use of tuna resources within their EEZs. To achieve this objective, the VDS applies a set of national, zone-based, transferable effort limits. This collaborative approach not only protects the sovereign rights of PNA members, but also enables them to implement sustainable conservation limits without bearing a disproportionate burden, and ensure that responsible fishing practices occur within their waters.

In legal terms, the VDS is a management scheme under the Palau Arrangement[7] (Aqorau, 2009), to which all PNA members are Parties. Tokelau has participated in the VDS since 2012 under the terms of a memorandum of understanding (MoU) with PNA. Under the VDS, purse-seine fishing effort, defined in terms of fishing days, is limited to an annual Total Allowable Effort (TAE). The TAE is an effort limit for purse-seine fishing in the EEZs of PNA members set within the broader range of measures for conservation and management of skipjack, yellowfin and bigeye tuna agreed by WCPFC.[8] These measures are agreed on a three- to four-year cycle, taking into account advice from the WCPFC Scientific Committee on the management of tropical tuna species targeted by the purse-seine fishery.

[6] Purse Seine Vessel Day Scheme, https://www.pnatuna.com/vds.

[7] Palau Arrangement for the Management of the Western Pacific Fishery as Amended, https://www.pnatuna.com/content/palau-arrangement-management-western-pacific-fishery.

[8] See Attachment 1, Table 1 of WCPFC Conservation and Management Measure, CMM 2018-01, https://www.wcpfc.int/doc/cmm-2018-01/conservation-and-management-measure-bigeye-yellowfin-and-skipjack-tuna-western-and.

The TAE is allocated among the eight PNA members as a set of Party Allowable Effort limits (PAEs), based largely on recent purse-seine effort history in each EEZ (Section D). In some years, estimates of tuna biomass in each EEZ have also been used in the formula for allocating PAE. Tokelau has its own separate TAE/PAE that is adjusted in relation to changes to the PNA TAE.

The Parties have substantial freedom in how they use their PAEs, but they are required to take all necessary measures, as adjusted by the provisions described in Section D(b), to ensure that their PAEs are not exceeded. Multilateral pooling arrangements are also used to provide access to the combined EEZs of several Parties, and one of these arrangements grants preferential access for vessels of the Parties to each other's EEZs.

Decisions on the VDS are generally taken by officials of Parties to the Palau Arrangement at meetings held at least annually. Where appropriate, issues arising from discussions by these officials are referred to meetings of Fisheries Ministers from PNA member countries. High-level oversight of the VDS is exercised by the Presidents/Prime Ministers of PNA member countries during occasional summits. The PNA office is required to brief the officials' meetings on catch and effort levels, any observed or potential effort creep, and any transfer of fishing days between Parties. Officials' meetings are also advised by the VDS Technical and Scientific Committee, and by the PNA Compliance Sub-Committee.

C. Climate implications

a) Effects of climate variability

The PNA VDS was designed from the start to take into account climate variability in the form of the variations in the distribution and abundance of skipjack tuna across the equatorial Pacific Ocean associated with ENSO events. The VDS design, described below, minimizes the effects of this interannual climatic variability on the equitable distribution of access revenue earned from the purse-seine fishery among PNA members (Geen, 2000; Aqorau *et al.*, 2018).

These effects stem from climate-driven variation in important features of the tropical Pacific Ocean, including upwelling of nutrient-rich water and sea surface temperature (Lehodey 2001; Ganachaud *et al.*, 2011), and the effects of this variation on the availability of micronekton (tuna prey) (Le Borgne *et al.*, 2011) and suitable spawning conditions for tuna (Lehodey *et al.*, 2011). In short, variation in ocean features influences the distribution of tuna, and the survival of eggs and larvae, with subsequent effects on purse-seine catches.

Despite the variable oceanic conditions, suitable habitat for tuna and areas for purse-seine fishing occur within the combined EEZs of PNA members every year. The prime area is the convergence zone between the two large ecological provinces dominating the equatorial Pacific Ocean: the 'western Pacific warm pool' and the 'Pacific equatorial divergence', also known as the 'cold tongue' (Le Borgne *et al.*, 2011). This convergence, which is several hundred kilometres wide, is characterized by relatively high concentrations of tuna prey and sea surface temperatures within the range preferred by skipjack tuna (Lehodey *et al.*, 1997, 2001, 2011).

The location of this convergence zone is influenced strongly by ENSO. During El Niño events, the warm pool can extend by up to 4 000 km, relocating the convergence zone further to the east (often within the EEZ of Kiribati). During La Niña episodes, the warm pool contracts and the convergence zone is located further west (often near the EEZ of PNG). Skipjack tuna follow the movement of the warm pool and convergence zone to remain in waters with relatively high concentrations of prey, and in conditions suitable for reproduction (Lehodey *et al.*, 1997). As a result, the locations where the best purse-seine catches are made correlate with the position of the warm pool and convergence zone (Lehodey *et al.*, 2011) (Figure 2).

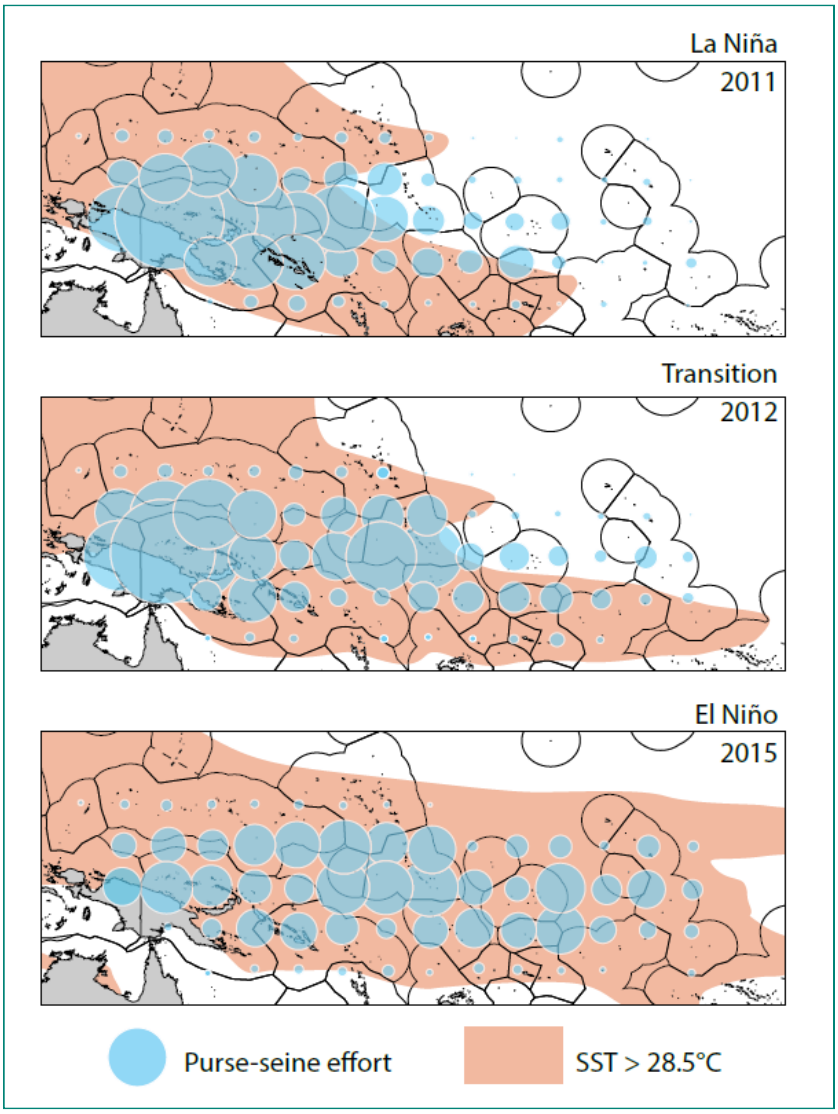

Figure 2. Examples of the influence of climatic variability (El Niño and La Niña events), and the associated extent of the western Pacific warm pool (defined by sea surface temperatures, SST, > 28.5 oC), on the distribution of purse-seine fishing effort in the tropical Pacific Ocean (source: Williams and Reid, 2018). The size of the blue circles indicates the level of fishing days in that 5ox5o square, with larger circles indicating relatively greater levels of fishing effort.

The east–west movements of skipjack tuna associated with the displacement of the warm pool have been demonstrated from tagging data (Lehodey *et al.*, 1997). Changes in the depth of the thermocline have also been proposed to explain the variability in purse-seine catch rates. During El Niño events, the thermocline becomes shallower in the west and deeper in the east. The opposite pattern occurs during La Niña periods. The depth of the thermocline influences the vertical distribution of skipjack, yellowfin and bigeye tuna; all of which generally remain above this strong vertical temperature gradient. A deeper thermocline allows fish to descend to greater depths, making them more difficult to catch with a purse-seine net deployed in surface waters, even where tuna are abundant. However, modern purse-seine fishing techniques (e.g. deeper nets) have reduced this difficulty, enabling fleets to take advantage of knowledge about the effects of climatic variability on the distribution and abundance of tuna.

b) Effects of climate change

The effects of continued high greenhouse gas (GHG) emissions on the distribution and abundance of tropical tuna species is modelled using a spatial ecosystem and populations dynamics model (SEAPODYM; Lehodey *et al.*, 2008; Senina *et al.*, 2008). Currently, bigeye tuna is primarily distributed in the eastern and central Pacific and its biomass in the western Pacific is limited, whereas skipjack and yellowfin tuna are primarily distributed in the western and central Pacific. The model indicates that the projected average distributions of skipjack and yellowfin tuna in 2050 generally approximate observed distributions of these species under strong El Niño conditions in recent decades (Figure 3) (Senina *et al.*, 2018). The biomass of skipjack and yellowfin tuna vulnerable to capture by purse-seine is projected on average to decrease in the EEZs of all PNA members except Kiribati by 2050 as the fish move progressively east, and to some extent poleward, into high-seas areas (Senina *et al.*, 2018; SPC, 2019b) (Table 2).

The redistribution of bigeye tuna is expected to be modest in the EEZs of PNA members, compared to skipjack and yellowfin tuna. Bigeye tuna has a longer life span and reaches larger sizes than skipjack and yellowfin tuna, and it has physiological adaptations to reach deeper ocean layers with low levels of dissolved oxygen concentration (Lowe *et al.*, 2000). These attributes provide bigeye tuna with a larger thermal habitat and the ability to dive regularly to the lower mesopelagic layer, increasing foraging opportunities. SEAPODYM simulates the differences in spawning and feeding habitat among tuna species and predicts a wider range of favourable spawning and feeding habitats for bigeye tuna (Table 2).

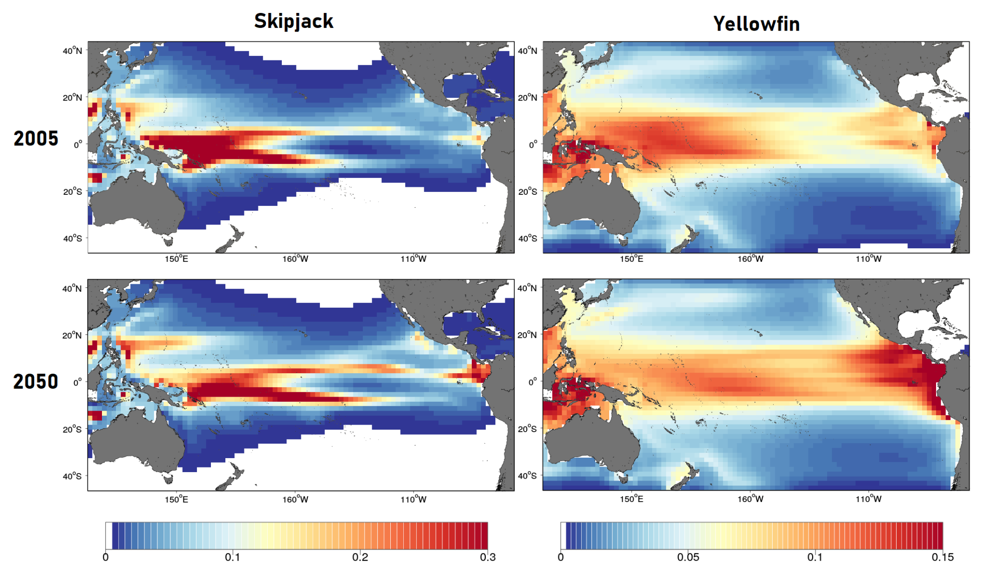

Figure 3. Projected mean distributions of skipjack and yellowfin tuna biomass across the tropical Pacific Ocean under a high-emissions scenario (IPCC RCP8.5) in 2050, relative to 2005 (Senina *et al.*, 2018).

Table 2. Projected changes (%) in biomass of skipjack, yellowfin and bigeye tuna by 2050 under a high-emissions scenario (IPCC RCP8.5) in the EEZs of the Parties to the Nauru Agreement (PNA) (source: Senina et al., 2018).

PNA EEZ		Skipjack	Yellowfin	Bigeye
West of 170°E	FSM	-29	-19	+3
	Marshall Islands	-17	-12	-3
	Nauru	-8	-16	-4
	Palau	-28	-12	+4
	Papua New Guinea	-43	-21	-4
	Solomon Islands	-17	-9	-2
East of 170°E	Kiribati	+18	+7	+1
	Tuvalu	-12	+3	-2
	Tokelau	-14	+14	-1

Based on this modelling, the average annual purse-seine catch from the combined EEZs of PNA members is projected to decrease by 10 percent (~140 000 tonnes) by 2050. Preliminary economic assessments indicate that total access revenue collected by PNA members could decrease by more than USD 60 million per year in the decades ahead (Table 3) (SPC, 2019b). Significant loss of tuna biomass can also be expected to reduce other opportunities to derive wealth from tuna, and to disrupt the Regional Roadmap for Sustainable Pacific Fisheries (FFA and SPC, 2015).

Table 3. Tuna access fees earned by PNA members in 2016, and projected changes in access fees and total government revenues by 2050 due to redistribution of tuna. Projected changes in tuna biomass are averages for skipjack (SKJ), yellowfin (YFT) and bigeye (BET) tuna (Table 2), weighted by 76%, 20% and 4%, respectively (adapted from SPC, 2019b).

PNA member	Tuna access revenue 2016 (USD million)	Change (%) in combined biomass of SKJ, YFT & BET tuna by 2050	Tuna access revenue 2050 (USD million)	Change from 2016 to 2050	
				Tuna access revenue (USD million)	Loss/gain in total gov't revenue (%)
West of 170°E					
PNG	128.8	-37	81.1	-47.7	-1.8
FSM	63.2	-26	46.8	-16.4	-14.6
Palau	6.8	-24	5.2	-1.6	-2.1
Marshall Islands	29.2	-15	24.8	-4.4	-9.0
Solomon Islands	41.6	-15	35.4	-6.2	-1.5
Nauru	27.8	-9	25.3	-2.5	-2.5
East of 170°E					
Tuvalu	23.4	-9	21.3	-2.1	-5.6
Tokelau	13.3	-8	12.2	-1.1	-7.8
Kiribati	118.3	+15	136.0	+17.7	+9.9

Another important result of the progressive redistribution of tuna from the combined EEZs of PNA members to high-seas areas is that a lower proportion of tuna biomass supporting the purse-seine fishery will be under the jurisdiction of PNA member countries.

D. Adaptations and lessons

a) Stock assessment and management advice

Knowledge of the effects of ENSO on the distribution and abundance of tuna has been incorporated to some extent into the integrated models used to assess the status of tuna stocks in the WCPO, particularly to refine estimated recruitment levels. However, stock assessment models either require assumptions about key biological parameters (e.g. growth, natural mortality), or estimate those parameters from supplied historical data. These biological parameters are currently assumed to be constant through space and time and so do not capture or easily incorporate the long-term effects of historical climate change.

There is also more scope for including the effects of ENSO, rather than the implications of climate change, in the development of harvest strategies for tuna stocks currently underway by the WCPFC (WCPFC, 2014, 2015). Development of these harvest strategies involves the design, testing and implementation of management procedures, which invoke pre-agreed decisions on data collection, assessment and management action, defined through harvest control rules. These rules need to be robust to uncertainties, and define future fishing opportunities to achieve specified management objectives and maintain stocks around corresponding target reference points.

Inclusion of the effects of climate change in future stock assessment models and harvest strategies will eventually need to incorporate information on the stock structure of tuna. Recent research on the population genetics of tuna species (Grewe *et al.*, 2015; Anderson *et al.*, 2019a,b) indicates that spatial structuring does occur within some of the tropical tuna species (Moore *et al.*, 2020a), and highlights the need to determine the number of self-replenishing stocks for each tuna species and their respective spawning grounds (Moore *et al.*, 2020b; see also Rodriguez-Espeleta *et al.*, 2019). The explicit description of fish movements, including feeding and spawning migrations, and the use of a robust parameter estimation method within SEAPODYM (Senina *et al.*, 2008, 2020), are also expected to help predict the occurrence of self-replenishing stocks for each tuna species.

Investments are now needed to: 1) identify the spatial structure of tropical Pacific tuna stocks; i.e. the number of self-replenishing populations (‘stocks’) within the geographical range of each tuna species; 2) gather new and independent data to strengthen model predictions for the responses of each stock under both high- and low-GHG emissions scenarios; and 3) compile integrated assessments of the effects of climate change on the expected redistribution of each tropical Pacific tuna species within its geographical range for each GHG emissions scenario (SPC, 2019b).

b) Formulation of norms to regulate harvest and access to resources according to established objectives

<u>The PNA VDS and the WCPO tuna fishery</u>

The WCPO tuna fishery is managed through conservation and management measures (CMM) agreed to and adopted by the WCPFC (Commission). The current CMM for tropical tuna (TT CMM) includes purse-seine effort limits for the high seas and EEZs over three-year periods, in addition to limits for other fisheries, especially longline (LL) fisheries. The TT CMM is evaluated each year for potential performance against management objectives.

Within the CMM, the PNA purse-seine effort limit is implemented through the VDS TAE, which covers approximately 80 percent of the WCPO purse-seine tuna fishery. For PNA, the VDS days are monitored using an electronic vessel tracking system and the TAE and PAEs are reviewed annually.

In theory, the PNA VDS could be expanded to cover the whole WCPO purse-seine fishery. In the past, some other Pacific Island countries have expressed an interest in participating in the PNA VDS – Tokelau was the first to do this, and was successful. However, the practical difficulties associated with maintaining the VDS coalition have resulted in it continuing to be limited to the 'like-minded' group of PNA members and Tokelau.

Like PNA, WCPFC annually assesses whether commission members: (i) have properly implemented the measures through their national laws; and (ii) are enforcing the laws effectively for their vessels and/or in their waters. To do this, WCPFC uses information from a range of reporting and monitoring arrangements, including onboard observers, vessel tracking, and inspections at sea and in port.

As mentioned in Section A, the WCPFC Scientific Committee regularly assesses the stock status of each tuna species. This is done comprehensively for each of the four main species at least once every three years. Reviews of short-term stock status indicators are also made annually for each of the four species. The WCPFC uses this information, and evaluations of the effectiveness of the management measures, to make annual adjustments where appropriate.

As noted, the Commission is also moving towards longer-term harvest strategies that will include agreed target reference points (TRPs) that reflect overall fishery management objectives, and mechanisms for adjusting catch and effort when the status of a tuna fishery is not consistent with the TRPs.

<u>Interannual climate variability</u>

Several elements of the structure of the VDS enable the performance of this fishing effort scheme to adapt to climatic variability. They include transferability, pooling, roaming and PAE adjustments. PAE vessel days can be transferred freely between Parties, and consequently between EEZs, but not between vessel operators. Inter-Party transferability, as a response to the effects of ENSO on skipjack tuna, was proposed during the design of the VDS, with the original proposal advising that *'Given the scale of fluctuations in abundance in some EEZs, transferability of fishing days between Parties will be an essential component of the management system'* (Geen, 2000).

In general, the transferability provision of the VDS can be seen as a trading mechanism among PNA members, allowing them to respond to the effects of ENSO on the prime fishing grounds for skipjack tuna (Aqorau *et al.*, 2018). During La Niña events, when the fleets fish in the west of the region, the countries there can buy days from members in the east. The converse occurs during El Niño episodes. Thus, regardless of where the fish are caught, all PNA members can receive license revenue each year.

When Parties pool fishing days, vessels purchasing pooled days can use them in the EEZs of any of the Parties contributing to the pool, increasing the value of the days and the scope for effort to be adjusted in response to changes in distribution of tuna, and variation in fishing conditions more generally. There are two major

[9] There is a separate allocation of days solely for the Kiribati EEZ, which is the most important EEZ for fishing by the United States of America fleet.

pooling arrangements – one for the United States of America fleet, which includes eight of the nine Parties and excludes Kiribati,[9] and one between five of the Parties (Marshall Islands, Nauru, Solomon Islands, Tuvalu and Tokelau).

Roaming enables fishing days to be used outside the EEZ of the PAE holder without the processes of transfer or pooling. The roaming arrangements enable domestic vessels of PNA members to fish in other Parties' EEZs beyond their home Party's EEZ, using fishing days provided from the PAE of their home Party. Designed primarily to provide support for the development of domestic fleets, roaming allows for greater flexibility in adjusting effort to short-, medium- and long-term changes in distribution of tuna resources targeted by purse-seine fishing. In 2018, domestic fleets accounted for 35 percent of the fishing effort under the VDS, and roaming is expected to increase this percentage further.

In addition, there have been varying forms of allocation models used to adjust PAEs, which have made the VDS responsive to climatic variability. The current allocation model no longer uses estimated tuna biomass within an EEZ as a factor in the allocation because of difficulties in making these estimates at the national scale, and because of the high degree of intra-regional variability from year to year. Rather, the allocation of PAE is based substantially on recent (previous eight to ten years) fishing effort within the Party's EEZ. Under this arrangement, the PAE allocations reflect the patterns of fishing effort driven by the influence of ENSO on the distribution of tuna, and enabled by the transferability, pooling and roaming provisions of the VDS.

Some examples of the implications of climatic variability for PNA members, and the ways they benefit from the provisions of the VDS, are summarized below.

Kiribati: With the largest EEZ area of all PNA members, Kiribati is at the eastern end of the range of the western and central Pacific tropical purse-seine fishery and hosts much of the effort by this fishery during El Niño events. Another feature is that Kiribati has closed 40 percent of its Phoenix Islands EEZ (one of the nation's three non-contiguous EEZs, the others being the Gilbert Islands and Line Islands EEZs) to commercial fishing. As the warm pool expands and the centre of distribution of the skipjack tuna stock moves east towards Kiribati over the next few decades (Figure 3), the VDS will enable Kiribati – if it wishes – to non-confrontationally obtain the rights to increase EEZ effort limits by acquiring days from other PNA EEZs further west, and thereby gradually increase its PAE (i.e. its share of the total purse-seine fishery). Without the PNA and the VDS, the consequences of this kind of climate-driven shift in skipjack tuna biomass would have to be accommodated by continuous and uncertain political negotiations within WCPFC. Like other tuna regional fisheries management organizations, WCPFC still lacks an adaptive and equitable fishing rights allocation framework, particularly one that can respond to climate change-induced shifts in fish biomass.

Nauru: Although Nauru has the smallest EEZ of any of the eight PNA members, its EEZ attracts considerable purse-seine effort because the convergence zone often occurs in the vicinity of the country during both El Niño and La Niña events. Even during strong El Niño events, there can be demand for days because purse-seine vessels often move between the east and central Pacific without going to the west. As a result, the average tuna catch from Nauru's EEZ is the fourth highest among all PNA members (Table 1). It is also interesting to note that the average purse-seine 'catch density' of tuna in Nauru's EEZ (78 kg per km^2 per year) is higher than for any other PNA member, and at least twice as high as for Kiribati and PNG. The pooling and roaming provisions of the VDS should assist Nauru to maintain PAE as the average position of the convergence zone moves eastward due to ocean warming.

Palau: Relatively low purse-seine fishing effort has occurred in Palau's EEZ since implementation of the VDS. Even lower levels of purse-seine effort are expected to occur in the future because the Palau National Marine Sanctuary (PNMS) Act, signed into law in 2015, resulted in the closure of 80 percent of the EEZ to all fishing, effective 1 January 2020. A practical approach to using the provisions of the VDS for Palau in the years ahead is likely to involve: (i) preserving transferability so that days can continue to be traded in response to demand created by El Niño events, even though there is a net redistribution of tuna to the east; and (ii) joining the five pooling Parties to maintain PAE, enhance the value of allocated days, and optimize revenue following the implementation of the PNMS.

Climate change

The methods for allocating PAE, and the pooling and roaming provisions of the VDS, are expected to also provide non-confrontational adaptations to climate change. Eastward redistribution of tuna (Figure 3) could result in proportional changes in allocation of PAE among PNA members. The latest modelling (Senina *et al.*, 2018) indicates that during the next couple of decades, Parties in the central and eastern regions of the WCPO could accumulate PAE, whereas Parties in the west may gradually lose PAE. However, by 2050, the PAE of all PNA members, except Kiribati, could be reduced to some extent by climate-driven redistribution of tuna. The VDS may buffer these potential impacts. The formula for allocating PAE (based on the past eight to ten years of effort history) will provide Parties with time to adapt. The pooling and roaming provisions can also be expected to provide some opportunities to help Parties maintain PAE, through use of their days further to the east.

However, as explained in Section D(a), there is still significant uncertainty associated with the current modelling with SEAPODYM stemming from multiple sources, such as biases in coarse spatial and temporal resolutions; coupled, global circulation and biogeochemical model predictions (Matear *et al.*, 2015); stock structure; imperfections in fishing data used in model fitting; and the structural uncertainty of the model itself, including the forage sub-model for which limited validation is possible due to the weak availability of forage observations. A robust, integrated modelling approach is needed, including estimation of forecast uncertainties and identification of the spatial structure of tuna stocks, before the potential risks to longer-term changes in PAE can be identified with confidence.

A separate, key issue for PNA members is to identify how to retain the full present-day benefits that they receive from their shared tuna resources, in a non-confrontational way, as tuna resources caught by purse-seine fishing move progressively into high-seas areas (Pinsky *et al.*, 2018; SPC, 2019b). In particular, PNA members are looking to secure a greater share of the benefits from high-seas fishing to compensate for the reduction in EEZ fishing opportunities and the adverse effects of climate change more generally.

c) Monitoring, control and surveillance

Monitoring the responses of tropical tuna species to climate change is essential but expensive. Monitoring changes in distribution and abundance of tuna among the EEZs of PNA members will continue to be done through: (i) the routine obligations for vessels to report catch, effort and other details to national and regional agencies; and (ii) verification of this information by independent observers onboard all purse-seine vessels. This monitoring also covers vessels fishing in the high seas because vessels are required to report on their fishing in the high seas as a condition of licences to fish in EEZs and under WCPFC requirements. This should ensure that effective monitoring of the purse-seine fleet is maintained, even if there is some shift in biomass of tuna to high-seas areas. Nevertheless, it will be important to continue to strengthen monitoring, including through the use of electronic and video systems, to ensure that this outcome is achieved.

In addition, while ongoing tuna tagging programmes and fishery observers collecting biological samples will help monitor changes in the tuna stocks, further support is needed to monitor and improve knowledge of the physical, chemical and biological features of the tropical Pacific Ocean that affect the abundance and distribution of tuna stocks. This information will increase the effectiveness of the global climate models and biogeochemical models used to inform SEAPODYM (Lehodey *et al.*, 2011), and will improve and validate the forage sub-model developed within SEAPODYM.

Purse-seine vessels fishing in PNA waters can make a significant contribution to the monitoring of fish abundance and ocean variables. For example, PNA members currently receive tracking data from satellite buoys attached to drifting fish aggregating devices (dFADs), and almost all of these buoys transmit fish biomass data (Escalle *et al.*, 2019a). Some preliminary work has been undertaken on using this data for scientific purposes (Escalle *et al.*, 2019b). A proposed new PNA FAD registration and tracking management measure provides scope for this information to be gathered systematically in the future.

Recommendations

The PNA members have demonstrated that fisheries targeting transboundary stocks affected by climatic variability can be managed cooperatively to distribute the benefits equitably. These Pacific Small Island Developing States have also shown that, providing target fish resources remain largely within their combined EEZs, the agreed allocations of fishing effort based on recent historical effort in each EEZ provides a non-confrontational way of adjusting the distribution of benefits as fish migrate in response to climate change.

Problems may arise, however, when climate-driven redistribution of fish results in a proportion of the resources moving from the combined EEZs of collaborating countries to high-seas areas and EEZs of countries that are not VDS participants. The effective management of the PNA purse-seine fishery, which has helped ensure that tuna resources have not been overfished or subjected to overfishing, raises a significant question about appropriate stewardship arrangements under future climate change scenarios. A pertinent question is whether countries that have demonstrated that they can manage transboundary fish stocks effectively should be given the opportunity to continue to do so when a proportion of the resource moves to high-seas areas. This question is particularly relevant to Pacific Small Island

Developing States, given the extraordinary dependence of their economies on tuna (Section A) (FFA, 2018a,b; SPC, 2019b), and their negligible contribution to the GHG emissions responsible for ocean warming and the redistribution of tropical Pacific tuna species. Fortunately, the WCPFC Convention requires consideration of such issues when determining allocations and/or fishing rights. For example, Article 10 requires the Commission, when considering criteria for allocation, to take into account, inter alia, the respective contributions of participants to conservation and management, and their record of compliance with conservation and management measures (WCPFC Convention, 2000).

Reducing uncertainty in the expected redistribution of fisheries resources due to climate change will assist in resolving this dilemma. Reducing uncertainty will depend on identifying the spatial structure of fish stocks, where such information does not exist already. Reliable maps of projected climate-driven changes in distribution and abundance of a fisheries resource among EEZs, and between EEZs and high-seas areas, cannot be produced unless the number, size and location of each stock are identified, and the response of each stock to climate change is correctly addressed by the modelling.

The models used to assess the likely responses of stocks to climate change (e.g. SEAPODYM) can also be progressively improved. Fishing fleets licensed to fish in the EEZs of countries managing transboundary stocks and on the high seas can play an important role in this. Licence conditions and/or incentives can be developed to ensure that fishing fleets contribute to the collection of physical and biological data at the scale needed to improve the predictive skills of global climate models, biogeochemical models, and forage and fish spatial dynamics models.

The experience gained by PNA in operating the VDS should provide useful insights for management of other transboundary stocks where the distribution of a target species varies over time due to climate variability, or where climate change is causing a shift in the range of the species across national boundaries. Indeed, the Environmental Defense Fund (EDF, 2018) has already identified that some of the key elements of the VDS would be useful for addressing difficulties that have arisen due to climate change in the governance of shared stocks in the North East Atlantic.

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Chapter 13: Considering climate change in fisheries management advice for cold-water adapted Greenland halibut *(Reinhardtius hippoglossoides)* in the Gulf of Saint Lawrence, Canada

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Summary

The Greenland halibut *(Reinhardtius hippoglossoides)* stock of the Gulf of Saint Lawrence is presently showing negative production owing to climate change that is rapidly warming their preferred deep-water bottom habitat. We examined the probability of halting a decline in current stock biomass and meeting previously proposed fishery target objectives under the new climate reality. We found that to meet what had previously been considered an attainable stock biomass objective would now be unattainable without a 70 percent decrease in catch from status quo levels, given the warming already observed and with a risk-equivalent exploitation strategy. Furthermore, the system continues to warm and the objective may not be attainable in future even without fishing. In light of this work and given the declining productivity of the stock, fisheries managers, stakeholders and First Nations have agreed that stock target objectives need to be decreased and a hold be put on harvest control rule development. Climate change has led to increases in productivity in some other species, however, and these may present an opportunity for displaced Greenland halibut fishers.

Fishery context

Greenland halibut *(Reinhardtius hippoglossoides)* is a cold-water adapted demersal flatfish common in the circumpolar deep water of the Northern Hemisphere, including in the Gulf of Saint Lawrence, Canada. The Gulf of Saint Lawrence (GSL) is an uncharacteristically cold water body for its latitude and hosts the most southern exploitable stock for the species. Most Greenland halibut fisheries in the GSL are conducted at between 150-300 m depth and most fishing effort is concentrated in three areas (Figure 1). Greenland halibut are fished with both mobile and fixed gears. Before the collapse of most of the groundfish fisheries in eastern Canada in the early 1990s, Greenland halibut were fished with demersal otter trawls in conjunction with other groundfish species such as cod *(Gadus morhua)*, Atlantic halibut *(Hippoglussus hippoglussus)* and redfish *(Sebastes spp.)*. Since then, only fixed gears (longline and gillnet) have been used and fishing effort is presently dominated by gillnets. Greenland halibut have been amongst the most important groundfish species by value and landings since about 1992, compared to historical groundfish catches in the region, even though catches have been relatively small (<4.5 kt) (Fig. 2).

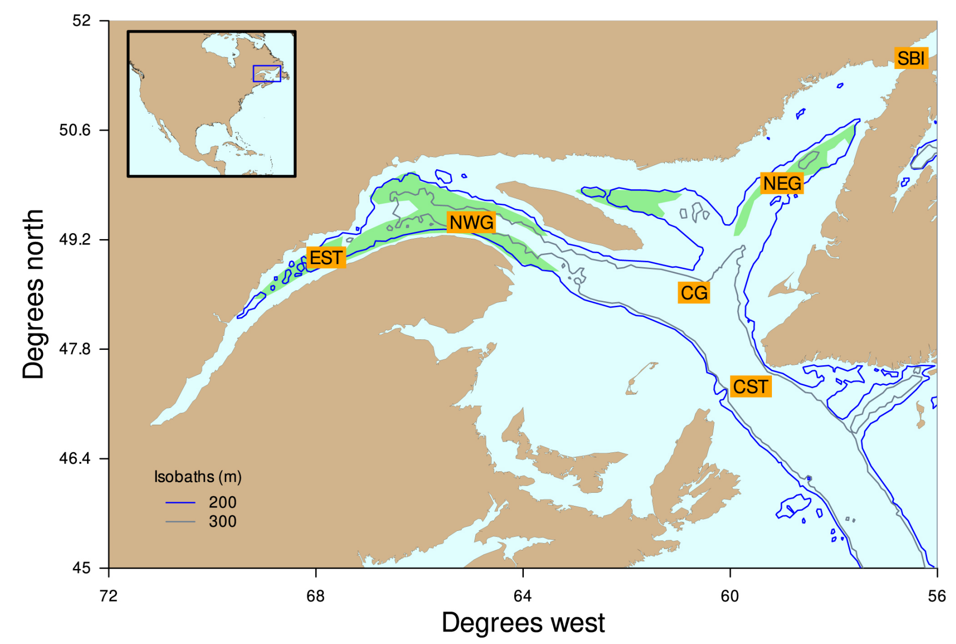

Figure 1. A map of the Gulf of Saint Lawrence, Canada, showing the three main fishing areas for Greenland halibut (green shaded polygons) and the 200 m and 300 m isobaths between which most Greenland halibut is fished. Some of the main geographic areas of the GSL are identified: the Estuary (EST), the Northwest Gulf (NWG), the Northeast Gulf (NEG), the Central Gulf (CG), the Strait of Belle Isle (SBI) and the Cabot Strait (CST). The inset map positions the Gulf of Saint Lawrence on a larger map of North America.

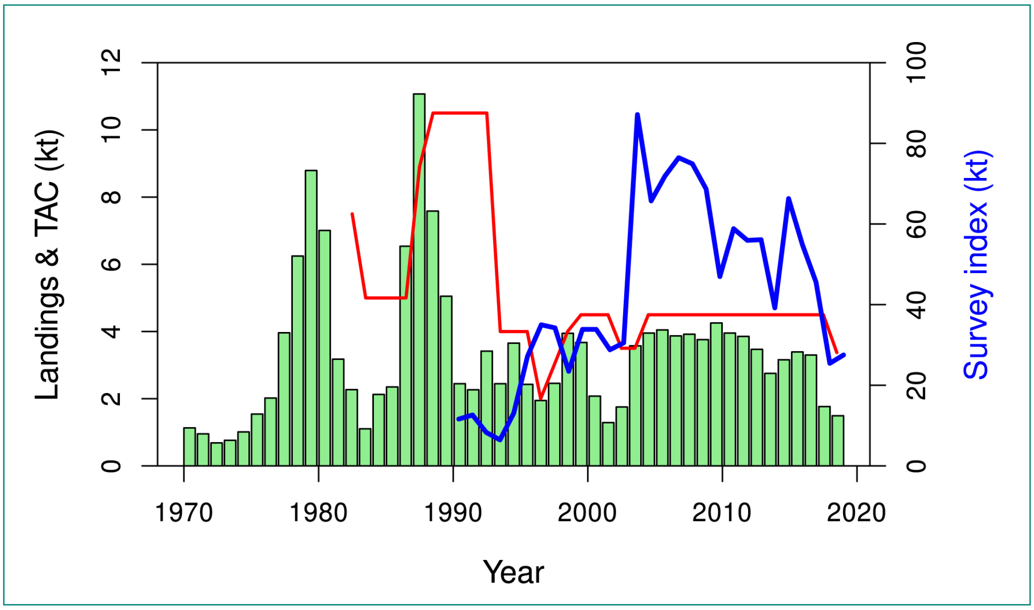

Figure 2. Fishery independent survey catches up-scaled to a stock area biomass estimate for Greenland halibut >40 cm (blue line) and reported commercial landings (bars) in the Gulf of St. Lawrence, Canada. A total allowable catch (TAC) was put into force in 1982 and has been the basis of catch limitation since. The TAC is depicted as the red line starting in 1982.

The GSL Greenland halibut fisheries supported about 152 harvesters in 2014, while that number had almost halved to 85 in 2018. Various regulatory changes explain some of that decline, including the mandatory use of vessel monitoring systems (VMS) on boats since 2013. Some fishers have individual quotas while others are part of a competitive fishery. Greenland halibut fishers in the GSL also target other groundfish species and sometimes snow crab *(Chionoecetes opilio)*, thus Greenland halibut fishing is one of several income streams for local fishers (and usually not the most lucrative). Vessels fishing for Greenland halibut are generally small (<20 m length), and are usually crewed by four or fewer fishers. Greenland halibut are landed in several ports along the northern shores of the GSL, primarily for a domestic market.

The Greenland halibut fishery targets fish of a total length above 40 cm. Because the species is sexually dimorphic, with mature females larger than males, the fishery disproportionately targets females –although males are still important in the commercial catch. The fishery is conducted from about May until November each year, while during the winter heavy ice conditions in the GSL hinder most fishing activities, including those for Greenland halibut. Greenland halibut quotas have been in place since 1982: 4.5 kt has been a common TAC for the past 20 years (Figure 2).

Major periods of change in the GSL Greenland halibut fisheries were in 1993 when most of the mobile otter trawl fishing effort ceased, and again in 1997 when larger mesh sizes for gillnets were mandated. Coincident with the decline of groundfish fisheries in the GSL was a rise in effort on northern shrimp *(Pandalus borealis)*, which is fished with a fine-mesh demersal otter trawl. Bycatch of Greenland halibut has been a feature of the shrimp fishery, but it was minimized with the introduction of the Nordmore grate and a protocol to limit small fish bycatch in 2014. Small Greenland halibut are still captured in the shrimp fishery but catches are a minor percentage of the total catch weight.

Since 1993, the Greenland halibut mobile gear fleet has ceased to fish, despite maintaining a catch share –but this can only be exercised if the TAC is raised above 4.5 kt. This represents an incentive for the dominant fixed gear fishers to maintain a conservative TAC ≤ 4.5 kt.

Management context

Gulf of Saint Lawrence Greenland halibut fisheries have been managed on the basis of a TAC since 1982 (Figure 2). The TAC for the stock often has been unrestrictive, and there have been very few instances of the actual catch meeting or surpassing the regulated maximum. Gear types, seasons and mesh size restrictions are used to regulate fishery operations, in addition to the TAC. The fishery resource is managed by the Federal Department of Fisheries and Oceans Canada (DFO). DFO conducts the science, sampling, management and decisions for the resource; and the Minister of DFO makes the final decision on the TAC on behalf of the people of Canada, who are considered the owners of the resource. DFO is guided by international and domestic policy, including the precautionary approach, to assist in determining what a sustainable and healthy fishery for GSL Greenland halibut should be. The DFO Science Branch developed a biomass limit reference point for the Greenland halibut stock (DFO 2019) during the rapid warming period and provides advice to the Management Branch based on stock status relative to this limit reference point and other sustainability considerations. The reference point is the lowest biomass from which the stock has recovered: this occurred in 1993, and thus is considered independent of the recent change in climate experienced by the stock.

The scientific information for the stock is collected throughout the year, while the official stock assessment runs on a two-year cycle with an update in interim years. Stock assessments are conducted out of the Quebec region of DFO and involve a peer-reviewed meeting called a Regional Advisory Process (RAP) attended by relevant stakeholders, including First Nations (Indigenous Peoples) and NGOs. RAPs for Greenland halibut usually last one to two days, and include presentations of information that may inform the assessment of stock health. RAP processes usually result in two products: a Research Document and a Science Advisory Report, both of which are available for public viewing on the Canadian Science Advisory Secretariat's website (http://www.isdm-gdsi.gc.ca/csas-sccs/applications/Publications/index-eng.asp).

Fishers and traditional knowledge are often considered in RAP meetings. However, there is currently no guidance on when and how to include other forms of knowledge (e.g. traditional ecological knowledge) in fisheries assessment, nor specific frameworks, methods or tools to facilitate their inclusion. As a result, fishers and/or traditional knowledge are either formally or informally included (or not included) on a case-by-case basis.

A key piece of information on stock status in a Science Advisory Report is how it relates to a biomass limit reference point. Stock status relative to other points may also be stated. The designation of stock status as 'Healthy', 'Cautious' or 'Critical' has specific meaning in the Canadian Precautionary Approach to Fisheries (DFO 2006), and the status health designation carries considerable weight in decision-making. Several directional advice statements may be provided, for example: 'keep catches as low as possible', 'status quo fisheries are not expected to lead to decreases in stock size', or 'a reduction in the exploitation rate may be necessary to promote stock recovery'. The advice is considered by the DFO Management Branch and feasible options are put forward for the minister to make a decision that strikes a balance between fishers' livelihoods, economic conditions, ecological conditions and stock conservation: the various options presented weigh these factors differently. The 4.5 kt TAC common for Greenland halibut in the past two decades is not only the preferred choice of stakeholders and representatives but has also been shown to represent a sustainable level of fishing for many years. Nevertheless, in recent years, the 4.5 kt TAC has been surmised to be potentially too large to be sustainable – a strong hypothesis to explain this change is the rapid warming of deep waters in the GSL since 2010 (Galbraith *et al.* 2018).

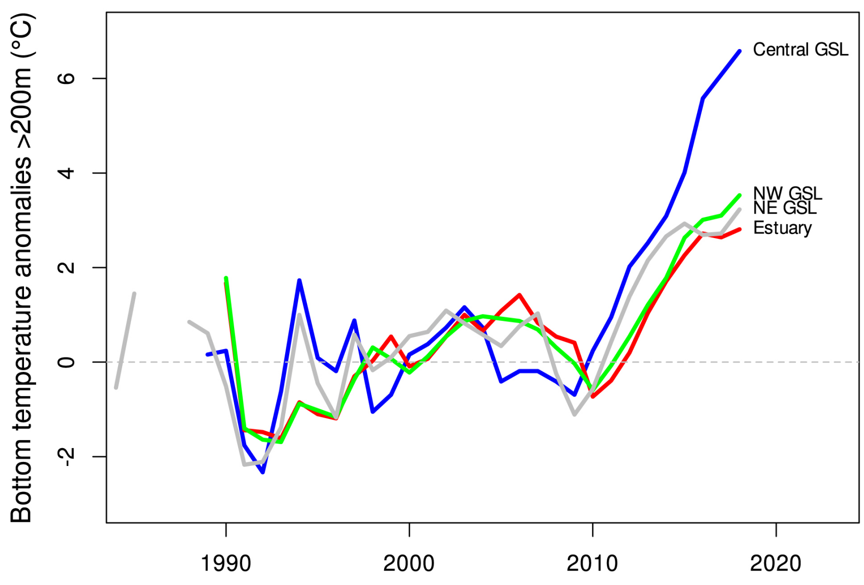

Figure 3. August bottom water temperature anomalies in different regions of the GSL where water depths are greater than 200 m. Warm Scotian Shelf and Gulf Stream waters enter the GSL at the Cabot Strait, affecting bottom water temperatures in the central GSL first, then the NE and NW GSL at about the same time, before finally reaching the head of the estuary two years later. Greenland halibut fisheries are conducted primarily in the NE and NW GSL.

Climate change implications in the Gulf of Saint Lawrence

The GSL is a relatively closed basin with two opening points to the northwest Atlantic Ocean: the Strait of Belle Isle to the northeast, which is a conduit for cold Labrador Current water entering the GSL; and the Cabot Strait to the southeast, which is an outflow for GSL surface water and an inflow of warmer and saltier deeper waters from the Scotian Shelf and the Gulf Stream (Figure 1). During summer, the GSL is a stratified system with a cold intermediate layer (CIL) (Galbraith 2006) between about 30 and 100 m deep. Warm Scotian Shelf and Gulf Stream waters enter the GSL at the Cabot Strait below the CIL depths. These deep waters move north and cover both the eastern and western deeper channels over a two to four year period (Gilbert 2004).

Since 2010, there has been a dramatic increase in the average August temperature of the deeper bottom water layer (>200 m) in the GSL (Figure 3). This is especially marked in the central GSL area (Figures 1, 3). Most Greenland halibut fishing in the GSL is conducted at the channel heads in the northeast and northwest GSL followed by the estuary, and there is less fishing in the central GSL area (Figure 1). Water temperatures at these depths do not show much seasonal variation (Galbraith *et al.* 2018), thus the August temperatures are similar to annual averages. This means that the primary Greenland halibut fishing habitat warmed between 2 and 4 °C between 2010 and 2018. This is a rapid increase in temperature for waters which are normally stable and experience only limited seasonal or annual fluctuations.

Increases in bottom water temperatures since 2010 have had impacts which appear to be directly and/or indirectly affecting Greenland halibut productivity. Increased water temperatures have resulted in increased stratification and decreases in bottom water oxygen concentrations, particularly in the Estuary and northwest GSL (Blais *et al.* 2019). Low oxygen concentrations, such as those observed in the GSL, have been shown to affect the growth of Greenland halibut under experimental (laboratory) conditions (Dupont-Prinet *et al.* 2013). One of the primary diet components of

Greenland halibut is northern shrimp *(Pandalus borealis)*, which is another species near the southern edge of its distribution and whose biomass has also shown rapid declines with the warming of GSL deep bottom waters (DFO 2019).

Another significant ecological change has been the rapid increase in GSL redfish (*Sebastes mentella* and *Sebastes fasciatus*) biomass since unprecedented large year classes in 2011, going from just above 100 000 tonnes in 2011 to almost 3 million tonnes in 2017 (Senay *et al.* 2019). Sebastes spp. have similar depth preferences to Greenland halibut and considerable diet overlap, at least on a seasonal basis (most of the existing stomach contents information is only available for the month of August) and during the adult stage of their ontogenetic life cycles (larval and juvenile stages can differ in both habitat and diet). However, unlike Greenland halibut, *Sebastes* spp. have semi-pelagic tendencies and are within their temperature tolerances even with the considerably warmer deep waters of the GSL since 2010.

A case can be made that GSL Greenland halibut have experienced decreased productivity ultimately stemming from climate change-driven warming of deeper bottom waters of the GSL that is leading to: i) a loss of favourable thermal habitat; ii) decreasing oxygen concentration; iii) decreasing productivity and abundance of an important food source *(P. borealis)*; and iv) an unprecedented increase in the abundance of a competitor species. These specific factors have impacted the individual growth rates and most likely recruitment and mortality rates that are the main components of production. The decline in Greenland halibut production is evident from the decrease in surveyed stock biomass in recent years, despite decreases in commercial landings (Figure 2).

Adapting Greenland halibut fisheries assessment to a changing climate

The TAC for GSL Greenland halibut decreased in 2018 by 25 percent (from 4.5 kt to 3.375 kt), but this TAC was not limiting and landings fell from 1.767 kt in 2017 to 1.493 kt in 2018. This decrease in TAC is an attempt to halt the declining stock biomass but the stock continues to decline despite this change. To date, however, there has not been an attempt to quantitatively link the stock's declining productivity with the very strong climate forcing seen in recent years. However, the development of a new empirical model that incorporates future climate change scenarios into stock assessments and advice – presented here – is one way to condition advice to climate change using a risk-based approach.

A simple empirical modelling approach incorporating climate for conditioning risk over the medium term

The DFO science sector developed a simple empirical method for determining how Greenland halibut production in the GSL changes with bottom water temperature (Duplisea *et al.* 2020a, b, https://github.com/Duplisea/ccca). This method was used to inform the development of alternative scenarios under a process called 'climate change conditioning of the science advice' (CCCA). Details of the method and an R library with several descriptive vignettes are freely available for download and testing. Essentially, the method develops an empirical relationship between stock production and an environmental variable. In the present case, a relationship between the bottom water temperature in the central GSL and the natural production was determined using a flexible generalized additive modelling (GAM) approach. The central GSL temperature was used to maximize contrast for GAM modelling. Realistic future climate scenarios were then simulated by sampling from temperature distributions with shifted means or variances.

Projections were made of Greenland halibut population dynamics following a simple phenomenological model where production values can take on values previously observed, i.e. similar to a parametric bootstrapping method where the probability of sampling from different parts of the production distribution depends on the temperature. For each stock projection, the probability of achieving reference point objectives in specified periods of time and for a given acceptable risk level (specified maximum probability of not achieving the objectives) was calculated. Climate change conditioned advice was then developed which showed how fishing pressure on the Greenland halibut stock could be adjusted to maintain a similar probability of achieving objectives at the acceptable risk level, given climate change impacts on stock production. By incorporating uncertainty in climate scenarios and in the relationship between Greenland halibut production and bottom water temperature, a range of possible outcomes (Monte Carlo sampling) were developed and acceptable fishing strategies were derived by applying the pre-determined risk level to the distribution of simulated outcomes.

This model is effectively a Leslie model where production can have both positive and negative values. The model was designed for relatively short-term projections for heavily exploited stocks where intraspecific density dependence is unlikely to be a strong driver of the stock dynamics. Furthermore, the model is used to forecast the stock only in so far as to determine a risk-equivalent exploitation rate and not actually for the biomass state of the stock, i.e. it is not an assessment model but a model to condition risk-based advice to climate change compared to null model advice that does not consider climate change. For sensitivity purposes a density-dependent version of the model was developed, but for stocks that are usually at 50 percent or less of their carrying capacity and for short-term projections. Effectively, the alternative version made no difference (see https://github.com/Duplisea/ccca).

We fitted a relationship between the (production/biomass) P/B ratio and the bottom water temperature (P/B vs T) at depths >200 m, in the central GSL. The relationship is a weak quasi-linear decrease in population growth with temperature (Figure 4). Because residuals were sampled for every Monte Carlo iteration, production is sometimes negative and sometimes positive even if the mean production is >0. This indicates that recent bottom water temperatures have pushed the Greenland halibut productivity to low levels and even negative levels of production. Although a model was fitted here, another sampling approach could be to just resample the P/B distribution in blocks where the blocking accords with predicted future temperature regimes. Therefore, even if a P/B vs T relationship is very weak but residuals are resampled, it is effectively doing a parametric block resampling and the significance of the P/B vs T relationship is not really of concern.

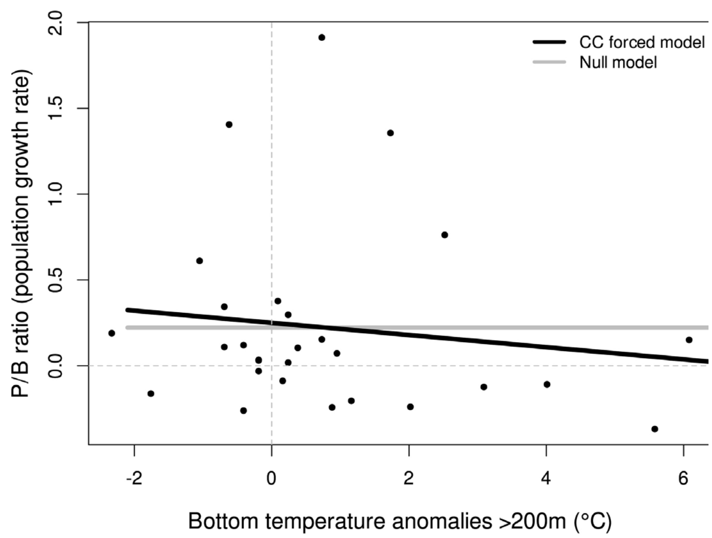

Figure 4. Gulf of Saint Lawrence Greenland halibut specific production rate (P/B ratio) as a function of central GSL bottom water temperature at depths >200 m and the null model where no relationship between production and temperature exists. The black line was fitted using a generalized additive model and though it appears quasi-linear, this was not a constraint of the fitting process. The dashed line represents the transition between positive and negative population growth rates.

The P/B ratio versus temperature relationship (Figure 4) was used to project the population 10 years into the future from the last data year by making assumptions about future temperature and fishing pressure. Observations show a rapid warming and 2–4 °C increase in August temperature from the previous period (2010–2018) in areas where Greenland halibut are commonly fished. We therefore modelled a null model scenario and five different climate change scenarios:

1. A null model where Greenland halibut production has no dependence on temperature and the population growth rates (production) into the future are randomly sampled from past observations irrespective of temperature.
2. Average temperature where the entire temperature time series was fitted with a normal distribution – 10 000 samples were drawn from this and P/B was determined for each temperature from the Figure 4 relationship.
3. A 2 °C increase in mean temperature with the same distribution about the mean and entered into the Figure 4 relationship (this is within the bounds of what has already been observed).
4. A 3 C increase in mean temperature with the same distribution about the mean and entered into the Figure 4 relationship (this is within the bounds of what has already been observed).
5. A 1 °C decrease in mean temperature with the same distribution about the mean and entered into the Figure 4 relationship.
6. The same mean as the average with an increase in the standard deviation of the normal distribution by a factor of 1.5 and entered into the Figure 4 relationship.

The +2 °C and +3 °C temperature mean scenarios conform to the recent observed trend (Figure 3), and when simulated they suggest that with status quo fishing (mean exploitation of the most recent five years) the stock cannot achieve the biomass objective with a 50 percent probability in any of the next 10 years (Figure 5a). A decrease in temperature by 1 °C will allow the objective to be achieved with a 50 percent probability in only two years, while the other scenarios suggest the objective could be achieved in three to four years. In order to achieve the target biomass objective with 50 percent probability in 10 years under a 2 °C warmer climate scenario, it would be necessary to decrease the exploitation rate to only about 2–3 percent; while a 1 °C cooling would allow the stock to be exploited at almost 15 percent while still achieving the stock biomass objective (Figure 5b). A 3 °C temperature increase would mean that the stock would be unable to achieve the biomass target objective even in the absence of fishing.

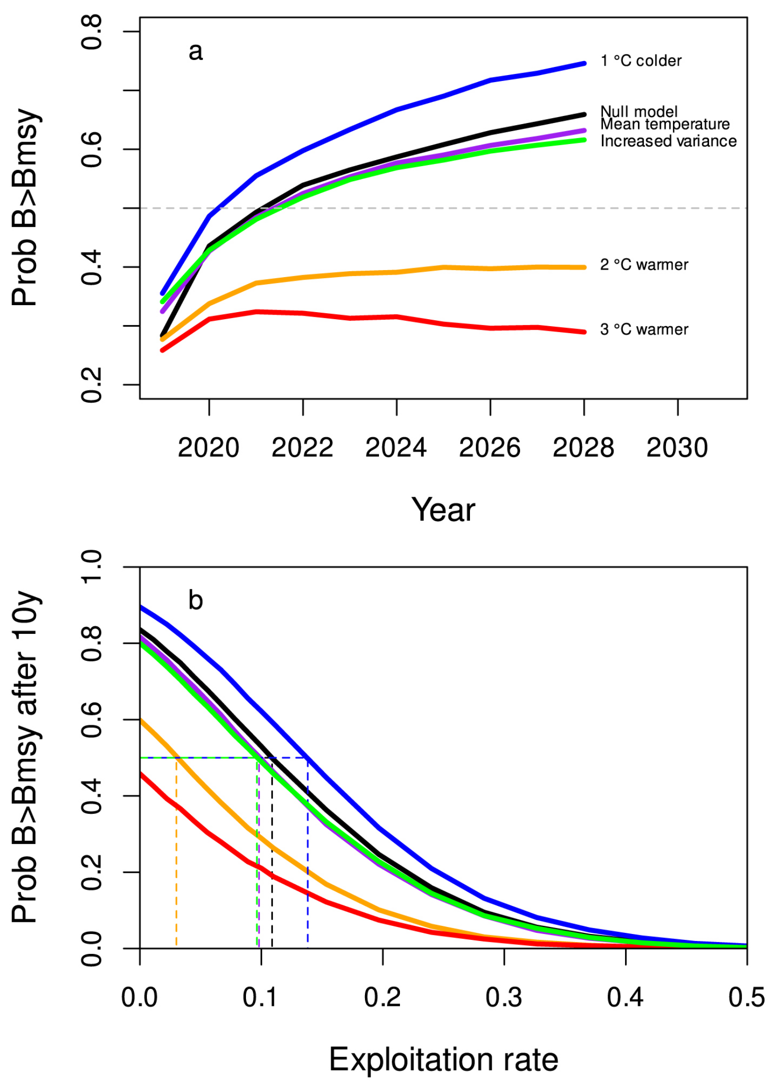

Figure 5. Probability that the biomass of the stock will be at or above the Bmsy target objective each year into the future under different climate change scenarios and a mean exploitation rate corresponding to the exploitation rate from the last five data years (a); and probability that the B_{msy} objective can be achieved after 10 years fishing at different exploitation rates. The acceptable risk level for not achieving a target objective is by definition 0.5 (or 50 percent) which is depicted at the horizontal line (a) and the exploitation levels that will not cause the stock to surpass that level of risk (b).

Table 1. Climate change scenarios tested for risk equivalent advice (exploitation rate) for the objective, timeframe and risk combination (see Figure 5). The highlighted row (Scenario 4) is where the risk equivalent exploitation rate is 0 or less, i.e. the objective is unachievable even with a moratorium on fishing.

	Scenario	Objective	Time allowed to achieve objective	Acceptable risk on not achieving objective	Allowable exploitation rate
1	Null	biomass target (B_{msy})	10 years	0.5	0.11
2	Average	biomass target (B_{msy})	10 years	0.5	0.10
3	+2 °C	biomass target (B_{msy})	10 years	0.5	0.03
4	+3 °C	biomass target (B_{msy})	10 years	0.5	-0.02
5	-1 °C	biomass target (B_{msy})	10 years	0.5	0.14
6	Increased T variance	biomass target (B_{msy})	10 years	0.5	0.10

Developing advice that considers climate

This empirical model approach and the results shown in Figure 5b can form the basis of climate change-conditioned advice for the GSL Greenland halibut stock. Future projections from downscaling global climate models suggest that sea surface temperature anomalies in the GSL in the period 2046–2065 will be in the order of 4–5 °C warmer (Greenan *et al.* 2018). We therefore expect that the modest 2 °C warming scenarios for deeper bottom waters inhabited by Greenland halibut are possibly conservative but not necessarily unrealistic. Even with just a 2 °C positive temperature anomaly in these areas, the sustainable exploitation rate would need to be about 30 percent of the sustainable exploitation rate under baseline temperature conditions. This is based on the concept of fixed target objective irrespective of the climate and the risk equivalent probability of achieving that target. In cases where it would be impossible to achieve the target with the same level of risk under climate change (the 3 °C scenario), then it would suggest that the productivity regime of the stock has changed so much that previous biomass objectives are no longer achievable even with a moratorium (Table 1; Figure 5). In such a case, it may be appropriate to change the target objective; however, it would not be prudent to change a target objective to a new fixed value if the system is still considered to be in flux.

Conclusion and recommendations

An empirical modelling approach employing a statistical relationship between Greenland halibut production and a climate variable illustrates the utility of these approaches for providing immediate short-term management advice conditioned to climate change. The approach shows that, under the climate change which has already been observed and which is expected to continue, this stock is unlikely to be able to achieve previously observed high biomass levels and that a status quo fishing strategy will only lead to more rapid stock decline.

This empirical modelling approach has been used for this stock in presentations to fisheries managers, the fishing industry and First Nations (25–26 November 2019 and 12–13 February 2020) to show that a previously proposed biomass target zone delimiting reference point is unlikely to be achievable (DFO 2019 – Figure 15 – Green line – 50.5 kt) under the present and projected climate. This then forced a re-evaluation of the biomass reference point, showing that the target zone should be much lower than proposed. It also showed that fishing mortality would need to be reduced substantially (about 70 percent) from status quo values in order to be sustainable. In light of the fact that the impact of climate warming on GSL deep water has been intensifying since 2010 and continues to change, it is not clear how to revise particular reference points. That is, it was not deemed useful to settle on static reference points in a system which is still changing quickly and directionally. Therefore the major impact of this approach to date has been to suggest large declines in fishing mortality and to not set unrealistic biomass targets.

Empirical approaches of this nature are not full mechanistic approaches, but this also liberates them from the need for long and rigorously defensible data time series combined with a large body of experimental and statistical modelling work. And while this approach cannot substitute or replace such necessary careful work, it can be used to provide operational guidance on fisheries being affected by climate change today. For instance it not only suggests that fishing mortality should decrease, but by how much it should decrease for fisheries management to stay risk-equivalent to its objectives. That is, it provides direction and magnitude advice to directly inform risk management of fisheries. Managers wishing to manage conservation risk to stocks in a consistent manner under climate change may find such approaches particularly informative, and find that this is an operational tool that can support difficult decisions.

The future for Greenland halibut fishing in the Gulf of Saint Lawrence does not look promising for the foreseeable future. This prognosis – supported by the approach presented here – suggests other adaptations to fisheries and fishers' livelihoods should be explored. For instance, the large abundance of redfish *(Sebastes mentella)* in the GSL presently can sustainably support a many fold increase in fishing mortality, and this can present an opportunity if appropriate markets can be found. Other positive fishing opportunities are also likely to present themselves owing to climate change, and creating a flexible fleet structure that can take advantage of these opportunities would be a useful adaptation measure. This is just one possibility for adaptation, but it would require major changes in the fleet shares structure that currently exists in most Canadian fisheries, and negotiating such changes is very complicated given the historical allocation of catches. Despite its difficulty, solutions are likely ultimately to be found in a system where fishers have more opportunity to easily switch between species, in a way that promotes overall system sustainability while still providing fishers with an economically sustainable livelihood.

Simple empirical approaches like this one, combined with the concept of risk equivalency, can be used to rapidly develop climate-conditioned advice for a range of situations where a survey index, catch time series and a climate or other strongly correlated oceanographic variable are available. These approaches can add a level of objectivity in providing advice in situations where only moderate data is available, or as a precursor for more detailed but more demanding modelling approaches. An R package is freely available (https://github.com/Duplisea/ccca): this can be applied to any similar data situation to provide climate change-conditioned strategic stock exploitation advice to maintain management objectives.

Acknowledgements

We acknowledge the contribution of Johanne Gauthier and Peter Galbraith who provided Greenland halibut data and physical time series for the Gulf of Saint Lawrence respectively. Important feedback on these ideas was provided by the DFO group on Incorporating Climate Change into Stock Assessment Advice in May 2018. Johanna Johnson, Xuechan Ma, Marcelo Vasconcellos and David Welch provided constructive comments that improved the manuscript.

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Chapter 14: Management of the Peruvian anchoveta (*Engraulis ringens*) fishery in the context of climate change

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Summary

The Peruvian anchoveta (*Engraulis ringens*) is a small pelagic fish endemic to the Peru Current Ecosystem. Anchoveta population dynamics are strongly influenced by environmental conditions: this fishery operates in a complex and highly variable ecosystem, which has resulted in a flexible and adaptive management system closely focused on incorporating near real-time observational data of both the ecosystem and the anchoveta population. In this context, Peruvian anchoveta assessment methods differ from traditional methods in three ways: i) use of a conservative projection horizon to set management limits; ii) use of near real-time direct observations as an initial condition for the projection of harvest scenarios; and iii) inclusion of environmental variability in the projections, using variable population parameters for different environmental scenarios according to the best available forecasts of the state of the ecosystem.

This assessment paradigm – developed within the framework of the natural environmental variability mainly driven by the El Niño Southern Oscillation (ENSO) – is a robust alternative for stock assessments in the context of climate change, where greater sensitivity of populations to environmental conditions is expected. In the same way, the constant and intensive monitoring of the fishery allows the near real-time implementation of additional management measures to protect the resource, facilitating a swift response to the rapid spatio-temporal changes that occur in the interaction of the fishery and the anchoveta. This use of near real-time direct observations to quickly adapt management measures to any departure from the assumptions used for stock assessment and TAC allocation is recommended for highly productive and valuable fisheries.

Fishery context

The Peruvian anchoveta (*Engraulis ringens*) is a small pelagic fish endemic to the Peru Current Ecosystem, with its major abundance within the Peruvian upwelling ecosystem (Figure 1). It has an average lifespan of three years and achieves a maximum total length of 20 cm (Whitehead *et al*. 1988). Anchoveta is a fast-growing species, reaching sexual maturity at one year of age at an average total length of 12 cm (Perea *et al.*, 2011), and being recruited to the fishery at six months at a total length of 8 cm (Oliveros-Ramos and Peña, 2011). Anchoveta is a partial spawner, and off Peru it has two spawning peaks: the main peak is between August and September, and a secondary peak occurs between February and March (Perea *et al*., 2011). Anchoveta diet is mainly zooplankton, especially Euphausiids and large copepods (Espinoza and Bertrand, 2014). Anchoveta population dynamics are strongly influenced by environmental conditions that affect prey availability, natural mortality, growth, recruitment success, and availability to the fishery and predators (Csirke, 1980; Csirke, 1989; Alheit and Ñiquen, 2004; Ñiquen and Bouchon, 2014; Oliveros-Ramos, 2014; Barbraud *et al*., 2018).

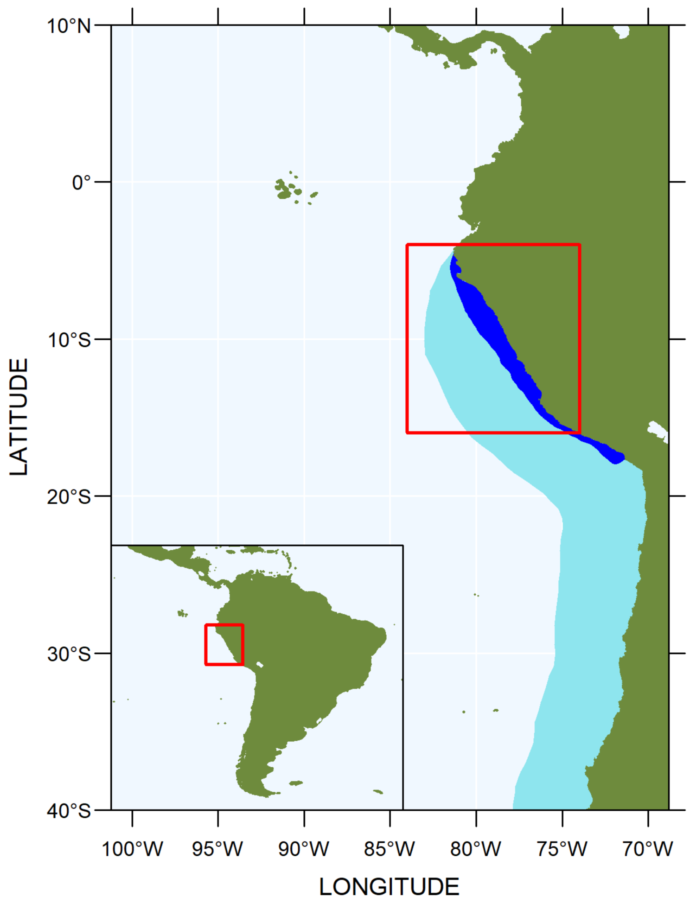

Figure 1. Case study area. The Peruvian upwelling ecosystem (dark blue) is located within the Northern Peru Current Ecosystem (light blue). The distribution area of the northern-central stock of Peruvian anchoveta is bordered in red.

Anchoveta is managed as two stocks within the Peruvian exclusive economic zone (EEZ): the northern-central stock (2°S-16°S) and the southern stock (south of 16°S, shared with Chile). The northern-central stock is the more important in terms of landings and profits, representing more than 90 percent of the landings of anchoveta (PRODUCE, 2018). The biomass of the northern-central stock has fluctuated between 6 and 11 million tonnes in recent years, while the biomass of the southern stock has fluctuated between 250 000 and 2 million tonnes within Peruvian waters.

An industrial fishery has exploited anchoveta since 1950, mainly for the production of fish meal and oil. There have been major fluctuations in the fishery over time: its record landing of over 13 million tonnes came in 1971, before a collapse in the fishery in the early 1970s and a subsequent recovery at the end of the 1990s. Currently, Peru is responsible for more than half of the global production of fish meal and a third of the fish oil (Fréon *et al.* 2014). Additionally, an artisanal fishery harvests anchoveta, mainly for canning. Both fisheries use purse-seines, with the mesh size regulated to a minimum of 13 cm (Yonashiro and Balbín, 2016). The industrial fishery works from 5 nm to approximately 50 nm offshore, while the artisanal fishery works inside the 5 nm limit (Yonashiro and Balbín, 2016).

During recent years, the annual catch of the northern-central stock has fluctuated between 2 and 4 million tonnes. Peru exports around 1 million tonnes of fish meal and 100 000 tonnes of fish oil each year, with a value of more than USD 1 billion (PRODUCE, 2018). Tens of thousands people are directly involved (fishing) in the anchoveta fishery and hundreds of thousands are indirectly involved (in processing and distribution).

Management context

All Peruvian fisheries are managed by the Ministry of Production (PRODUCE), with scientific advice from the Peruvian Marine Research Institute (IMARPE). The management of the northern-central stock of anchoveta is based on two objectives: (1) maintain a stock biomass over 5 million tonnes, and (2) maintain an explotation rate below 0.35 (IMARPE, 2016). Fishing occurs in two seasons each year, and is regulated with a total allowable catch (TAC) and – since 2009 – an individual transferable catch share system. The individual transferable quota (ITQ) of each vessel can only be transferred to another vessel already in possession of an ITQ (so-called 'semi-transferable' quotas), and the fishery is closed to new vessels (Yonashiro and Balbín, 2016). Fishing seasons are limited by full closures during the two main spawning seasons (reproductive closures, Figure 2). Temporal closures (for a minimum of three days) in specific fishing areas, controlled by remote sensing, are implemented during each fishing season in areas with juvenile catches over 10 percent, as an additional measure of protection for the stock (PRODUCE, 2016).

To address environmental variability, which is particularly influential in the Peruvian Upwelling System, IMARPE carries out intensive and continuous monitoring of the ecosystem using remote sensing and in situ observations at sea and on land. Direct observations in the sea are carried out with two to four scientific surveys each year, covering the entire Peruvian coast. These surveys collect oceanographic and ecosystem information, including a hydroacoustic assessment used for the estimation of total biomass, egg and larvae production, size structure of the anchoveta population and reproductive condition. Additionally, during anomalous environmental conditions, a 'Eureka' operation conducts hydroacoustic assessment surveys with data collected simultaneously by several industrial fishing vessels under the coordination of IMARPE.

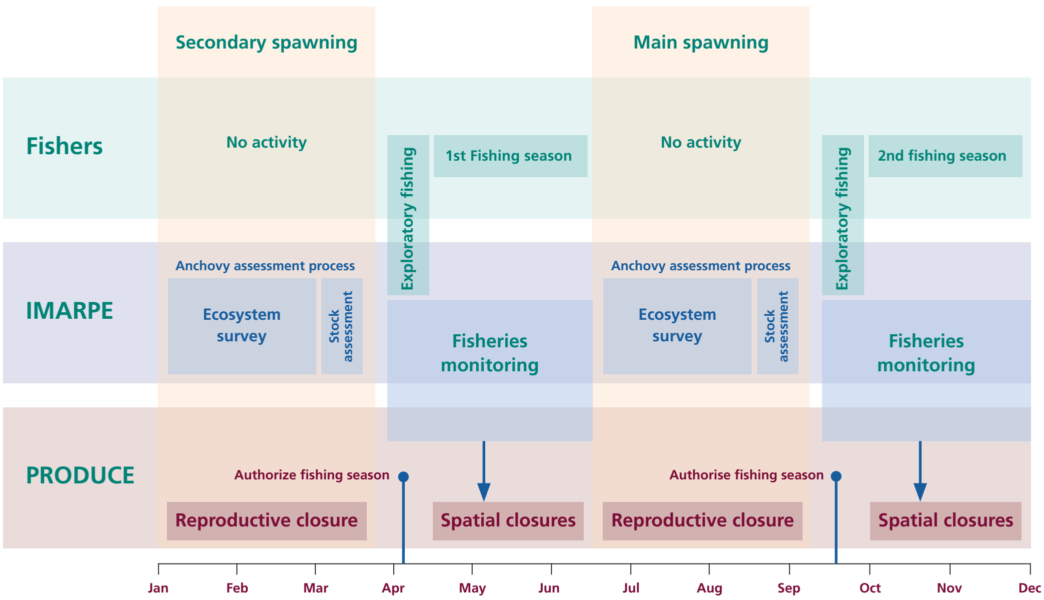

Figure 2. Stakeholder participation in anchoveta fisheries management. Activities related to fisheries management and stakeholders involved are shown.

The Eureka operations are carried out to collect additional information on the distribution and abundance of the stock (Gutierrez *et al*. 2000). Landings and size composition of the industrial fleet are monitored continuously (24/7) at every landing site. Currently, IMARPE and PRODUCE onboard observers collect information from up to 80 percent of fishing trips, with vessel monitoring systems (VMS) mandatory for the industrial fleet.

Stock assessment is carried out by IMARPE, estimating the population structure from the results of the hydroacoustic surveys and projected under several harvest scenarios. Harvest scenarios are projected up to the next reproductive peak, and use different population parameters (e.g. growth, mortality) according to the environmental conditions (favourable or unfavourable) predicted during the period. The results are presented in the form of a decision table (IMARPE, 2016; IMARPE, 2019) used by PRODUCE to set the TAC for the current fishing season.

The fishing season starts 15 days after authorization by PRODUCE. Between the authorization date and the beginning of the fishing season, an exploratory fishing trip is supervised by IMARPE (Figure 2). The objective is to update knowledge on the spatial distribution of the resource and particularly to identify areas with a high proportion of juveniles, in order to set temporal closures. The catch during the exploratory fishing is taken into account for the final setting of the TAC.

Climate change implications

The Peruvian upwelling ecosystem is one of the most productive in the world, due to the abundance of nutrients upwelled with the cold waters near the coast that nurture large populations of phytoplankton, zooplankton and fish (Chávez *et al.*, 2008). The sea surface temperature off Peru has shown a cooling trend in recent decades, but Earth system models (ESM) project a warming for the region, higher than the levels of natural variability, after 2050 (Henson *et al.* 2016). In addition, there has been an increase in the frequency of observed coastal warming events since 2002 (IMARPE, 2019). Climate change is expected to have negative impacts on the anchoveta population, due to the warming of the system and a reduction of coastal upwelling and primary productivity (Gutierrez *et al.*, 2019). Coastal warming events, in particular, alter the spatial distribution of anchoveta (Mathisen, 1989; Joo *et al.*, 2014; Castillo *et al.*, 2019; Moron *et al.* 2019), which affects both the interaction of the fishery with the resource and the capacity to collect scientific information for the anchoveta population assessment (IMARPE, 2019).

The potential impact of climate change scenarios on the anchoveta population has been studied for the Peruvian upwelling ecosystem (Oliveros-Ramos, 2018), using an ecosystem model (OSMOSE). The model integrates information on the projected changes in the spatial distribution of fish and plankton production from Earth system models (IPSL CM5A-LR and GFDL-ESM2M) under four climate change scenarios (RCP 2.6, 4.5, 6.0 and 8.5) for the period 2009–2100, assuming historical fishing exploitation rates (2005–2008). These simulations show an expected reduction in the total population biomass of 8.2 percent to 13.9 percent per decade. A similar trend, with biomass below the biological reference point (IMARPE, 2016), was observed during the 1980s after the 1972–1973 El Niño event and the subsequent collapse of the fishery, with recovery observed from the mid-1990s. This historical recovery followed a moratorium on fishing and a cooling of the marine system that progressed to a new colder regime after the 1997–1998 El Niño event (Espinoza-Morriberón *et al.* 2017). Additionally, a southward displacement of the anchoveta population closer to the coast is projected (Oliveros-Ramos, 2018; Gutierrez *et al.*, 2019) under all RCP scenarios considered, as is currently observed during warming events. These alterations in the spatial distribution of the resource can affect fishing activity, since the displacement of the main biomass southward will impact on the spatial distribution of the fishing fleet – and therefore on the fuel costs to reach the fishing grounds as well as to transport the catch to processing plants. Anchoveta catchability could increase with a more coastal distribution: this would also increase the overlap in the distribution of adults and juveniles, as the latter are more coastal and less tolerant of thermal changes (Luján, 2016).

On the other hand, an ecological risk assessement (Ramos, 2017) assigned a medium level of risk to anchoveta in the face of climate change, due to its phenotypic plasticity. Ongoing studies, taking into account the resilience of anchoveta to environmental fluctuations and possible evolutionary adaptations to permanent climatic changes in productivity and ecosystem conditions, may improve the forecast for management of the Peruvian anchoveta fishery and population.

Adaptations and lessons

Stock assessment and management advice

The dynamics of the Peruvian upwelling ecosystem and the interactions between anchoveta and its environment are too complex to ascribe to changes in ocean temperature alone. For this reason, IMARPE uses an integrated approach to monitor ecosystem conditions (physical, chemical and biological) to assess the impacts on the population dynamics of anchoveta, also taking into account the bias that anomalous conditions may produce in the information collected for stock assessment. These changes in the anchoveta assessment process have been reflected in an update of the protocol for explaining the decision table to determine the TAC (IMARPE, 2019). Currently, the most recent forecast of environmental conditions provided by the ENFEN expert panel (National Commission for the Study of El Niño Events) is used to set the population parameters for the TAC projection estimate. Notably, depending on the intensity of the impact that anomalous conditions in the ecosystem may have on anchoveta stock, a more robust or more precautionary approach to the assessment can be chosen (IMARPE, 2019). In addition, during particularly intense ocean warming events, IMARPE considers whether to conduct an extra scientific survey before recommending a TAC, in order to update the information used for management recommendations.

Formulation of norms to regulate harvest and access to resources according to established objectives

Under normal conditions, anchoveta juveniles have a more coastal distribution than adults, allowing the fishery to target the adult population without compromising the juvenile portion. However, during warming events, the increased overlap between adult and juvenile distribution causes an increased harvest of juvenile individuals, potentially compromising the sustanaibility of the population. During the anchoveta assessment process, the number and weight of juvenile individuals expected in the landings during a fishing season (as a fraction of the TAC) is calculated and reported to PRODUCE. This figure, called 'juvenile TAC', provides an additional management criterion that strengthens the protection of juvenile individuals: it allows PRODUCE to close the fishery once the landings reach the juvenile TAC even if the full TAC has not been completed, effectively protecting the more highly mixed population during warming events.

Monitoring, control and surveillance

Since 2016, fishing vessels have reported on their fishing areas and the proportion of juveniles in catches. This data is analyzed by IMARPE to define critical fishing areas with a high incidence of juvenile catch, in order to recommend to PRODUCE the temporary closures of these areas. This measure of protection of the juvenile population is particularly important during warming events where the increased overlap in the spatial distribution of adults and juveniles increases the catchability of the latter. Additionally, an electronic landing monitoring programme has been implemented and a self-sampling procedure for fishing vessels has been promoted, both for fishing effort and biological, population and ecological monitoring (e.g. size structure of anchoveta, bycatch).

Key recommendations

The Peruvian anchoveta fishery operates in a complex and highly variable ecosystem, which has led to a more flexible and adaptive management system strongly focused on incorporating near real-time observational data. In this context, the Peruvian anchoveta assessment methods differ from traditional methods in three ways: i) their use of a conservative projection horizon (less than six months, until the next reproductive period) to set management limits; ii) their use of near real-time direct observations (ecosystem surveys) as an initial condition for the projection of harvest scenarios; and iii) their inclusion of environmental variability in the projections, using variable population parameters for each environmental scenario (favourable, unfavourable or neutral), according to the best available forecasts of the state of the ecosystem during the projection horizon (IMARPE, 2016; IMARPE, 2019). This assessment paradigm, developed within the framework of the natural environmental variability mainly due to the El Niño Southern Oscillation (ENSO), is a robust alternative for stock assessments in the context of climate change, where greater sensitivity of populations to environmental conditions is expected.

In the same way, the constant and intensive monitoring of the fishery has allowed the implementation of additional management measures in near real-time for the protection of the resource. This 'dynamic ocean management' approach (Maxwell *et al.*, 2015) allows a timely response to the rapid spatio-temporal changes that occur in the interaction of the fishery and the anchoveta, allowing a better balance between economic (completion of TAC) and ecological (sustainability of the population through the protection of juveniles) objectives.

In general, managing fisheries under large-scale environmental fluctuations like ENSO is becoming increasingly important under climate change, and explicit consideration of environmental uncertainty is recommended. While the forecasts of environmental conditions improve, the best response to an unfavourable forecast should be analyzed (e.g. Miller *et al*. 2019). Additionally, for highly productive and valuable fisheries, the use of near real-time direct observations to quickly adapt management measures to any departure from the assumptions used for stock assessment and TAC allocation is recommended.

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Chapter 15: Lessons and recommendations for the climate adaptation of key Tasmanian fisheries

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Summary

The Australian fishing industry is an important component of Australia's economy. The industry, however, is undergoing significant pressure from climate change – in particular, fisheries in the south-east Australian marine region that form the 'powerhouse' of Australia's production by value and volume. As the most southern state in Australia, Tasmania lies within the south-east marine region and is experiencing the amplified effects of climate change in the form of more frequent marine heatwaves and an intensification of the poleward transport of warmer waters with the East Australian Current extension. The region is a fast-warming hotspot, warming at nearly four times the global average. Climate-driven environmental changes experienced and predicted are mostly negative, although some positive impacts are also expected. However, both negative and positive effects of climate change require fast and effective management to maximize opportunities and minimize undesirable impacts. Tasmanian fisheries management is currently reactive in responding to the effects of climate change, and the ability of management to respond is limited by resourcing and politics. This case study summarizes the fishery responses in a global temperature hotspot, provides examples of adaptations that are already underway which could be applied to other similar fisheries, and discusses key recommendations to improve the climate adaptation of Tasmanian commercial wild-catch rock lobster and abalone fisheries.

Fishery context

Within Australia, wild-catch fisheries are a valuable industry, with a total production value of AUD 1.74 billion (USD 1.18 billion) and a volume of 166 022 tonnes for the 2016–17 fishing season (Mobsby, 2018). The Australian fishing industry is divided into state wild-catch and commonwealth wild-catch, with production values of AUD 1.34 billion (USD 899 million; 117 431 tonnes) and AUD 403 million (USD 279 million; 48 592 tonnes) respectively for 2016–17 (Mobsby, 2018). In 2017–18, Australian state fisheries contributed AUD 2.61 billion (USD 1.81 billion) Gross Value Added to the Australian economy (out of a total Gross Domestic Product of AUD 1.8 trillion (USD 1.21 trillion) in 2018 (ABS, 2018)), as well as 18 959 full-time equivalent (FTE) jobs (FRDC, 2019a). Australia also places great community and cultural significance on recreational and other non-commercial fishing sectors.

One of the largest wild-catch fisheries regions is in south-east Australia, encompassing the coastlines of four states: New South Wales, Victoria, South Australia and Tasmania. The south-east Australian marine region is also particularly vulnerable to climate change, and has been identified as a 'climate hotspot' (Hobday and Pecl, 2014).

Tasmania is the most south-eastern Australian state, an island separated from the mainland with a wild-catch fisheries landscape comprised of six main commercial fisheries: abalone, rock lobster, giant crab, scallop, scalefish, and commercial dive (urchins, periwinkles, clams and seaweed). These had a total production value of AUD 175 million (USD 121 million; 3 620 tonnes) in 2016–17 (Mobsby, 2018), and AUD 188 million (USD 130 million) in 2017–18 (FRDC, 2019a). Tasmania also boasts an important aquaculture industry, valued at AUD 771 million (USD 533 million; 55 119 tonnes) in 2016–17, mostly farming salmonids and oysters (Mobsby, 2018).

Tasmanian state fisheries employed 778 people (FTE) directly and 564 people indirectly in 2017–18 (FRDC, 2019a). Additionally, Tasmania has various recreational and indigenous fisheries, with 22 percent of Tasmanian residents (98 000 people) participating in recreational fishing activity at least once a year (Lyle *et al*., 2014). Of the Tasmanian wild-catch fisheries, the largest and most valuable to the state's economy are the commercial rock lobster fishery and the commercial abalone fishery (Mobsby, 2018). This case study will cover the key Tasmanian fisheries, with these two fisheries – rock lobster and abalone – providing many of the examples.

The Tasmanian commercial rock lobster fishery targets southern rock lobster (*Jasus edwardsii*) using pots and traps. It is the largest wild-catch fishery in Tasmania by participation size, with 194 active vessels in the 2017–18 fishing season (Hartmann *et al.*, 2019), and 383 people directly employed in 2016 (Ogier *et al.*, 2018) (Table 1). Most exports of commercial southern rock lobster catch are live, fresh product, though markets are also available for frozen rock lobster exports (Hartmann *et al.*, 2019). Of all Tasmanian fisheries, rock lobster has had the highest commercial wild-catch production value since 2014–15; however, recent reports show a slight decline in catch value for 2016–17 to AUD 83 million (USD 57 million), and this was overtaken by abalone wild-catch with a value of AUD 84 million (USD 58 million; Mobsby, 2018) (Table 1). Additionally, Tasmania also has indigenous and recreational southern rock lobster harvests (Hartmann *et al.*, 2019).

The Tasmanian rock lobster fishery has a history of being affected by habitat degradation, indirectly linked to climate change – for example, caused by the climate-driven poleward range extension of the long-spined sea urchins (see Ling and Keane, 2018). Management interventions have aimed to rebuild the virgin biomass of the stock to 20 percent by 2023 through implementing an East Coast Stock Rebuilding Zone (SRZ), and adjusting total allowable catch (TAC) (Hartmann *et al.*, 2019). Current fisheries management is aimed at ensuring that healthy egg production is maintained at 20 percent or more of unfished levels, with only one area of the fishery not currently achieving this level (Area 5 – north-west fishery area), and with a regional size limit change to address this currently under consideration (Hartmann *et al.*, 2019). Southern rock lobster have a long pelagic larval period of up to two years (Fitzgibbon *et al.*, 2014), which may lead to variability in stock recruitment from year to year depending on environmental or anthropogenic stressors (Hartmann *et al.*, 2019). However, TAC settings are more influential on stock biomass, and have therefore been an effective management response (Hartmann *et al.*, 2019).

Tasmania's commercial abalone fishery is the largest wild abalone fishery in the world (Ogier *et al.*, 2018; TSIC, 2017) and predominantly targets blacklip abalone (*Haliotis rubra*) through diving (approximately 95 percent of catches), with greenlip abalone (*H. laevigata*) making up around 5 percent of the total wild catch (Mundy and McAllister, 2018). Although Tasmania's commercial wild-catch abalone fishery has recently become the most valuable, it is not the largest in participation size, with 102 active divers and 170 people directly employed (Table 1) (Mobsby, 2018; Ogier *et al.*, 2018).

The abalone fishery is divided into various fishing zones (Table 1), which are used in assessing and managing the fishery. Overfishing in the 1990s, long-term habitat degradation caused by long-spined sea urchins (*Centrostephanus rodgersii*; indirectly linked to climate change), and multiple marine heatwaves over the past decade have together contributed to reduced abalone stocks, particularly in the Eastern Zone (Mundy and McAllister, 2018). Stocks in the Western Zone more recently appeared to be rebuilding, however stocks in the Central Western Zone have been rapidly declining over the past five years, likely due to a decline in stock biomass, despite efforts to reduce the TAC over several years, or to redistribute effort within zones (Mundy and McAllister, 2018). The Central Western Zone – recently merged with the Northern Zone as part of a boundary realignment – also has a declining catch rate (Mundy and McAllister, 2018). The Bass Strait Zone is stable, and the Greenlip Zone (which resides within the Northern and Bass Strait Zones) is also relatively stable, although still shows signs of stock decline in some areas (Mundy and McAllister, 2018). Overall, since 2010, commercial wild-catch abalone TAC limits have been continually reduced to address falling stock levels across much of the fishery (Mundy and McAllister, 2018).

Table 1: Tasmanian commercial state fisheries profiles: production value, volume and licence holders based on 2016–17 season reported in Mobsby (2018), with number of employees reported in a recent economic and social assessment (Ogier *et al.*, 2018). All other data has been collated from recent fishery assessments (referenced in last row) and FRDC Status of Australian Fish Stocks Reports (FRDC, 2019b). Distribution maps and abalone image from Pecl *et al.* (2011), rock lobster image credit Bruce Miller.

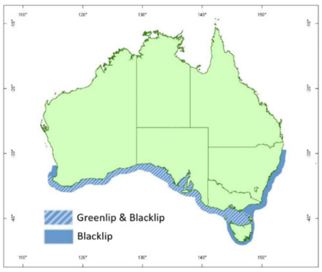
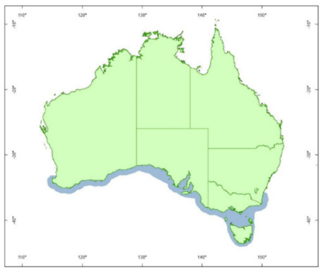
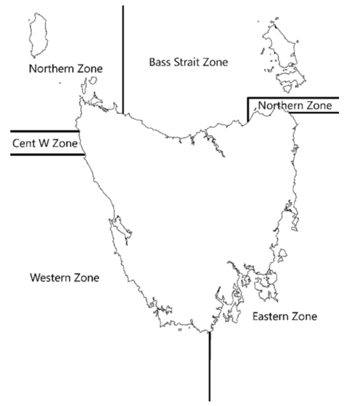
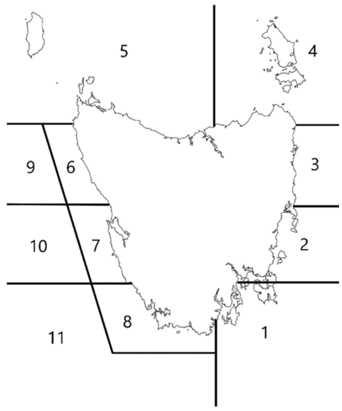
Fishery	Abalone fishery	Rock lobster fishery
Target Species	 • Blacklip abalone (*Haliotis rubra*) • Greenlip abalone (*H. laevigata*)	 • Southern rock lobster (*Jasus edwardsii*)
Species distribution		
Gear type	• Diving	• Pots • Traps
Economic value (millions)	AUD 83 726 (USD 57 913)	AUD 83 274 (USD 57 601)
Volume (tonnes)	1 641	1 083
Fishery size	121 licence holders (2017) 170 direct employees (2016) 102 active divers (2016)	311 licence holders (2016) 194 active vessels (2017–18) 383 direct employees (2016) 233 active fishers (2016)
Tasmanian spatial management	TAC is divided across six zones, with smaller scale block caps within these.	TAC is divided across two zones (east and west regions), with 11 stock assessment areas.

Table 1: (continued)

Fishery	Abalone fishery	Rock lobster fishery
		
Exploitation status	*Blacklip abalone:* • Sustainable = 2 zones • Depleting = 2 zones • Depleted = 1 zone *Greenlip abalone:* • Depleting	Sustainable
Management methods	• Limited entry • Quota • Size limit • Spatial closures • TAC	• Gear restrictions • Limited entry • Quota • Size limit • Spatial closures • Temporal closures • TAC
Fishery assessment	Mundy and McAllister (2018)	Hartmann *et al.* (2019)

Management context

Many Australian state fisheries extend to 3 nautical miles (nm) offshore and are managed by the respective state government. Outside state jurisdiction, fisheries are commonwealth fisheries and span areas ranging from 3–200 nm off the Australian coastline. Australian fisheries management includes three main activities: science and research (e.g. developing research plans and ecological risk assessments), management and regulation (e.g. implementing fishery management plans and harvest strategies), and monitoring and enforcement (e.g. using satellite monitoring systems, checking catch records, and undertaking investigations and prosecutions) (AFMA, 2019).

Tasmania is fortunate to have a fisheries management landscape where there are close relationships between industry, science, and government: this may facilitate co-development of adaptation actions, and provides a strong history of management underpinned by multi-disciplinary research (Frusher *et al.*, 2013; Pecl *et al.*, 2019a). Tasmanian commercial state fisheries are managed by the Wild Fisheries Management Branch of its Department of Primary Industries, Parks, Water and Environment (DPIPWE). Tasmanian commercial wild-catch fisheries are managed through overarching legislation – the Living Marine Resources Management Act 1995 – as well as individual management plans for each fishery set as 'Rules' (e.g. Fisheries (Abalone) Rules 2017) and harvest strategies, issued and updated by the Wild Fisheries Management Branch. Tasmanian fishery management rules are set out as policy documents and currently do not discuss the effects of climate change on the industry or associated environments.

Decisions on significant issues around the management of Tasmanian commercial state fisheries are issued by the State Fisheries Minister (local member of parliament), and may or may not be based on recommendations and advice provided by the Fishery Advisory Committees (FAC; peak advisory groups) of each major Tasmanian fishery (DPIPWE, 2019b). The Fisheries Minister must seek consultation around determining key arrangements, such as size limits, seasonal closures, gear restrictions and TAC. FAC meetings are generally held two to four times per year for each fishery, with committee membership made up of a diverse range of fishery stakeholders, including members of industry, DPIPWE, researchers, Tasmania police, and environmental non-government organization (NGO) representatives (DPIPWE, 2019b). The Fisheries Minister may also be advised on management recommendations though annual fishery assessment reports, as well as from other advisory groups such as the Abalone Fishery Resource Advisory Group (FRAG) (DPIPWE, 2018, Tasmanian Abalone Council Ltd, 2020).

The management methods for Tasmanian commercial state wild-catch fisheries, set out by the Fisheries Minister, typically include arrangements such as gear restrictions, licensing, limited entry to the fishery, quotas, size limits, spatial closures, temporal closures and annual TAC (Table 1). Implementation of arrangements varies between fisheries, and is flexible so it can be changed relatively quickly in response to new data (such as if stock recruitment has not been as successful as previously predicted).

Climate change implications

The south-east Australian marine region is under threat from climate change, and has been identified as a marine climate 'hotspot', where ocean warming is rapid (Hobday and Pecl, 2014). The Tasman Sea region off the east coast of Tasmania has recently experienced multiple marine heatwaves (Hobday *et al.*, 2016) over the summers of 2015/16 and 2017/18, occurring due to anomalous intensification of the poleward transport in the East Australian Current (EAC) extension, and anthropogenic influences (e.g. global carbon emissions increasing the likelihood of event duration and intensities) respectively (Oliver *et al.*, 2017; Oliver *et al.*, 2018; Perkins-Kirkpatrick *et al.*, 2019). Being a western boundary current, the EAC spans most of the east coast of Australia. Over the past 60 years, it has been observed to be strengthening and extending further poleward, bringing warmer waters to the east coast of Tasmania. This trend is expected to accelerate over the next 100 years (Ridgway, 2007; Ridgway and Hill, 2012).

The increasing influx of warmer waters into the east coast of Tasmania from the EAC is bringing with it an increasing number of range-shifting species. Among those warmer-water species that have been observed likely extending their distributions or increasing their abundance off the coast of Tasmania are the eastern rock lobster (*Sagmariasus verreauxi*), redbait (*Emmelichthys nitidus*), snapper (*Chrysophrys auratus*), gloomy octopus (*Octopus tetricus*) and yellowtail kingfish (*Seriola lalanndi*) (Champion *et al.* 2018; Last *et al.*, 2011; Ramos *et al.*, 2018; Robinson *et al.*, 2015). The incursion of these species has differing implications for current Tasmanian marine ecosystems and fisheries. Recreational fishers in Tasmania benefit from the range extension of some species such as kingfish, which is a popular sportfish (Champion *et al.*, 2018; Redmap, 2019). However, of greatest significance to the Tasmanian coastline is the climate-driven poleward range extension of the long-spined sea urchin, which has had detrimental and widespread impacts on the Tasmanian marine environment and associated marine sectors (Ling, 2008; Ling and Keane, 2018). The long-spined sea urchin has a long pelagic larval phase, when it is transported with the EAC, and is able to settle and persist in Tasmanian waters due to rapidly increasing water temperatures (Ling *et al.*, 2008).

The southern rock lobster is a principal predator of the long-spined sea urchin in Tasmania; however, due to heavy fishing of this valuable commodity the sea urchin has overgrazed Tasmanian giant kelp beds (*Macrocystis pyrifera*), and now over 15 percent of the eastern Tasmanian coastline has been left as urchin barrens (Ling *et al.*, 2009a; Ling and Keane, 2018). Climate change amplifies the stress this sea urchin places on Tasmanian kelp beds and associated ecosystems, with past giant kelp die-offs due potentially to marine heatwaves (Oliver *et al.*, 2017; Sanderson, 1990). The increasing abundance and persistence of the long-spined sea urchin in Tasmanian coastal waters has driven a shift in the marine environment, which has increased pressure on Tasmanian wild-catch fisheries that depend on seaweed bed habitat, in particular the rock lobster and abalone fisheries (Ling *et al.*, 2009b).

The Tasmanian abalone fishery was also negatively impacted by the 2015/16 summer marine heatwave, with five percent of blacklip abalone biomass reported as dead during research surveys in early 2016 – previously these surveys had reported zero morality in the catches (Oliver *et al.*, 2017). Abalone processors reported abalone in poor condition across southern Tasmania over the 2015/16 summer, with above-average mortality experienced during processing and live export (Oliver *et al.*, 2017). Following this heatwave, fisheries managers decreased or maintained TAC limits in 2016 and 2017, with the only exception being an increased TAC for the Bass Strait Zone in 2016 from 70 to 77 tonnes, which remained the same for 2017 (Mundy and McAllister, 2018). Managers did not change the number of fishing licences issued, and catch limits were reached in all fishing zones (Mundy and McAllister, 2018).

Other implications of warmer waters and marine heatwaves off the Tasmanian coast include new diseases and more frequent algal and jellyfish blooms. Harmful algal blooms (HABs) present a food safety issue for marine resource industries and can result in temporary closures of fisheries, including wild-catch abalone and rock lobster as well as oysters and scallops. These climate-driven impacts, however, are often felt more strongly by the Tasmanian aquaculture industry. For example, the range extension of red-tide dinoflagellate (*Noctiluca scintillans*) into southern Tasmanian waters since 1994 caused issues for salmonid farming (Hallegraeff, 2010); and the first incidence of an oyster disease – Pacific oyster mortality syndrome (POMS) – coincided with the 2015/16 marine heatwave (Oliver *et al.*, 2017). Warming waters also mean shellfish wild-catch and farming in Tasmania is increasingly affected by the harmful alga *Alexandrium tamarense*, which causes paralytic shellfish poisoning (PSP) when consumed by humans and has resulted in significant economic losses to the industry (Hallegraeff and Bolch, 2016; Pecl *et al.*, 2019a).

Adaptations and lessons

Tasmanian fisheries management is flexible within its set management methods, in the sense that managers can implement changes to strategies relatively quickly – within a matter of months in some cases. This flexibility is deliberate in order to allow for faster management response and reaction to observed short-term environmental changes. Management may respond to environmental changes by implementing new management methods or adaptations in response to regularly updated probabilities of future productivity status (which are conservative to account for climate change), or after an environmental change has been observed and is underway (e.g. lowering TAC limits in response to an observed decrease in stock biomass). Reactive fisheries management usually requires negative (or positive) impacts to have already started, which can lead to further negative impacts (or missed opportunities) if management adaptations are not implemented quickly enough. However, reactive management is logical when responding to unexpected or unknown factors affecting the environment and dependent industries, as there may be many factors at any given time causing changes which may be difficult to disentangle (e.g. agricultural and urban runoff, pest and disease presence, overfishing and illegal fishing, oil spills and marine pollution, climate changes and climate-driven physical and chemical changes, etc.). As climate change is arguably also one of the greatest threats facing fisheries, fisheries may stand a better chance of remaining productive and sustainable into the future if a more proactive management landscape is implemented. Tasmanian fisheries management is designed to respond to observed and projected changes in production, especially recruitment, from any source, including climate change. Some of the responses to observed climate changes have been incorporated into the research that underpins the general fisheries management methods and levers, and therefore some aspects of climate change can be addressed though traditional management responses to changes in the stock levels or environment.

Climate adaptation may be autonomous or planned. In other words, there may be 'bottom-up' adaptation actions initiated by non-government actors rather than those with direct powers (i.e. government), or 'top-down' planned management of the changing resources (Pecl *et al.*, 2019a). There are numerous instances where industry and marine-dependent individuals in Tasmania have taken the initiative and are acting autonomously (Pecl *et al.*, 2019a) (Table 2).

Table 2 provides examples of adaptation measures adopted in different fisheries and aquaculture sectors in Tasmania.

Table 2: Forms of behaviours undertaken by Tasmanian marine resource users and managers to adapt to climate change, adapted from Pecl et al. (2019a), using the typology from Biagini et al. (2014). Dark grey = the group is implementing the adaptation behaviour, light grey = the group is beginning to, or trialling the adaptation behaviour. This table does not include adaptations that are "under consideration". "Physical infrastructure" is removed here from the Biagini et al. typology as a "form of adaptation behaviour" as no adaptations were identified among stakeholder groups in that category.

Fishery	Description	Recreational fishers or divers (public)	Commercial abalone fishers (industry)	Commercial rock lobster fishers (industry)	Aquaculture (industry)	Fisheries management (government)
Capacity building	Developing human resources, local institutions and communities, equipping them with the capability to adapt to climate change.					
Management and planning	Incorporating understanding of climate science, impacts, vulnerability and risk into government and institutional planning and management.					
Practice change	Revisions or expansion of practices and on-the-ground behaviours that are directly related to building resilience.					
Public policy	Creation of new policies or revisions of policies or regulations to allow flexibility to adapt to climate change.					
Information	Systems for communicating climate information to help build resilience towards climate impacts (other than communication for early warning systems).					

Table 2: (continued)

Fishery	**Description**	**Recreational fishers or divers (public)**	**Commercial abalone fishers (industry)**	**Commercial rock lobster fishers (industry)**	**Aquaculture (industry)**	**Fisheries management (government)**
Warning or observation systems	Implementation of new or enhanced tools and technologies for communicating weather, climate and climate-driven risks, and for monitoring changes in the climate or resource system.					
"Green" infrastructure	New, improved or restored soft, natural infrastructure aimed at providing direct or indirect protection from climate impacts or hazards.					
Financing	New financing or insurance strategies to prepare for future climate disturbances.					
Technology	Develop or expand climate-resilient technologies.					

Management and planning, and financing

With improved science and forecasting, and policy uptake of scientific recommendations, fisheries will be better equipped to proactively respond to climate-induced environmental changes. Within Australia, some gaps are evident in the scientific knowledge to inform management decisions around climate-driven species effects and climate-driven socio-ecological implications for Australian fisheries species (Pecl *et al.*, 2014b). Only one-third of Australian fisheries species (mostly those with higher numbers of commercial fish stocks and/or larger catch volumes) are the focus of scientific studies relating to climate change and its implications (Fogarty *et al.*, 2019). Increasing and improving knowledge relating to climate change and Australian marine life, particularly economically important species, is important; but other areas of focus are also needed. While knowledge on the direction of change and likely biological responses is well researched within Australia and globally, this is not the only method of forecasting what species will move where and when. Additionally, it may be more important to increase resilience in harvest strategies to changes in productivity by implementing conservative, flexible and responsive strategies.

In response to the devastating impacts the long-spined sea urchin is having on the Tasmanian marine environment, and therefore Tasmanian fisheries, the abalone industry and Tasmanian government have jointly introduced an Abalone Industry Reinvestment Fund (AIRF). This is supported through fees collected from abalone licence holders as well as with additional funds from the government. The AIRF is an allocation of AUD 5.1 million (USD 3.5 million) over five years, which has been invested into recovery of abalone stocks and subsidies for harvesting the long-spined sea urchin for commercial use, as well as technology development and monitoring of these fisheries and ecosystems (DPIPWE, 2019a). It is evident that these sea urchins will likely never be fully removed from the Tasmanian coastline, as they recruit so effectively. Therefore, the government priority in managing the species on the east coast is to remove the role of the sea urchin as a major problem in barren formation. One solution to this has been to identify a commercial use for the sea urchin and to introduce a new licensed fishery targeting the species, which largely exports the urchin roe to overseas markets, to help balance the ecosystem and stop barren formation. This new fishery has resulted in 555 tonnes (more than 1.6 million individuals) of long-spined sea urchin being removed from the east coast in the 2018/19 season (DPIPWE, 2020), which has helped the habitat begin to recover. A recent resurvey has shown that over 15 years the biomass of the long-spined sea urchin increased annually by approximately 80 tonnes between 4–18 m depth, and by 170 tonnes annually between 4–40 m depth (Ling and Keane, 2018). Introducing a developmental fishery to help manage and control an invasive range-shifter in this way shows that some climate change impacts may also present opportunities.

Another initiative implemented and funded by the Tasmanian government is a rock lobster translocation programme which supports the further stock rebuilding efforts on the Tasmanian east and west coasts (DPIPWE, 2019c) and helps control the long-spined sea urchins (large lobsters may eat them). Translocation of southern rock lobsters from (low-growth) deep-water locations to (high-growth) shallow-water inshore locations has been shown to increase lobster growth and has increased the productivity of the fishery (Chandrapavan *et al.*, 2010). In the first three years of the programme (2015–18), 145 000 lobsters were translocated (DPIPWE, 2019c). Further funding injected in 2018 will enable 25 000 to 30 000 lobster to be translocated each year for a further four years (DPIPWE, 2019c). Rock lobster translocations have the greatest net benefit where they take place over long distances between regions with extreme differences in growth, such as translocating from the southwest to the east or northwest Tasmanian coast (DPIPWE, 2019c, Gardner and Van Putten, 2008). Rock lobster translocations are a direct intervention in adapting to climate change, and combined with appropriate TAC limits the additional lobster numbers result in extra biomass for the region, not just catch, and therefore help reduce habitat degradation by the long-spined sea urchin. The Tasmanian commercial rock lobster fishery has had a commercial TAC of 1 050.7 tonnes for the last four years preceded by three years at 1 103.24 tonnes. It currently holds a sustainable stock status, with catch per unit effort (CPUE) increasing steadily over the last six years, and significantly increasing in the last two years (Hartmann *et al.*, 2019).

Practice change

As more species shift into Tasmanian marine waters, there may be other opportunities to develop new fisheries which will benefit local people and economies, and may help prevent endemic species from being outcompeted and becoming extinct. Although management of existing commercial fisheries is somewhat flexible, recreational fishers can currently adapt more easily than commercial fishers as new species emerge along the Tasmanian coastline. Species such as snapper and yellowtail kingfish have made recreational and charter fishers particularly eager, as they take advantage of and adapt to these new fishing opportunities in Tasmania (Champion *et al.*, 2018; Last *et al.*, 2011; Robinson *et al.*, 2015). The development of new commercial fisheries takes time to develop stock assessments, and to implement evidence-informed management strategies – such as appropriate TAC and size limits – where required. Commercial fishers must also apply for a licence to fish a species, meaning that most commercial fishers (with the exception of scalefish fishers) cannot simply begin targeting new range-extending species as they appear along the coastline. As such, commercial fisheries would be better able to take advantage of these new opportunities if legislation for establishing new fisheries were more simple, flexible and responsive.

Other adaptation behaviours include many commercial fishing operators changing their landing practices so they unload live catch in areas with cooler waters, to help minimize the negative effects warmer water may have on it (Pecl *et al.*, 2019a). Similarly, fishers avoid landing their catch at some ports at times of heavy rain, as freshwater in the surface layer increases lobster mortality. Practice changes such as these reduce industry vulnerability to periodic changes in weather and climate, and can be useful strategies in adapting to longer-term climatic changes.

Information and warning or observation systems

For the past decade, commercial abalone processors and divers have utilized global swell forecast models, and are increasingly using sea surface temperature and seasonal climate outlooks to plan their fishing activities, in order to avoid the warmest sea temperatures and dangerous conditions that may impact the productivity and safety of fishing operations (Pecl *et al.*, 2019a). Meanwhile, due to an increase in the frequency of HABs in Tasmanian marine waters, the fishing industry strongly supports implemented measures to increase testing a variety of invertebrates, including abalone and rock lobster, for toxins, to ensure public health and safety (Pecl *et al.*, 2019a). Although the monitoring and HABs policy was funded and prioritized by the government, implementation of a rapid immunological test-kit used by fishers to screen for shellfish toxins has come at an additional financial cost to the industry (Pecl *et al.*, 2019a).

Communication as preparing for adaptation

Tasmania, and Australia in general, has many recreational fishers and marine users (Ogier *et al.*, 2018). Most people involved in, or associated with, the marine sector are aware of climate change impacts on the marine environment, although many may not see it as a pressing issue (van Putten *et al.*, 2014). To increase community awareness of climate change requires an increase in public trust in experts through improved scientific communication and media literacy education (Cooper, 2011; Pidgeon and Fischhoff, 2011). As political decisions are often based on what will win the most public votes, improving community awareness of climate change may in turn act to increase resources and funding in areas working on climate adaptations. A number of citizen science marine monitoring programmes and initiatives have been developed and operate out of Tasmania, and have been shown to be beneficial in both identifying future climate-driven species range shifts (Fogarty *et al.*, 2017; Hill *et al.*, 2016) and engaging marine stakeholders constructively on climate change (Nursey-Bray *et al.*, 2017). For example, Redmap Australia (Range Extension Database and Mapping Project; www.redmap.org.au) is an Australia-wide project which aims to monitor early detection of range-shifting species as well as engage the public on the ecological impacts of climate change by collecting unusual sightings of out-of-range species by regular marine users (Pecl *et al.*, 2014a; Pecl *et al.*, 2019b). Citizen science monitoring programmes can also be directly beneficial for fisheries adaptation to climate change, as they can provide useful data to inform fisheries management decisions.

Key recommendations

This case study provides key lessons and recommendations to improve climate adaptation in Tasmanian fisheries, which could be applied to other similar fisheries, including:

- Systematically record autonomous adaptations and develop adaptation plans in concert with an awareness of autonomous and planned adaptations.
- Promote, increase and introduce funding opportunities for the fishing industry to invest in new technology and operations which protect or restore ecosystems impacted by climate change, such as the Abalone Industry Reinvestment Fund which partly reinvests funds collected from licensing fees to assist in developing a new fishery targeting the long-spined sea urchin, and recovering abalone stocks.
- Implement appropriate harvest strategies and control rules for harvest rates on shorter timeframes, which ensure species biomass can recover where necessary by taking known environmental effects into account.
- Industry and individuals with livelihoods dependent on marine systems do not need to rely solely on planned climate adaptation by government, and can autonomously implement strategies to manage the effects of climate change – for example, rock lobster fishers avoid landing catch at some ports during heavy rain to minimize lobster mortality. However, industry should engage with institutions to ensure autonomous adaptation does not lead to maladaptation.
- Fishers can utilize global swell forecast models, sea surface temperature data and seasonal climate outlooks when planning fishing activities to decide when and where they fish, to help adapt to environmental changes affecting the fishery such as increased storm frequency and duration, which may put personnel at unnecessary risk.
- Establish sentinel monitoring and implement screening programmes for toxins and strains of harmful algae to mitigate deleterious effects on human health and public safety, such as test-kits to detect and diagnose toxins from HABs, which are becoming more frequent with warming waters. Government/institutional assistance may help offset some of the costs to industry, to aid with ongoing implementation.
- Species translocations from low-growth (less suitable) to high-growth (more suitable) regions can benefit ecosystem health by increasing biomass of declining stocks.

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Chapter 16: Canadian Fraser River sockeye salmon: A case study

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Abstract

The Fraser River in Western Canada historically supported among the largest numbers of sockeye salmon (*Oncorhynchus nerka*) in the world. These salmon sustained aboriginal communities for thousands of years, and were an important contributor to Canada's west coast economy through its commercial and recreational fisheries in the last century.

In recent decades, however, survival and numbers of this iconic group have been exhibiting concerning declines, and fisheries have been restricted. Out of the 24 fundamental units of biodiversity identified for these salmon, termed conservation units (CUs), close to half have been designated Endangered or Threatened by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC), facing imminent risk of extinction or likely to become Endangered if trends continue.

Fraser sockeye typically return to their natal freshwater rivers and lakes to spawn as four-year-old fish, after spending their first two winters in freshwater, and their last two winters in the ocean. The poor status of many of these CUs is linked to large climate- and habitat-related changes in both ecosystems.

Fraser River temperatures increasingly exceed the upper thermal limits of salmon in summer months, and the frequency of droughts and extreme rain events has increased. These climate effects have been exacerbated by large amounts of deforestation occurring in the Fraser River watershed.

In the Northeast Pacific Ocean, unprecedented marine heatwaves occurred intermittently from late 2013 to 2020. The base of the salmon marine food web shifted during this period to higher proportions of smaller southern zooplankton species, considered poorer quality food for salmon.

Many new approaches have been applied to model Fraser sockeye population dynamics to account for their rapidly declining productivities, and these are used in fisheries management processes. Uncertainty is communicated in model results by applying different model forms, and using Bayesian statistics to present information probabilistically. These fisheries are also intensely monitored and managed in-season to adjust pre-season predictions, with in-season observations of fish and environmental conditions.

However, in-season management is increasingly uncertain with changing conditions and low numbers of many CUs in mixed stock fisheries. Future salmon fisheries will look quite different from the past due to climate change and habitat deterioration. As fisheries shift, greater adaptability will be required in the allocation of science and management resources, guided by our current understanding of salmon trends and habitat requirements. More precautionary approaches to management are recommended in light of these changes.

Freshwater habitat actions may also provide some support to salmon stocks under climate change. This includes actions such as restoring and increasing riparian and watershed vegetation, creating cool water reservoirs, deep pools and off-channel habitats. Hatcheries may also play a role in conservation and production as the climate changes.

A. Main characteristics of Fraser River sockeye fisheries

Fraser River sockeye stocks

Sockeye salmon (*Oncorhynchus nerka*) are anadromous and semelparous, migrating from the ocean to freshwater to spawn, and dying shortly after spawning. Fraser sockeye typically return to their natal freshwater rivers and lakes to spawn as four-year-old fish, after spending their first two winters in freshwater, and their last two winters in the ocean (Figure 1a).

The earliest returning populations enter the river in mid-June, and the latest populations generally by mid-September. Fraser River sockeye can migrate more than 1 000 km upriver to spawning areas, and are vulnerable to various challenges en route. Spawning usually occurs in tributaries to the Fraser River where there are suitably sized clean and well oxygenated gravels. Fry typically emerge from the gravel substrate in the spring, move into rearing lakes adjacent to their spawning grounds (Figure 1b), and generally rear there for one year prior to outmigration.

Fraser sockeye comprise 24 fundamental CUs of biodiversity (DFO, 2005; Holtby and Ciruna, 2007; Grant *et al.*, 2011), characterized by their life-history, genetics and ecology (Holtby and Ciruna, 2007).

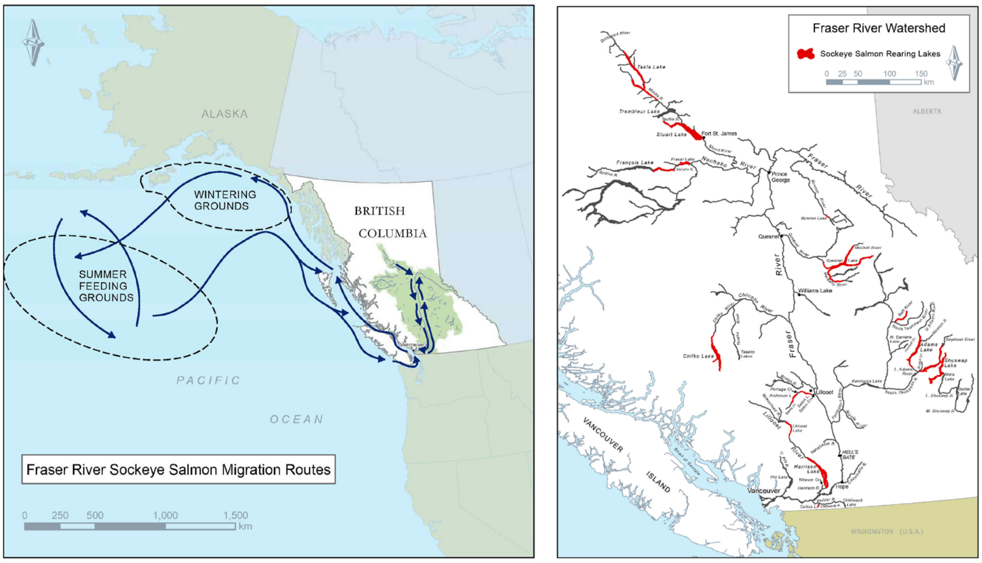

Figure 1. Fraser River sockeye **a)** marine and freshwater migration and major juvenile rearing lakes for the 24 conservation units (fundamental units of biodiversity) within the Fraser River watershed. Figures reprinted from DFO and Cohen (2012a).

Close to half of these Fraser Sockeye CUs have been designated Red (poor) status by Fisheries and Oceans Canada (DFO) due to the low relative numbers estimated on their spawning grounds and declining trends (Annex 1, Table A-1; Grant & Pestal, 2012; Grant *et al.,* 2020). Subsequently, COSEWIC designated these CUs as Endangered or Threatened (COSEWIC, 2017), meaning they are, respectively, facing an imminent risk of extinction, or are likely to become Endangered if nothing is done to reverse the factors contributing to their trends (Annex 1, Table A-1).

The Fraser River historically supported the largest numbers of sockeye salmon in the world (Cohen, 2012a). Fraser River sockeye continue to be of great importance to Indigenous communities for food, social and ceremonial (FSC) purposes, with approximately 140 different groups across the full marine and freshwater migratory routes relying on these fish stocks to support their communities. These populations have also historically supported the most important commercial fisheries on Canada's west coast. Although recreational fisheries can account for the harvest of large numbers of Fraser sockeye in some years, they account for less than 5% of Canadian total allowable catch (TAC) given a DFO policy that determines allocations across fishing sectors.

Management and decision-making system

Background: High seas directed fishing on Fraser River sockeye and other anadromous fish stocks is prohibited through the Convention for the Conservation of Anadromous Stocks in the North Pacific Ocean. Member countries include Canada, Japan, the Republic of Korea, the Russian Federation, and the United States of America. This includes areas outside of the 200-mile zones of coastal countries. Incidental catch is limited to the maximum extent practicable to reduce such incidental taking to insignificant levels in accordance with this Convention. These member countries work together within the North Pacific Anadromous Fish Commission (NPAFC) to promote conservation of anadromous fish stocks in the Convention Area (Figure 2). Member countries manage their own harvest strategies and conduct conservation actions to sustain their stocks within their respective 200-mile zones.

Most Fraser sockeye fisheries occur in coastal Canada and the United States of America waters during their adult return migration to their spawning grounds in the Fraser River of British Columbia (B.C.), Canada. A bilateral Canada-the United States of America Pacific Salmon Treaty (PST) was established in 1985 to manage these stocks in Panel waters (Figure 3). Decisions are made by the PST bilateral Fraser River Panel regarding Fraser sockeye run size, anticipated adult river migration mortalities due to river temperature and flow conditions, availability of TAC, and the opening and closure of sockeye salmon fisheries in designated waters of northern Puget Sound in Washington State, in the United States of America, and in southern B.C., Canada. These decisions are guided by their ability to (1) achieve the spawning escapement targets for each of the four management units (MUs) of Fraser River sockeye, (2) meet international catch allocation goals, and (3) meet domestic catch allocation objectives.

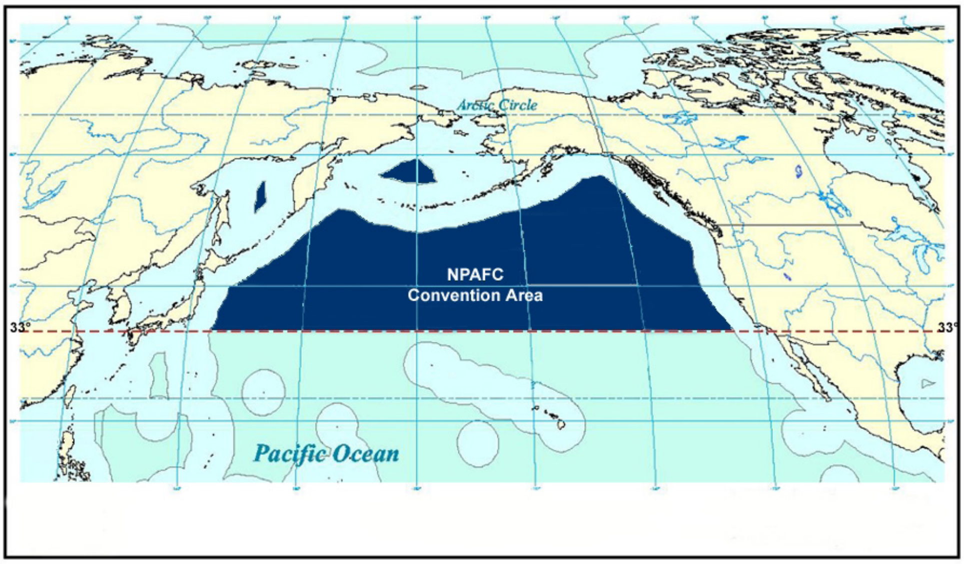

Figure 2. North Pacific Anadromous Fish Commission Convention Area. This Area pertains to the area of the North Pacific Ocean and its adjacent seas, north of 33 degrees north in international waters (high seas) beyond the 200-mile zones of the coastal States. Reprinted from the NPAFC website: https://npafc.org/convention/

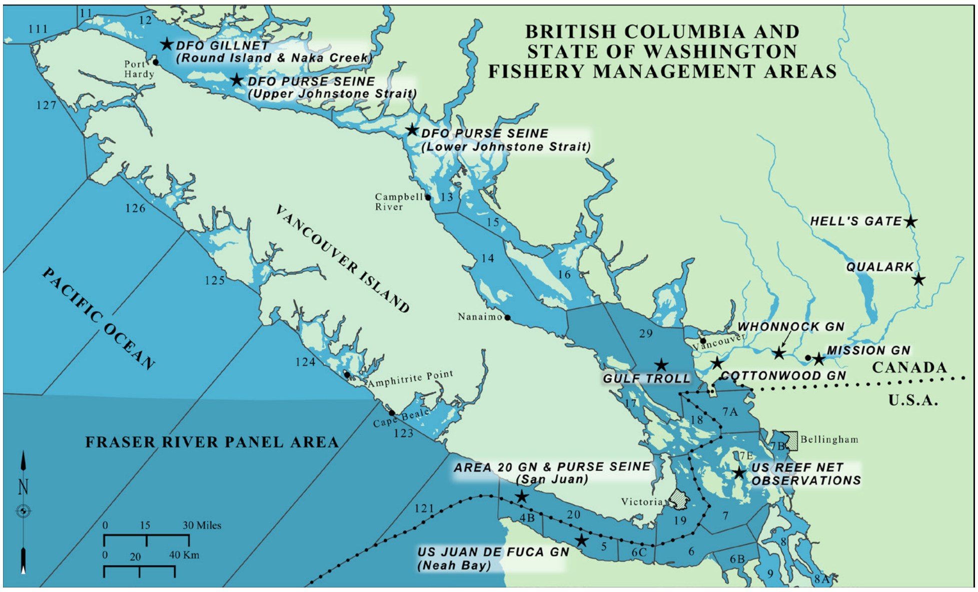

Figure 3. Pacific Salmon Treaty (PST) Fraser River Panel Area indicated by darker blue colour. The black filled stars indicate marine and Fraser River test fisheries and in-river hydro-acoustics stations that inform in-season estimates of Fraser River sockeye returns and fisheries management decisions. Sockeye adults return to the Fraser River from their Gulf of Alaska marine rearing areas via either the northern Johnstone Strait route (see top of map between Vancouver Island and the mainland), or the southern Juan de Fuca route (see bottom of map between Canada's Vancouver Island and the US's Washington State). Panel waters are those managed through the United States of America-Canada Fraser River Panel of the PST.

The 24 Fraser sockeye CUs are grouped into one of the four MUs based on their adult migration timing through coastal B.C. marine areas en route to their Fraser River spawning grounds (Figure 3). Most of the larger mixed stock fisheries occur in these coastal marine and Fraser River waters. The Early Stuart MU arrives first in these areas and is comprised of only the Takla-Trembleur-Stuart CU, which migrates to the Takla, Trembleur and Stuart Lake system near the north end of the Fraser watershed. This MU is followed by the Early Summer (10 CUs), Summer (7 CUs), and Late Run (6 CUs) MUs that spawn in different tributaries and lakes throughout the Fraser watershed. There is considerable overlap in timing among these MUs.

Inputs to support all stages of the fisheries management cycle: Fraser sockeye status has been evaluated every five years to support conservation considerations for fisheries management (Grant & Pestal, 2012; Grant *et al.,* 2020) (Table 1, #1). Initial modelling has recently been done to explore recovery actions for CUs with poor status (Table 1, #2).

The Fraser River Sockeye Spawning Initiative (FRSSI) provides spawning escapement targets to set annual exploitation rates, across the range of possible predicted pre- and in-season return abundances (Table 1, #3). The FRSSI model allows DFO to evaluate the effect of different fisheries escapement strategies for most Fraser sockeye stocks against management objectives or performance measures.

Pre-season fisheries management: The first step in this pre-season process is the development of a pre-season spawning escapement plan for each MU by Canada. This is informed by FRSSI (Table 1,#3), forecasted return numbers (Grant *et al.,* 2010; MacDonald and Grant, 2012; DFO, 2018a; MacDonald *et al.,* 2019) (Table 1, #4 & #5), and consultations with Canadian First Nations and other stakeholders.

Next, a pre-season fishing plan is developed that uses the pre-season escapement plan, and considers forecasted return numbers (Table 1, #4 & #5), predicted timing and diversion rates around Vancouver Island (Folkes *et al.,* 2017) (Table 1, #6), and predicted Fraser River temperatures and discharge (Hague and Patterson, 2007; MacDonald *et al.,* 2018; MacDonald *et al.,* 2019) (Table 1, #7). This plan attempts to minimize exploitation of CUs of concern, while allowing for fisheries on abundant co-migrating CUs and species (Table 1, #1).

In-season fisheries management: The in-season management is initiated as the Fraser River sockeye begin their migration through the Johnstone Strait or the southern Juan de Fuca Strait en route to their spawning grounds in the Fraser River. In-season catch rates and salmon DNA are sampled from multiple test fisheries located at the north end of Johnstone Strait, southern Vancouver Island, and several in-river locations (Figure 3).

These data inform in-season estimates of Fraser sockeye abundance, run timing and stock composition. This information is combined with in-river hydro-acoustics data on migrating salmon numbers (Table 1, #8), and river temperature and discharge data, to inform decisions regarding management adjustments (MAs) (Table 1, #9). These MAs provide the incremental numbers of fish that must be protected from fisheries to compensate for upstream migratory losses, in order to achieve spawning escapement goals. MAs have been increasing in recent years as river temperatures increasingly exceed upper thermal limits for salmon, resulting in stress and high pre-spawn mortality (MacDonald *et al.,* 2018, 2019).

Data on return abundances and MAs are compared against pre-season escapement plans to determine TAC, updated several times a week. Canadian catch is broadly partitioned into First Nations sockeye FSC, recreational and commercial fisheries, and at finer allocation scales within each of these groups.

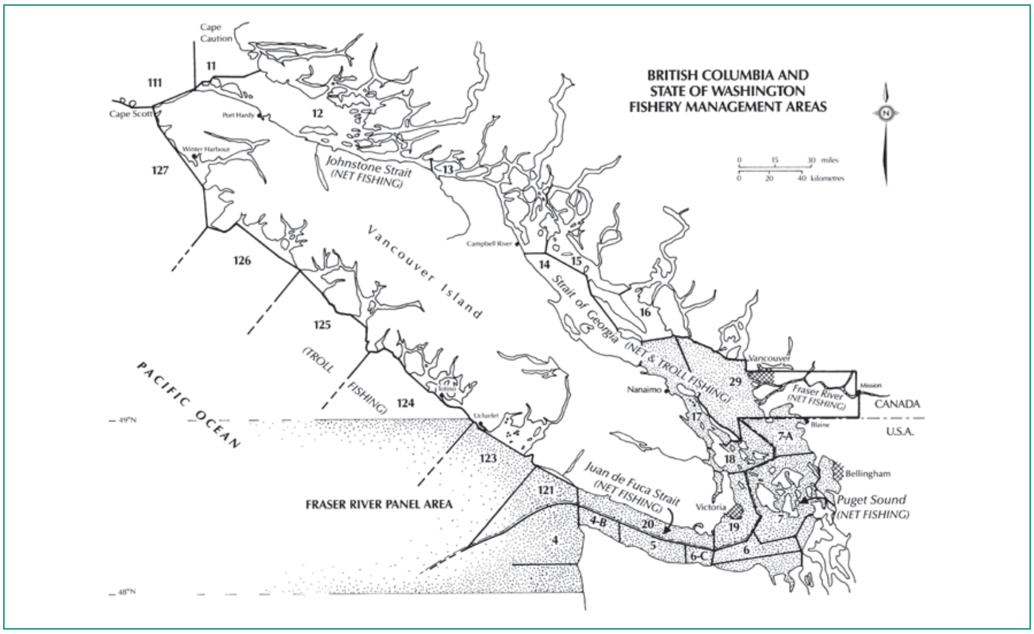

Figure 4. Commercial fishing areas for Fraser River sockeye include marine areas and the lower Fraser River. The Fraser River Panel Area of the United States of America-Canada Pacific Salmon Treaty Process is highlighted in grey. Source: Pacific Salmon Commission: https://www.psc.org/publications/fraser-panel-in-season-information/test-fishing-results/about-the-test-fisheries/

Since most fisheries are in marine and lower Fraser River habitats, decisions on in-season abundances must be made with preliminary information, before all the fish have migrated to their spawning grounds, and well before more accurate estimates are available post-season from spawning ground plus catch estimates.

First Nations Food, Social and Ceremonial (FSC) Fisheries: First Nations FSC are the highest sockeye fishery priority within Canada once conservation needs are accounted for (DFO, 1999). These fisheries may occur anywhere along the sockeye migration route, including marine areas on the inside and outside of Vancouver Island, and throughout the Fraser River and tributaries.

Gear types vary widely depending upon fishery location. Marine FSC fisheries may involve the use of seine, gillnet and troll, and recreational hook and line gear. Within the river, gillnets and recreational gear may be used, as well as selective gears such as shallow seine, beach seines, fish wheels and dip nets. Gear types reflect First Nations preferences, methods best suited to the river conditions in a given area, and constraints implemented to address conservation needs of co-migrating stocks of concern.

Commercial fisheries: *Regular commercial fleet:* Commercial fleets are managed through a combination of seine, gillnet or troll gear types and geographic areas (Figure 4). Fraser River sockeye returns have become less predictable since the 1990s (Grant *et al.,* 2020b), and fluctuating returns and reduced productivity have largely limited commercial sockeye fishing opportunities to one out of every four years, when run sizes are larger ranging from ~10-28 million. Some of the fleets have shifted from a derby-style fishery to a transferable quota approach in response to reduced opportunities, and to support fisheries manageability and improved value.

First Nations in-river economic fisheries: DFO has relinquished some regular commercial licences and provided the associated commercial TAC to inland First Nations, replacing some of the large mixed-stock ocean fishery effort with more selective in-river commercial fisheries in semi-terminal and terminal areas. Such fisheries use selective gear and occur upstream from tributaries with at-risk CUs, enabling use of commercial TAC while reducing impacts on smaller CUs.

Recreational fisheries: Sockeye retention is typically permitted in southern B.C. marine and freshwater recreational fisheries if there is adequate TAC available to open commercial fisheries. Bag limits, possession limits and other management parameters are identified in Fishery Notices published online.

Specific management measures may be implemented to protect Endangered or Threatened CUs, and in-river recreational fisheries targeting other species may be closed to prevent incidental impacts on Fraser River sockeye in years of low return. Periods of high river temperatures may also prompt the closure of in-river recreational fisheries to protect non-target species from handling stress.

B. Main stressors related to climate change

Freshwater conditions: British Columbia air temperatures have warmed by 1.9°C from 1948 to 2016 (PCIC, 2019). These temperatures were particularly warm from 2015 to 2018 (Figure 5), coinciding with the marine heatwave in the North Pacific Ocean (Figure 6). Warmer air temperatures, lower spring snow packs and receding glaciers are causing Fraser River temperatures to rise well above seasonal averages. River temperatures exceeding 18°C to 20°C in summer months are becoming increasingly common in the Fraser River (MacDonald *et al.,* 2019). Precipitation patterns are also becoming more extreme in B.C. in response to climate change, with more droughts in the summer, and increased frequency and magnitude of rain events leading to flash flooding (Pike *et al.,* 2010).

Warmer river and lake temperatures can impact adult salmon migrating upstream, egg incubation, juvenile rearing and smolt downstream migration (Burt *et al.,* 2011; Eliason *et al.,* 2011; Sopinka *et al.,* 2014). During upstream migration, warmer temperatures are more consistently exceeding sockeye upper thermal limits, decreasing their swimming performance, contributing to pre-spawning mortality, and potentially causing legacy effects on their offspring (Tierney *et al.,* 2009; Burt *et al.,* 2011; Eliason *et al.,* 2011; Sopinka *et al.,* 2016; MacDonald *et al.*, 2019).

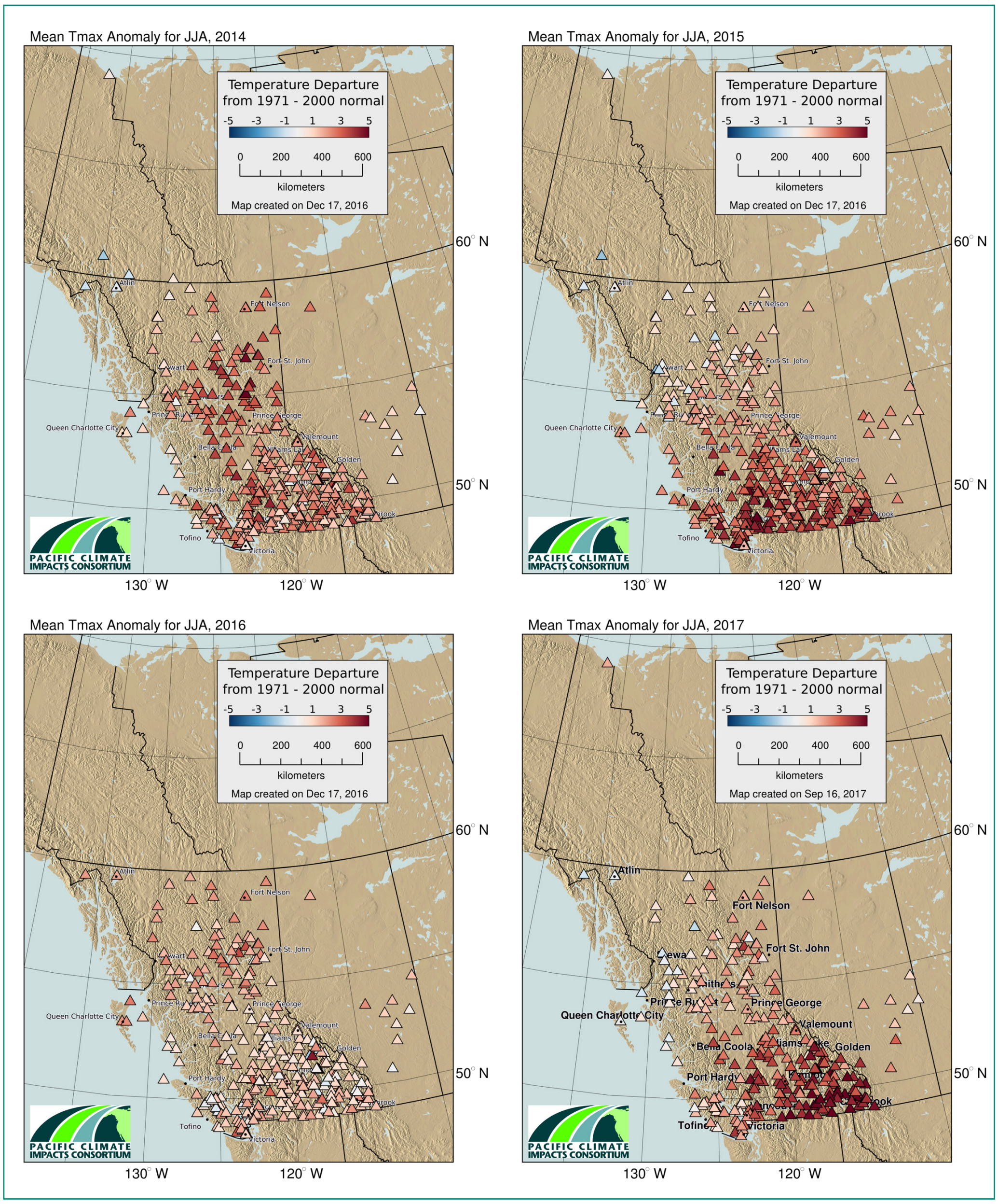

Figure 5. Maximum summer air temperature anomalies in British Columbia from 2014 to 2017. These are seasonal maximum monthly average temperatures for the summer months of June, July and August minus the total mean from 1971 to 2000. Data are from the University of Victoria Pacific Climate Impacts Consortium (PCIC). The colour table at the top of each map indicates the deviations from average; reds are above average and blues are below average temperatures. In recent decades, air temperatures have been anomalously warm for most seasons and years. Website: https://www.pacificclimate.org/analysis-tools/seasonal-anomaly-maps

Increased frequency of drought can create migration barriers to salmon and loss of incubating eggs and juveniles. More intense rain events that lead to flash floods can result in increased egg losses from scouring (Holtby and Healey, 1986; Lisle, 1989; Lapointe *et al.*, 2000).

The loss of forest canopy due to fires, pine beetle, logging and other human activities has compounded the intensity of these peak rain events for a number of B.C. interior watersheds. Canopy loss coupled with heavy rain have increased the sediment inputs into salmon-bearing watersheds, reducing the quality and amount of available spawning and juvenile rearing habitat. Incubating salmon eggs can get smothered by increased sediment and debris loads, and juveniles have less relief from higher temperatures from the loss of deep pool refuges.

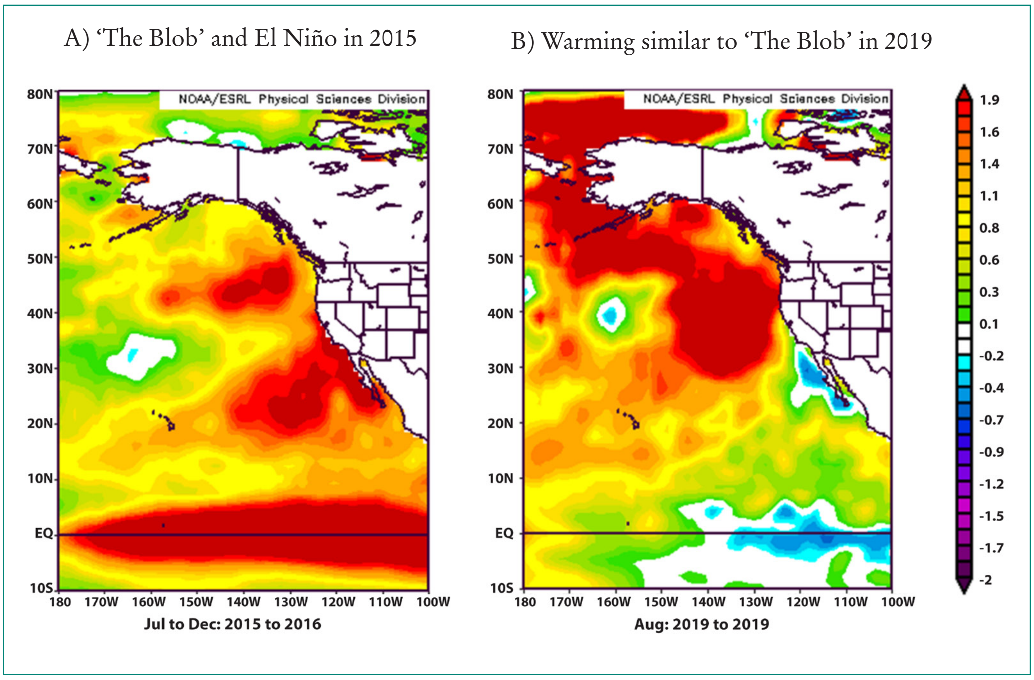

Figure 6. SST anomalies in the northeast Pacific Ocean for: **a)** July to December 2015 when both 'The Blob' and an El Niño event occurred, and **b)** recent warming in August 2019. These maps do not show absolute temperatures, but indicate how much above (red) or below (blue) average the ocean surface water temperatures were, compared to a 30-year average from 1981 to 2010. The coloured bar on the right of the maps provides detail on deviations from average. Images are provided by the NOAA/ESRL Physical Sciences Division, Boulder, Colorado from their website at http://www.esrl.noaa.gov/psd/.

In severe cases, landslides restrict access to suitable spawning and rearing habitats, and in some cases result in blockages of portions of river systems. A major landslide occurred on the Fraser River in 2019, the Big Bar Slide, blocking upstream migration of sockeye salmon CUs, particularly in the spring and early summer months (Government of B.C. *et al.,* 2019). This slide remains a barrier, and mitigation work is ongoing.

Marine conditions: A notable Northeast Pacific Ocean heatwave, nicknamed 'The Blob,' was present from the latter half of 2013 to Sept/Oct 2016 (Figure 6; Bond *et al.,* 2015). Sea-surface-temperatures (SST) during this period were 3 °C to 5 °C above seasonal averages, and extended down to depths of 100 m (Bond *et al.*, 2015; Ross and Robert, 2018; Smale *et al.*, 2019). Concurrently, a strong El Niño event occurred in late 2015 to early 2016 (Figure 6a), further increasing temperatures to the hottest observed throughout the 137-year time-series of data.

Although the El Niño transitioned to cooler La Niña conditions by the end of 2016 (Ross, 2017), and surface waters cooled, subsurface water temperatures remained warm at depths of 100-200 m until early 2018 (Ross, 2017; Ross and Robert, 2018). Any reprieve from these warm ocean temperatures was short-lived, as warm temperature anomalies in the northeast Pacific and Bering Sea have again been observed, starting in mid-2018 (Britten, 2018; Livingston, 2018). Beginning in August 2019, renewed warming in the northeast Pacific Ocean again resembles the physical characteristics of 'The Blob' from previous years (NOAA, 2019).

Salmon's metabolic demands increase with temperature, so that food consumption must increase accordingly. Thus, salmon growth and survival will decrease under warming conditions without a concurrent increase in prey quality or quantity (Holsman *et al.*, 2018). Predation also can intensify in warmer ocean conditions, increasing mortality of salmon during these periods (Holsman *et al.*, 2012).

Food quality near the base of the salmon food web deteriorated during this period of marine warming. Zooplankton composition shifted towards a greater abundance of lipid-poor southern copepods in the warm 'Blob' years, a key pathway potentially linking reduced salmon survival to temperatures in the northeast Pacific Ocean (Mackas *et al.*, 2007; Galbraith and Young, 2019). The warmer water species are considered to be poorer quality food for species higher up the food chain, due to their smaller size and lower fat content (Mackas *et al.*, 2007). The proportion of lipid-rich subarctic and boreal copepods typically found in the northeast Pacific Ocean concurrently decreased during these warmer years (Galbraith and Young, 2018; Young *et al.*, 2018).

C. Fisheries impacts from stressors and implications for fisheries management

Fraser River sockeye salmon returns declined from a peak of 24 million in 1993 to 490 000 in 2019 (Grant *et al.*, 2011, 2017; MacDonald *et al.*, 2018; Grant *et al.*, 2020a) (Figure 7a). Preliminary 2020 returns are 290 000, setting a new record low. Returns are the total number of adult salmon returning to the river for spawning.

Declining numbers of returning adults coincided with concurrent declines in productivity, defined as returns-per-spawner, for the aggregate from 1994 to 2019 (Figure 7b). The Late Shuswap CU's dominant 2010 cycle line has generally diverged from this trend, and contributes the highest proportion to total returns once every four years (Figure 7a). Given that trends were consistent across many sockeye populations, including many outside of the Fraser River, the most likely drivers of these patterns after the mid-1990s are broader scale patterns that include changing environmental conditions (Cohen, 2012b; Peterman and Dorner, 2012).

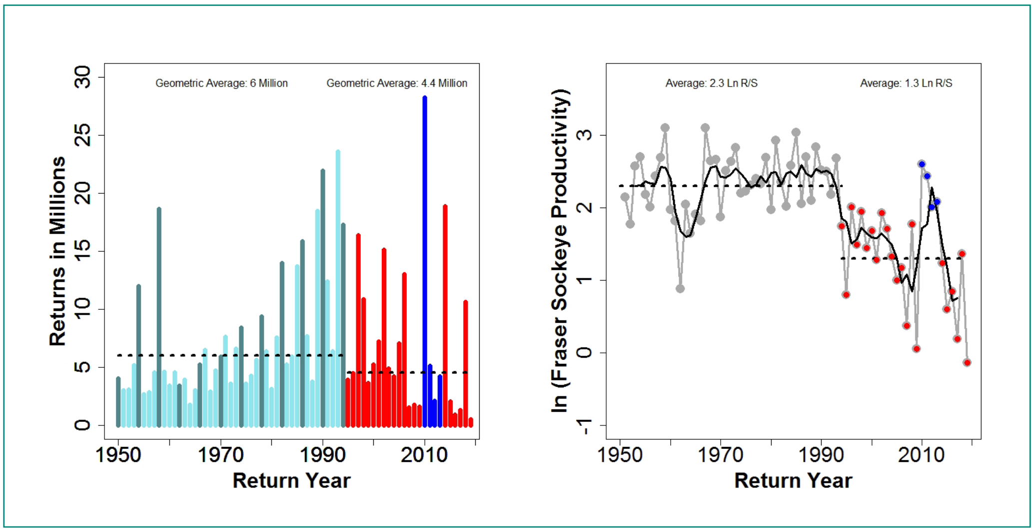

Figure 7. A Total Fraser River sockeye a) returns, which is the number of spawners estimated on the spawning grounds plus all catch and b) productivity (loge (returns/spawner) has generally declined for this aggregate from 1994 to 2019 (red lines or circles, respectively). There was a brief period from 2010 to 2013 (blue lines or circles) when productivity was above average. On both plots, averages are presented for the higher and lower productivity period as dashed horizontal lines, with values presented above these lines. On the return graph, the Late Shuswap CU dominates return numbers once every four years on the 2018 cycle, and as identified by darker blue lines. On the productivity graph, the grey dots and lines represent annual productivity estimates and the black line represents the smoothed four-year running average. The final 2019 data point in both graphs is preliminary based on an early in-season estimate only. The 2020 data are not yet finalized but preliminary estimates are 290 000, the new lowest on record.

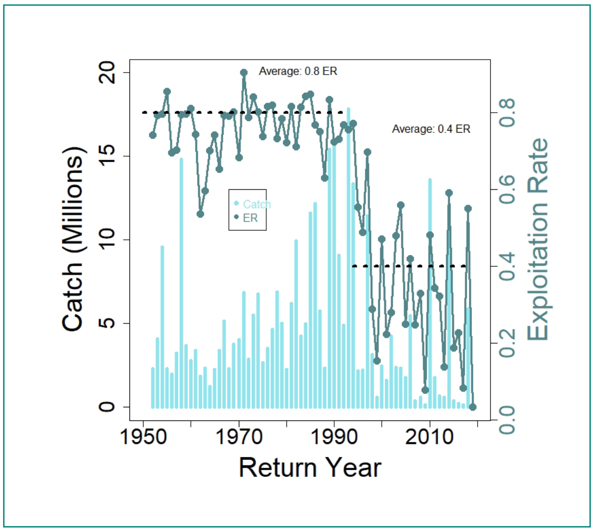

Figure 8. Catch (blue bars) and exploitation rate (ER; darker blue lines) for the Fraser River sockeye aggregate. This includes Canada and the United States of America catches. From 1950-1994 catch was 5 million (geometric average) and exploitation rates were 0.8, which is higher than recent years from 1995-2019 at 2 million (geometric average) and 0.3 respectively. These data were provided by S. Latham of the PSC and combine DFO and PSC data. Note the 2018 and 2019 return years are preliminary results.

Catch and exploitation rates were reduced to compensate for declining Fraser sockeye returns and productivity (Figure 8). Catch and exploitation rates were relatively high from 1950 to 1993 at 5 million and 0.8 respectively (geometric averages; Figure 8). Catch and exploitation rates declined by half from 1994 to 2019, to respectively 1 million and 0.4 (geometric average). In the past decade, catch has been relatively low, with the exception of the dominant Late Shuswap cycle line, which includes the recent years of 2006, 2010, 2014 and 2018 (Figure 8).

D. Lessons learned, challenges, gaps and solutions

Stock assessment and management advice

Overall, the Fraser sockeye salmon fishery is among the most intensely managed and assessed on Canada's West Coast (Grant *et al.*, 2011; Cohen, 2012a). One key element of science advice to support these fisheries is its inclusion of uncertainty. Results from more than one model are frequently used to represent different assumptions about sockeye population dynamics. In addition, Bayesian statistics are used to present information probabilistically (Grant *et al.*, 2010, 2011; Grant and Pestal, 2012; Saltelli *et al.*, 2020).

Preseason, many of these analyses use stock-recruitment models that rely on historical data (Table 1: #1-#4). These models, such as the classic Ricker model (Ricker, 1954), typically assume average productivity across the entire time series in their parameter estimates. However, in recent years this assumption does not align with observations of declining Fraser sockeye productivity (Figure 7b; Grant *et al.*, 2019b). Therefore, using standard Ricker models alone is increasingly problematic.

New models like Kalman filter approaches are being used to capture declining salmon productivity in parameter estimates (Peterman *et al.*, 2000, 2003; Holt and Michielsens, 2020). These have been used to assess Fraser sockeye biological status (Grant *et al.*, 2011; Grant and Pestal, 2012), develop pre-season return forecasts (Grant *et al.*, 2010; MacDonald and Grant, 2012), and for more recent recovery planning (DFO, 2020) (Table 1: #1–#4). These models are best used in combination with other models for comparisons, similar to how multiple models are used to project climate change by the IPCC (IPCC, 2013). Presenting multiple model results in science advice best captures the range of uncertainty across different assumptions about current and future productivity (Saltelli *et al.*, 2020).

Similarly, since Bayesian approaches are used in most Fraser sockeye analyses, stochastic uncertainty in the model fit to the data is also included (Table 1, #1-#4). These approaches have been used to estimate Fraser sockeye CU status (Grant and Pestal, 2012), and pre-season and in-season run size predictions (Grant *et al.,* 2010; MacDonald and Grant, 2012; Folkes *et al.,* 2017). For example, pre-season Fraser sockeye return forecasts are not presented as single deterministic point estimates, but rather a probability distribution to reflect this uncertainty (Grant *et al.,* 2010; MacDonald and Grant, 2012).

Environmental conditions are frequently falling outside historical ranges, making predicting salmon abundances increasingly difficult (Boldt *et al.,* 2019; Grant *et al.,* 2019c; MacDonald *et al.,* 2019). Although quantitative models attempt to capture these unprecedented environmental conditions, it remains challenging to predict the future when these conditions have not been observed in the past.

Further, Fraser sockeye life-history encompasses a range of freshwater and marine ecosystems, spanning rivers and lakes in the Fraser watershed to the Northeast Pacific Ocean. The cumulative effects of factors affecting their survival, and gaps in assessments in both these ecosystems, makes modelling unusually demanding. It was surprising when returns shifted from extremely low numbers in 2009, at 1.5 million, to extremely high numbers in 2010 of 30 million, as these extremes fell outside of the distributions predicted by quantitative models (Grant *et al.,* 2019b).

To address this gap, the authors added a qualitative science process to integrate observations across experts working on salmon throughout their life-stages in recent years (Grant *et al.,* 2019b; MacDonald *et al.,* 2019; Macdonald *et al.,* 2020) (Table 1, #5). This work provides qualitative scientific advice to inform whether survival will range from below to above average, to reduce these surprises for fisheries management. This approach provided additional information to determine whether survival leading up to the upcoming return year would result in below or above average returns.

River temperatures now frequently exceed the upper thermal tolerance of upstream migrating salmon (MacDonald *et al.,* 2019) en route to their spawning grounds. This is increasing stress and upstream mortality, before the fish arrive on their spawning grounds. Models have been developed to account for these losses for fisheries management (Macdonald *et al.,* 2010) (Table 1 #7 & #9). These estimates improve in-season management but remain uncertain, so that exact numbers from these models are heavily debated in-season, given the low numbers of annual data points that coincide with increasingly warm temperatures.

In-season, additional Bayesian models (Michielsens and Cave, 2019; Table 1, #8) are used to revise pre-season forecasts based on marine test fishery data in combination with in-river hydroacoustic-based abundance estimates. These updated forecast estimates have become increasingly uncertain due to increased variability, both in catchability estimates as well as return timing and abundances making it increasingly difficult to discern whether MUs are arriving late, or abundances are extremely low.

This uncertainty had made it more problematic to initiate fisheries, with higher risks of over-or underfishing, as decisions are required in advance of all fish having migrated through the test fisheries, and well in advance of more accurate estimates obtained from spawning grounds (Grant *et al.,* 2011).

In-season fisheries are particularly problematic in one out of four years when larger returns are expected to the Late Shuswap CU, as there will be management trade-offs between optimizing catches of the abundant Late Shuswap CU, and conservation concerns for smaller CUs that have a lower tolerance for high exploitation rates (DFO, 2018b). In the remaining three out of four years when Fraser sockeye abundances are generally low, the risk of over- or underfishing is generally much lower as catch expectations are low, and there are fewer management trade-offs required.

Table 1: The Fraser sockeye fisheries management stages (pre- and in-season), the corresponding science advice that supports each stage, and the climate adaptation measures currently used for Fraser sockeye fisheries management.

Stock assessment advice	Climate change adaptations
Applicable to all stages in the fisheries management cycle	
#1 Salmon CU status evaluations conducted every 5-10 years	• To account for the current lower salmon productivity, the biological benchmarks related to spawners at maximum sustainable yield (SMSY) are derived using stock-recruitment models that include time varying productivity parameters. The resulting stock status zones of healthy (Green), cautious (Amber) and critical (Red) are based on Canada's Wild Salmon Policy. • Bayesian statistics are used to account for stochastic uncertainty in the model fit to the data (Grant *et al.,* 2011; Grant and Pestal, 2012; Grant *et al.,* 2020a). • **Gaps:** Benchmarks will lag behind changes in salmon productivity, given the 5-10-year lag between assessments. New annual streamlined approaches are being developed to fill the gaps in these interim years.
#2 Recovery planning	• Advice on the probability of achieving recovery targets under different management scenarios is based on projection models for future CU abundances that include varying productivity parameters in the stock-recruitment relationship (DFO, 2020)
#3 Fraser River Sockeye Spawning Initiative (FRSSI) to inform escapement strategy options	• For each MU, lower and upper escapement-based management reference points are derived using a population dynamics model that includes a stock-recruitment relationship parameterized based on historical data (Pestal *et al.,* 2011; Huang, 2014). In-season, forecasts of return abundances plus en-route migratory losses are compared against these reference points to adjust sustainable exploitation rates and allocate catch to various fisheries groups. • Gap: This approach assumes that productivities observed in the past are representative of future productivities (MacDonald *et al.,* 2018; Grant *et al.,* 2019c, 2019a). Therefore, escapement goals may not reflect productivity changes anticipated under climate change. The next phase of this project, beginning in late 2019, will test the robustness of current and alternative harvest control rules to anticipated changes in productivity due to climate change.
Pre-season fisheries management	
#4 <u>Quantitative</u> pre-season return forecasts	• Environmental co-variates are included in Ricker models to track current environmental changes, improving the accuracy and precision of quantitative forecast predictions. • Bayesian statistics include stochastic uncertainty in the model fit to the data (Grant *et al.,* 2010; MacDonald and Grant, 2012; Xu *et al.,* 2019). • New modelling approaches are being explored to attempt to improve these forecasts including the use of the Kalman filter approach (Peterman *et al.,* 2000, 2003; Holt and Michielsens, 2020). • **Gaps:** Quantitative forecasts are becoming increasingly uncertain, since environmental conditions are frequently exceptional. It is challenging to predict the future when the past is less applicable.

Table 1: (Continued)

Pre-season fisheries management	
#5 Qualitative pre-season returns predictions	• To address the gap described in #4 above, a qualitative process was started in 2013 integrating salmon and environmental observations across life-stages to inform survival for the upcoming year's returns (MacDonald *et al.*, 2018, 2019; Grant *et al.*, 2019b). This process is designed to improve our ability to predict extreme return events, for example in 2009 and 2010, when respectively 1.5 million and 30 million Fraser sockeye returned. Qualitative input supports the quantitative forecasts, indicating to what extent survival is expected to deviate from average. • **Gaps:** Given the complex life-history of Fraser sockeye, considerable gaps exist in the knowledge on freshwater and ocean survival.
#6 Run timing and migration route forecasts	• Preseason forecasts of the timing of the return of the salmon return to the river and their migration route will impact fisheries. Both of these factors are influenced by environmental conditions and associated forecasts are improved by including relevant environmental covariates (Folkes *et al.*, 2017). • **Gaps:** These models are associated with high uncertainty. Changing environmental conditions linked to climate change are increasing this uncertainty.
#7 Pre-season adult upstream migration mortality forecasts (conducted prior to the fishing season with early environmental data)	• Mortality associated with adult upstream migration can be predicted using environmental conditions encountered within the Fraser River watershed such as snow pack, water temperature and discharge. • Temperatures exceeding upper thermal limits for salmon and river discharge levels that would cause upstream migration to be delayed by more than 7 to 10 days are associated with higher fish mortality (Hague *et al.*, 2008; MacDonald *et al.*, 2019). These predicted losses removed the number of salmon expected to reach the spawning grounds and compared with lower and upper management reference points to determine exploitation rates and catch for each of the four Fraser sockeye MUs. • **Gaps:** Migratory losses between the entry of the Fraser River and the spawning grounds are challenging to predict given the uncertainty in both these estimates. In addition, the substantial changes in environmental conditions in recent years reduce the relevant historical data with similar conditions, leading to considerable uncertainty in the pre-season predictions of en-route losses.
In-season fisheries management	
#8 In-season predictions of returning Fraser sockeye based on relative and absolute indicators of abundance	• Updated in-season predictions of returning salmon numbers and timing based on test fisheries information collected along the two main marine migration routes and hydroacoustic-based abundance estimates obtained in the Lower Fraser River. These estimates are updated three times a week, and used in combination with upstream migration mortality estimates to predict salmon numbers at the spawning grounds and guide in-season fisheries decisions when comparing spawning ground predictions against escapement targets. • Bayesian approaches are used in conjunction with pre-season return and run timing forecasts as priors, and updated with this in-season information, to factor in less predictable survival conditions for these fish (Michielsens and Cave, 2019). • **Gaps:** At the start of the season, there is a lot of uncertainty as to whether returns are low or just late, impacting in-season fisheries management decisions.
#9 In-season adult upstream migration mortality forecasts	• These forecasts are similar to #7 above but based on in-season data on environmental conditions.

Monitoring, control and surveillance

The North Pacific Anadromous Fish Commission (NPAFC) is the organization where member countries cooperate on enforcing the prohibitions of directed fishing on anadromous stocks like Fraser sockeye on the high seas, and limit incidental catch to the maximum extent practicable (Figure 2; see previous section). These countries conduct enforcement activities on illegal, unreported and unregulated (IUU) fisheries within the NPAFC Convention Area.

The nature and extent of threats facing salmon as they migrate in the North Pacific in the NPAFC Convention Area on the high seas (Figure 2) is difficult to quantify due to the size of the monitoring area and the limited resources for monitoring available to NPAFC member countries.

The North Pacific high seas are subject to intense fishing pressure for species such as squid, saury and mackerel by foreign fleets. There are more than 1,000 vessels registered to fish in this zone, a majority large-scale factory ships operating with crews of 60-70, running 24 hours per day. Elements of this fleet have been moving northward and eastward, away from Asia, as temperatures and species distributions are changing. These fleets often use high-intensity lights to attract target species to the surface.

Data are not available to understand the potential impact of this fishing activity on salmon where there is convergence between fishing and salmon migration routes, particularly the impact on food sources for salmon given the massive capacity of these ships. Crews have reported anecdotally that salmon are visible in the lights at night, and caught by some crew for food, indicating some convergence between this fleet with salmon. Should salmon migration patterns extend north or westward due to climate change, the interaction with the Asian foreign fleet will increase.

A more direct consideration is the potential for targeted catch of salmon by vessels operating illegally using driftnets. A regular occurrence in the 1990s, the past decade has seen an average of one significant seizure every two years. Patrol resources on the high seas are very limited, so the detection of a few vessels targeting salmon could represent a more widespread issue. There is a risk that this practice could increase as stocks decline, and salmon retains a high value.

E. Key recommendations

Many future fisheries will look quite different from the past due to climate change, as fish productivities and distributions respond (Barange *et al.*, eds. 2018). This will increase uncertainty in the information provided to make conservation-related and fisheries management decisions. Therefore, it will be important to ensure these management systems are extremely flexible and responsive to ecosystem changes (Schindler and Hilborn, 2015).

Fraser sockeye have been historically a data-rich fishery, with considerable resources available for research, monitoring and fisheries management. However, under climate change information is becoming increasingly uncertain, requiring a greater degree of precaution in the implementation of these fisheries. The following recommendations have emerged from the Fraser sockeye fisheries management process to provide increasing adaptability to salmon fisheries:

- Modelling approaches such as the Kalman filter are recommended to track time varying productivity parameters used in stock-recruitment models (Peterman *et al.,* 2000, 2003; Holt and Michielsens, 2020). This is important for stocks that have exhibited persistent shifts in productivity over time (DFO, 2013). These approaches can be useful when used to estimate status benchmarks (Grant *et al.,* 2011; Grant and Pestal, 2012) or management reference points (DFO, 2013), or in forecasting future fish production (Grant *et al.,* 2010; MacDonald and Grant, 2012). Examples of best practices have been provided in recent publications when applying these approaches (Holt and Michielsens, 2020).
- Communicating uncertainty in fisheries management inputs is increasingly important with climate change, and as ecosystems and fish respond. It is recommended that both structural and stochastic uncertainty are captured in advice and input into fisheries management processes.
    - o Capturing structural uncertainty in science advice should include the presentation of results from multiple models that capture different assumptions about fish population dynamics (Grant *et al.,* 2010, 2011; Grant and Pestal, 2012; Folkes *et al.,* 2017), similar to how the IPCC presents climate projections (IPCC, 2013).
    - o Bayesian statistical approaches are recommended to capture stochastic uncertainty and also provide information on model assumptions more transparently. Using Bayesian statistics, model results can be presented as probability distributions, rather than as single point estimates, to capture this uncertainty (Grant *et al.,* 2010, 2011; Grant and Pestal, 2012).
- As ecosystem and salmon respond to climate change, observations are increasingly exceptional. Since data from the past are less relevant to current and future conditions, other qualitative approaches are recommended to improve our understanding of fish population dynamics in response to ecosystem changes. Improving linkages between scientific disciplines, and integrating observations through structured processes, can provide additional insight to manage fisheries and project future stock trajectories (Grant *et al.,* 2019b; MacDonald *et al.,* 2019; DFO, 2020).
- Increasing emphasis on in-season management is recommended for salmon fisheries, as opposed to reliance on pre-season predictions, which are becoming increasingly uncertain under climate change. This includes the use of test fisheries and other information in-season to estimate in-season run sizes.
- Increasingly precautionary approaches should be applied for fisheries management. Predicting and estimating salmon information required for management is also becoming more uncertain since environmental conditions are increasingly unprecedented. Mixed stock fisheries increasingly include incidental catch of poorer status stocks that are challenging to estimate and avoid, given their small numbers relative to the more abundant stocks being targeted.
- Sufficient information already exists for this data-rich group of salmon to advance climate adaptation measures for salmon through fisheries, habitat and hatchery actions.
- The past no longer reflects future salmon productivity and numbers. Predictions of future salmon responses to climate change can be finetuned through salmon vulnerability assessments (Hunter *et al.,* 2015; Hare *et al.,* 2016; Grant *et al.,* 2019c; Crozier *et al.,* 2019). Extinctions are already extensive in response to climate and habitat changes across plant and animal species (Wiens, 2016). Since resources to support recovery and habitat restoration actions are limited, vulnerability assessment results will help to prioritize among these (Grant *et al.,* 2019c). This can also be used to identify appropriate fisheries adaptations to climate change based on the future stock trajectories, rather than the past.

- As fisheries continue to change, greater flexibility in the allocation of science and management resources to various fish stocks is required. Many salmon stocks, particularly in southern latitudes, are declining, and particular species appear to be more vulnerable to climate and habitat changes (Grant *et al.,* 2019c). Historically large-scale fisheries like Fraser sockeye have been allocated much resourcing, relative to other species. Anticipating future shifts, and collecting the necessary information now to manage these future fisheries, will be important for human resiliency and adaptations.
- Freshwater habitat is another area where environmental conditions could potentially be managed under climate change. Increased riparian and watershed vegetation, for example, can improve run-off, sedimentation, and lake and river temperatures for migrating, spawning, and rearing eggs and juveniles (Nelitz *et al.,* 2007a, 2007b). Other examples are related to created cool water reservoirs, restoring connectivity among systems, conserving pristine habitats, creating deep pools and off-channel habitat in rivers. Hatcheries may be another option to maintain populations for conservation or production purposes under climate change.

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Glossary

Anadromous: fish that migrate from the ocean to freshwater to spawn.

The Blob: a notable Northeast Pacific Ocean heatwave, nicknamed 'The Blob,' was present from the latter half of 2013 intermittently through to 2019. Sea surface temperatures during this period were 3-5°C above seasonal averages, and extended down to depths of 100m.

Conservation Unit (CU): A CU is a group of wild salmon sufficiently isolated from other groups that, if extirpated, is very unlikely to recolonize naturally within an acceptable timeframe, such as a human lifetime or a specified number of salmon generations. These are characterized by their life-history, genetics and ecology. There are 24 Fraser sockeye CUs.

COSEWIC: The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) is an independent advisory panel to the Minister of Environment and Climate Change Canada that meets twice a year to assess the status of wildlife species at risk of extinction. Members are wildlife biology experts from academia, government, non-governmental organizations and the private sector responsible for designating wildlife species in danger of disappearing from Canada.

Diversion rates: the proportion of returning adult Fraser sockeye that use the northern Johnstone Strait route, versus the southern Juan de Fuca Strait route to reach the Fraser River after returning from rearing at sea (Figure 3). This changes the accessibility to these fish to different fisheries, including the United States of America in Washington, and varies within the season and between seasons.

En-route migratory losses: these are the number of Fraser sockeye that do not survive upstream migration to their spawning grounds, after being enumerated through downstream methods.

Escapement: the number of salmon that reach the spawning grounds in their natal rivers and lakes.

Fisheries and Oceans Canada (DFO): Fisheries and Oceans Canada is the federal lead for safeguarding our waters and managing Canada's fisheries, oceans and freshwater resources. We support economic growth in the marine and fisheries sectors, and innovation in areas such as aquaculture and biotechnology.

Fraser River Sockeye Spawning Initiative (FRSSI): provides spawning escapement targets to set annual exploitation rates, across the range of possible predicted pre- and in-season return abundances. The FRSSI model allows DFO to evaluate the effect of different fisheries escapement strategies for most Fraser sockeye stocks against management objectives or performance measures.

First Nation Food, Social, and Ceremonial (FSC) fisheries: First Nation FSC fisheries are the highest sockeye fishery priority within Canada once conservation needs are accounted for (DFO, 1999). These fisheries may occur anywhere along the sockeye migration route, including marine areas on the inside and outside of Vancouver Island, and throughout the Fraser River and tributaries.

Hydroacoustic abundance estimates: these are sonar methods used in the Fraser River near Mission, British Columbia, to enumerate the numbers of Fraser sockeye returning in-season.

Late Shuswap CU: this CU returns in large abundances once every four years, and in recent years these have been the key years where major Fraser sockeye fisheries occur. These years for example include 2010, 2014 and 2018.

Management Adjustments (MA): provide the incremental numbers of Fraser sockeye that must be protected from fisheries to compensate for upstream migratory losses, in order to achieve spawning escapement goals. MAs have been increasing in recent years as river temperatures increasingly exceed upper thermal limits for salmon, resulting in stress and high pre-spawn mortality.

Management Unit (MU): one or more Canadian salmon CUs grouped together based on their adult migration timing through coastal B.C. marine areas en route to their spawning grounds. For Fraser sockeye there are four MUs. The Early Stuart MU arrives first in these areas and is comprised of only the Takla-Trembleur-Stuart CU, which migrates to the Takla, Trembleur and Stuart Lake system near the north end of the Fraser watershed. This MU is followed by the Early Summer (10 CUs), Summer (7 CUs) and Late Run (6 CUs) MUs that spawn in different tributaries and lakes throughout the Fraser watershed. There is considerable overlap in timing among these MUs.

Spawners at maximum sustainable yield (SMSY): is the number of spawners that produce maximum sustainable catch under existing environmental conditions.

North Pacific Anadromous Fish Commission (NPAFC): member countries include Canada, Japan, the Republic of Korea, the Russian Federation and the United States of America. This includes areas outside of the 200-mile zones of coastal countries. Incidental catch is limited to the maximum extent practicable to reduce such incidental taking to insignificant levels in accordance with this Convention. These member countries work together within the NPAFC to promote conservation of anadromous fish stocks in the Convention Area (Figure 2).

Pacific Salmon Commission (PSC): The Pacific Salmon Commission is the body formed by the governments of Canada and the United States of America in 1985 to implement the Pacific Salmon Treaty.

Pacific Salmon Treaty (PST): A bilateral Canada-the United States of America Pacific Salmon Treaty (PST) was established in 1985 to manage these stocks in Panel waters (Figure 3). The United States of America and Canada agreed to cooperate in the management, research and enhancement of Pacific salmon stocks of mutual concern by ratifying the Pacific Salmon Treaty.

Salmon productivity: the number of recruits (adult offspring: escapement plus catch by age) produced by parent spawners.

Returns: this is the number of fish that return and includes catch plus escapement, which is the number of fish that reach the spawning grounds to spawn.

Semelparous: a species with a single reproductive event before death.

Wild Salmon Policy: Canada's Department of Fisheries and Oceans policy whose goal is to restore and maintain healthy and diverse salmon populations and their habitats for the benefit and enjoyment of the people in Canada in perpetuity. Key strategies to achieve this goal include tracking salmon and habitat/ecosystem status, integrated planning, annual programme delivery and programme review.

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Annex 1. Fraser sockeye WSP and COSEWIC statuses

There are 24 Fraser sockeye CUs that were first assessed by DFO in 2012 (DFO, 2012; Grant and Pestal, 2012). These were re-assessed in 2017 (DFO, 2018c). There are currently seven Fraser sockeye CUs in the Red status zone, two in the Red/Amber status zone, four in the Amber status zone, six in the Amber/Green status zone, three in the Green status zone, and one data deficient CU (Table 3, first column). COSEWIC aligned its Fraser sockeye DUs exactly with DFO's WSP CUs. COSEWIC statuses also align with DFO's WSP statuses for Fraser sockeye and COSEWIC identifies eight Endangered DUs, two Threatened, five Special Concern, and eight Not-at-Risk (Table 3, last column).

Table A-1: The 2017 integrated status designations for the 24 Fraser River sockeye salmon CUs, ranked from poor (Red zone) to healthy (Green zone) status based on the current 2017 assessment. Cyclic CU statuses are determined including abundance benchmarks estimated using the Larkin model (DFO, 2018c). For each CU, more commonly used stock names are presented. An asterisk (*) indicates provisional status designations; R/A: Red/Amber; A/G: Amber/Green; DD: data deficient; Undet: undetermined. The previous assessment's integrated statuses are also listed for 2012 (DFO, 2012; Grant and Pestal, 2012). The COSEWIC 2017 status designations are presented in the final column (released 2018).

2017	2012	Conservation Unit	Stock	COSEWIC 2017
R	R	Bowron-ES	Bowron	Endangered
R	R	Cultus-L	Cultus	Endangered
R	R	Takla-Trembleur-EStu	Early Stuart	Endangered
R	R*	Taseko-ES	Miscellaneous E. Summ	Endangered
R	R	Widgeon – River*	Miscellaneous Lates	Threatened
R	A	Harrison (U/S)-L	Weaver	Endangered
R	UD	Seton-L	Portage	Endangered
R A	R A	Quesnel-S	Quesnel	Endangered
R A	R A	Takla-Trembleur-Stuart-S	Late Stuart	Endangered
A	R	Nahatlatch-ES	Miscellaneous E. Summ	SC
A	A	North Barriere-ES	Fennel & Miscellaneous E. Summ	Threatened
A	A	Kamloops-ES	Raft & Miscellaneous E. Summ	SC
A	A G	Shuswap-ES	Scotch, Seymour, Mis. E. Summ	NAR
A	G*	Lillooet-Harrison-L	Birkenhead	SC
A G	R	Nadina-Francois-ES	Nadina	NAR
A G	R A	Chilliwack-ES	Miscellaneous E. Summ	NAR
A G	R A	Francois-Fraser-S	Stellako	SC
A G	A	Anderson-Seton-ES	Gates	NAR
A G	G	Harrison (D/S)-L	Miscellaneous Lates	SC
A G	G	Shuswap Complex-L	Late Shuswap	NAR
G	A G	Pitt-ES	Pitt	NAR
G	G*	Chilko-S & Chilko-ES agg.	Chilko	NAR
G	G	Harrison River – River	Harrison	NAR
DD	DD	Chilko-ES	Harrison	NA

Abbreviations: EStu: Early Stuart; ES: Early Summer; S: Summer; L: Late; Mis: miscellaneous;
**Widgeon (river-type) CU has a small distribution, therefore, this CU will be consistently in the Red status zone*

Appendix: Workshop participants

Expert Workshop on Fisheries Management Adaptation to Climate Change (12-14 November 2019, Rome, Italy)

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Gunnstein Bakke (Directorate of Fisheries, Norway)
Manuel Barange (FAO)
Xavier Basurto (Duke University, the United States of America)
Miguel Bernal (FAO)
Merrick Burden (Environment Defense Fund)
Sangaalofa Clark (Parties to the Nauru Agreement Office, Republic of Marshall Islands)
Omar Defeo (UNDECIMAR, Uruguay)
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Beth Fulton (CSIRO Oceans and Atmosphere, Australia)
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Ricardo Oliveros-Ramos (Instituto del Mar del Perú)
Hazel Oxenford (University of Barbados)
Ian Perry (Fisheries and Oceans Canada)
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Merete Tandstad (FAO)
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Vahdet Ünal (Ege University, Turkey)
Marcelo Vasconcellos (FAO)
David Welch (C_2O, Vanuatu)

[Bahri, T., Vasconcellos, M., Welch, D.J., Johnson, J., Perry, R.I., Ma, X. & Sharma, R., eds. 2021. *Adaptive management of fisheries in response to climate change*. FAO Fisheries and Aquaculture Technical Paper No. 667. Rome, FAO. https://doi.org/10.4060/cb3095en]

Corrigendum

[07 April 2021]

The following corrections were made to the PDF of the report after it went to print.

Page	Location	Text in printed PDF	Text in corrected PDF
p.ii	After copyright date	© FAO, 2021	© FAO, 2021, Last updated 07/04/2021
p.41			Deleted extra spaces before "Challenges"
p.97	Figure 11 caption	Eva Plagyani, CSIRO, Brisban, Australia	Eva Plagányi-Lloyd, CSIRO, Brisbane, Australia
p.195	Footnote		This case study is based on a draft version of the open access article **Gullestad,P., Sundby, S., Kjesbu, O.** 2020; 21:1008-1026, Management of transboundary and straddling fish stocks in the Northeast Atlantic in view of climate-induced shifts in spatial distribution - Gullestad - 2020 - Fish and Fisheries - Wiley Online Library. The text relies fully on the information on biology and oceanography in the article written by Sundby, S. and Kjesbu, O, both affiliated to the Institute of Marine Research, Bergen Norway (Gullestad, Sundby and Kjesbu, 2020). All editing of this case study are, however, the sole responsibility of Peter Gullestad and Gunnstein Bakke, both affiliated to the Directorate of Fisheries, Bergen Norway. Readers are invited to consult the article for a more in depth description of the issues. This applies in particular to information on biology and oceanography. The article also provides information related to another fish stock whose area of distribution is influenced by climate change with consequences for management. The Directorate of Fisheries would not have been in a position to contribute with a unique case study to this valuable work of FAO if the article had not been in preparation when the authors were asked by FAO to contribute.
p.206	References		**Gullestad, P., Sundby, S., Kjesbu, O.** 2020. Management of transboundary and straddling fish stocks in the Northeast Atlantic in view of climate-induced shifts in spatial distribution. *Fish and Fisheries*, 21(5):1008-1026. doi:10.1111/faf.12485.
p.264	Figure 4 caption	https://www.psc.org/publications/fraser-panel-in-season-information/test-fishingresults/fisheries-maps/	https://www.psc.org/publications/fraser-panel-in-season-information/test-fishing-results/about-the-test-fisheries/

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This report aims to accelerate climate change adaptation implementation in fisheries management throughout the world. It showcases how flexibility can be introduced in the fisheries management cycle in order to foster adaptation, strengthen the resilience of fisheries, reduce their vulnerability to climate change, and enable managers to respond in a timely manner to the projected changes in the dynamics of marine resources and ecosystems. The publication includes a set of good practices for climate-adaptive fisheries management that have proven their effectiveness and can be adapted to different contexts, providing a range of options for stakeholders including the fishing industry, fishery managers, policymakers and others involved in decision-making. These good practices are linked to one or more of the three common climate-related impacts on fisheries resources: distributional change; productivity change; and species composition change. Therefore, these three impacts can serve as practical entry points to guide decision-makers in identifying good practice adaptation measures suitable for their local contexts. These good practices are based upon transferable experiences and lessons learned from 13 case studies across the globe and hopefully will contribute to greater uptake and implementation of climate-adaptive fisheries management measures on the ground.

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