OCEANS NORTH
1533 Barrington St, Suite 200, Halifax, NS, B3J 1Z4
www.oceansnorth.org

Incorporating climate change into fisheries management in Atlantic Canada and the Eastern Arctic

Prepared by Dr. Daniel G. Boyce, The Ocean Frontier Institute at Dalhousie University for Oceans North

Citation:
Boyce, D. G., Schleit, K., & Fuller, S. (2020). Incorporating climate change into fisheries management in Atlantic Canada and the Eastern Arctic. Halifax, Nova scotia, Canada.

Table of Contents

List of tables

List of figures

Glossary and abbreviations

ACCASP: Aquatic Climate Change Adaptation Services Program
AOS: Area of interest
BMSY: Biomass removals to achieve maximum sustainable yield
CAD: Canadian dollar
CCCA: Climate change conditioning of science advice
CEATTLE: Climate Enhanced Age-based model with Temperature-specific Trophic Linkages and Energetics
CMIP: Coupled Model Intercomparison Project
CSAS: Canadian Science Advisory Secretariat
DFO: Fisheries and Oceans Canada
DOM: Dynamic ocean management
EAF: Ecosystem approach to fisheries
EAFM: Ecosystem approach to fisheries management
EEZ: Exclusive economic zone
ENGO: Environmental non-governmental organization
ESM: Earth system model
FAO: Food and Agriculture Organization of the United Nations
FSCVAT: Fish Stock Climate Vulnerability Assessment Tool
Gadget: Globally applicable Area-Disaggregated General Ecosystem Toolbox
GCM: Global climate model
GFDL-ESM2M: Geophysical Fluid Dynamics Laboratory Climate Model
HSC: Herring Science Council
HII: Human impact index
ICES: International Council for the Exploration of the Sea
IFMP: Integrated fishery management plan
IPBES: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC: Intergovernmental Panel on Climate Change
IPSL-CM5A-LR: Institute Pierre Simon Laplace Climate Model
IQ: Individual quota
ITQ: Individual transferable quota
IUCN: International Union for Conservation of Nature
LRP: Limit reference point
MPA: Marine protected area
MSE: Management strategy evaluation
MSY: Maximum sustainable yield
NAFO: Northwest Atlantic Fisheries Organization
NARW: North Atlantic right whale (*Eubalaena glacialis*)
NGO: Non-governmental organization
NMFS: National Marine Fisheries Service
NOAA: National Oceanic and Atmospheric Administration
NPP: Net primary productivity
POAMA: Predictive Ocean Atmosphere Model for Australia
PR-DOC: Peer-reviewed published research document
RCP: Representative concentration pathway
RES-DOC: Fisheries and Oceans Canada Canadian Science Advisory Secretariat research document
SAR: Science advisory report
SBT: Southern bluefin tuna
SPERA: Strategic Program for Ecosystem-Based Research and Advice

SSB: Spawning stock biomass
SSR: Stock status report
SST: Sea surface temperature
SWNS-BoF: Southwest Nova Scotia and Bay of Fundy
Mt: Metric mega tonne
TAC: Total allowable catch
TEK: Traditional ecological knowledge
ToE: Time of emergence
ToR: Terms of reference
t: Metric tonne
USD: US dollar
USL: Upper stock limit

Acknowledgements

We would like to thank G. Britten, A. Buchholz, C. Karbowski, H. Lotze, N. Shackell, D. Tittensor, C. Ward-Paige, and B. Worm for reviewing this report and providing critical and insightful feedback. We are grateful to all marine ecosystem modellers for performing simulations and contributing results in accordance with the Fish-MIP protocol, particularly S. Jennings, T. Silva, E. Galbraith, D. Bianchi, O. Maury, N. Barrier, P. Verley, J. Blanchard, V. Christensen, M. Coll, J. Steenbeek, W.W.L. Cheung, and T. Eddy. We are also grateful to S. Henson for providing the time of emergence estimates and C. Karbowski for compiling the Integrated Fisheries Management Plan documents. We would like to acknowledge the staff at the Pew Charitable Trusts and the Ocean Foundation, including Karen Font and Kate Williams, who fact-checked the report; Zeynep Çelik, who reviewed the statistical analyses; and Margaret Murphy and Katharine Deuel, who oversaw and coordinated the production of the report.

Introduction

In 1883, T. H. Huxley famously stated: "I believe, then, that the cod fishery … and probably all the great sea fisheries are inexhaustible: that is to say that nothing we do seriously affects the number of fish. And any attempt to regulate these fisheries seems … to be useless." Since this time, our understanding of how humans and fishing affect marine populations has changed considerably, as has our approach to their management and conservation. Quantitative approaches to fisheries management rooted in population modelling were developed through the 1940s and serve as the backbone on which current fisheries management still relies. The original models focused heavily on fishing as the sole driver of population production and largely neglected the effect of environmental conditions. Since that time, there has been increasing recognition of the importance of ecosystem dynamics (1980s), environmental variation, and climate change (1990s) on fish population dynamics (e.g. Cushing, 1990; Kennedy, 1990; Glantz, 1992). From this understanding, a range of different approaches to fisheries management now exist that can evaluate different management strategies for exploited species given past and projected future environmental and ecosystem conditions. Despite this, the extent to which fisheries incorporate environmental, ecosystem, or climate considerations into their management strategies is variable but generally low and may be a contributing factor in the shortcomings of many fisheries management approaches around the world (Garcia and Grainger, 1997; Worm *et al.*, 2009; Brander, 2010; Pershing *et al.*, 2015), and associated fish population collapses (Baum *et al.*, 2003; Myers and Worm, 2003, 2005; Worm *et al.*, 2009; Hutchings *et al.*, 2010). To date, almost a third (34%) of fish stocks that have been scientifically assessed are considered overfished (FAO, 2020).

The effects of climate change on marine ecosystems and exploited species are varied but are projected to increase in magnitude and extent over the next century, posing an unprecedented risk to food and economic security for billions of people worldwide (Barange *et al.*, 2010; Hollowed *et al.*, 2013; Poloczanska *et al.*, 2013; IPCC, 2014; Gattuso *et al.*, 2015; Lotze *et al.*, 2019; Boyce *et al.*, 2020). For example, it has been estimated that climate change could drive annual global losses in gross revenues of USD $17–41B annually, with disproportionate effects on developing nations (Sumalia and Cheung, 2010; Boyce *et al.*, 2020). Such changes are having and will continue to have large effects on the distribution, yield, and productivity of fishing both in Canada and elsewhere. However, studies also indicate that management measures can improve fisheries status (Hilborn *et al.*, 2020) and can offset climate change effects, in some situations compensating for negative effects and possibly amplifying positive effects (Le Bris *et al.*, 2018). However, the risks to fisheries posed by climate change will also increase with each passing delay in the implementation of adaptation measures (Melvin *et al.*, 2016). In consequence, there is an increased urgency to understand how fisheries can be managed in a climate-smart manner (Lawler *et al.*, 2010; Pinsky and Mantua, 2014; Gattuso *et al.*, 2015; Busch *et al.*, 2016; Ojea *et al.*, 2017; Holsman *et al.*, 2019a), and many nations are now incorporating climate change considerations into the management of their fisheries. For example, the US National Marine Fisheries Service (NMFS) has developed a Climate Science Strategy to identify steps to ensure that their ocean management mandate is robust to the uncertainties associated with climate change (Busch *et al.*, 2016). Climate change adaptation reports exist for the US (Gregg *et al.*, 2016), the UK (Defra, 2013), Ireland (Kopke and O'Mahoney, 2011), and other nations and organizations (Barange *et al.*, 2018). For example, fisheries management in Australia now includes explicit components that are intended to increase the resilience of fisheries to climate change (Bryndum-Buchholz, 2020). Canada has a long coastline, extensive fishing fleets, and a culture that is deeply connected to the ocean. Despite this, Canada lacks a clear climate change adaptation strategy for its fisheries (but see: Duplisea *et al.*, 2020; Pepin *et al.*, 2020 for recent developments), and it is unclear to what extent climate change is being considered in the management of its fisheries. Expert assessments funded through Canada's Aquatic Climate Change Adaptation Services Program (ACCASP) have reported that there is a high probability of significant climate change impacts in all of Canada's marine and freshwater basins and that the impacts will generally increase over time (DFO, 2012a, 2012b). The Arctic has experienced, and is anticipated to continue to experience, the largest impacts of climate change on living resources, including fisheries (DFO, 2012a). For example, a recent study projected that unabated climate change might lead to the extinction of polar bears (*Ursus maritimus*) in the Arctic by 2100 (Molnár *et al.*, 2020). Such findings have recently been reinforced by peer-reviewed studies reporting significant climate-driven changes in marine animal biomass across much of the Canadian exclusive economic zone (Lotze *et al.*, 2019; Boyce *et al.*, 2020; Bryndum-Buchholz *et al.*, 2020).

The primary intent of this report is to (1) review the state of Canada's fisheries and the past and future projected climate change effects on them; (2) review the best tools and approaches that are currently used to adapt fisheries management to climate change; (3) evaluate the extent to which climate change and its effects are being considered in the management of marine fisheries in Atlantic Canada and the Eastern Canadian Arctic, hereafter referred to as the area of study (AOS), and (4) recommend steps to increase the robustness of Canadian fisheries management to climate change. The majority of the data used in this report are publicly available from the sources listed in Table 10.1.

1. The value of healthy and productive fisheries

1.1 Culture and nutrition

The status of marine species and commercial fisheries has critical consequences for the economy, health, food security, and culture of all Canadians, especially in Atlantic Canada and the Eastern Arctic. Seafood is essential to the nutritional well-being of many coastal communities worldwide. Seafood provides the primary source of animal protein for 7% of the population globally, and the consumption of seafood has increased more rapidly (3.1% yr^{-1}) than all other animal protein (meat, dairy, milk; 2.1% yr^{-1}) between 1961 and 2017 (FAO, 2020). In Canada, fisheries provide coastal communities with an important source of cost-effective and high-quality protein, contributing to dietary health (Lowitt, 2013). In addition to the importance of energy and macronutrients (e.g. protein), key micronutrients such as iron and zinc have been the focus of recent global efforts to address malnutrition,. Globally, deficiencies of these essential micronutrients are among the leading causes of malnutrition, with associated adverse effects on early childhood mortality and national gross domestic product (Hicks *et al.*, 2019). A recent study highlighted the importance of seafood as a source of these essential micronutrients and suggested that reorienting fisheries towards a more efficient and equitable distribution of micronutrient consumption would improve diet and health (Hicks *et al.*, 2019). While the biomass of fisheries yield can affect the protein supply to coastal communities, the catch composition drives the nutrient content. Thus, both the biomass and composition of the catch can have strong effects on nutrition and food security. Since seafood often constitutes a more affordable animal-based food source for many coastal communities and has a lower environmental impact, fisheries should be a central component of food and nutrition policies globally and in Canada.

The nutritional and cultural importance of fisheries is felt across the AOS, but particularly so for Indigenous communities. Seafood consumption is critically important to Indigenous communities in Canada, particularly Inuit communities in the Arctic, where it is the main source of protein (Baum and Fuller, 2016). Indigenous fishing communities that rely on traditional fisheries for food and economic security are also especially vulnerable to climate change through a reduced capacity to conduct traditional harvests because of limited access to or availability of resources (Weatherdon *et al.*, 2016). Such changes to traditional fisheries could have consequences for the food and economic security of Indigenous coastal communities, the preservation and transfer of their traditional knowledge, and the legal upholding of their rights to access traditional resources (Lynn *et al.*, 2013). Such issues are of special importance to Inuit communities in the Arctic. Inuit are disproportionately food insecure relative to the rest of Canada. Studies have reported food insecurity prevalence as high as 68.8% in Nunavut, 45.7% in Nunatsiavut, and 43.3% in the Inuvialuit Settlement Region (Rosol *et al.*, 2011), compared with the Canadian average of 9.2% (Canada, 2007). These high levels of food insecurity mean that fish, seafood, and other wild foods are especially important to the health and well-being of Inuit communities and that changes in fisheries productivity may have disproportionate effects on Arctic communities. In addition to increasing nutrition and food security (Lawn and Harvey, 2003; Kuhnlein and Receveur, 2007), hunting and fishing are an integral part of social cohesion, cultural identity, and well-being in Inuit communities. Coincidentally, it is in the Arctic that some of the most rapid warming and associated climate-driven changes are occurring. Climate change is already impacting the availability and distribution of wild plants and animals, a trend that is projected to continue over the coming century (Bryndum-Buchholz *et al.*, 2020; Molnár *et al.*, 2020), with unknown consequences for Inuit communities.

1.2 Economic

The fishing sector is also a major contributor to the Canadian economy, particularly across Atlantic Canada. Nationally, 300,000 Canadians are employed on or around the oceans, and ocean-reliant industries contribute over CAD $26B a year to the Canadian economy (Bailey *et al.*, 2016). Between 2017 and 2018, commercial fishing and aquaculture sectors provided an average of ~77,000 direct jobs (Figure 1.1), with fish and seafood exports worth CAD $6.9B in 2018 (DFO, 2018a). Harvesting accounts for 60% of employment, followed by processing (36%) and aquaculture (5%; Figure 1.1b). Aquaculture constitutes a larger fraction of total employment in BC, relative to most other provinces. Harvesting and processing of fisheries is the largest private sector employer in the AOS and is thus of disproportionate economic importance there. For example, when standardized by population, proportional employment in the fishing and aquaculture sectors was notably higher within Atlantic provinces such as Prince Edward Island (4.5%), Newfoundland and Labrador (3.3%), Nova Scotia (1.9%), and New Brunswick (1.8%), relative to others.

In 2018, the total landed volume of Canada's fisheries was 784,477 t (live weight), representing a landed value of ~CAD $3.7B (Table 1.1). Three-quarters (76%) of the total seafood landed in Canada came from within the AOS, representing 86% of the total value of fisheries (Table 1.2). Since 1990, the total landed volume of seafood in Canada has declined, a trend that was relatively consistent across provinces, except for Quebec, where the decline was less marked (Figure 1.2). Despite this, the value of landed fisheries has increased in most provinces except BC, where it has declined. The trend of increasing value despite declining volume has been driven by the expansion of invertebrate fisheries and their higher price per unit volume, relative to groundfish or pelagic fishes. For example, in 2018, invertebrate fisheries accounted for 48% of the total landings in Canada by volume but a disproportionate fraction (82%) of the total landed value (Table 1.2). These invertebrate fisheries are driven by lobster, shrimp, crab, and scallop. Lobster accounted for 50%, crab for 27%, shrimp for 13%, and scallop for 6% of the value of all landed invertebrates across the AOS in 2018. Greenland and Atlantic halibut are by far the most valuable groundfish in the AOS, accounting for 29% and 28% of the value of all landed groundfish in 2018 across the AOS, respectively. Atlantic herring represented the most valuable pelagic fishery in the AOS and accounted for 40% of the value of all landed pelagic species in the AOS in 2018.

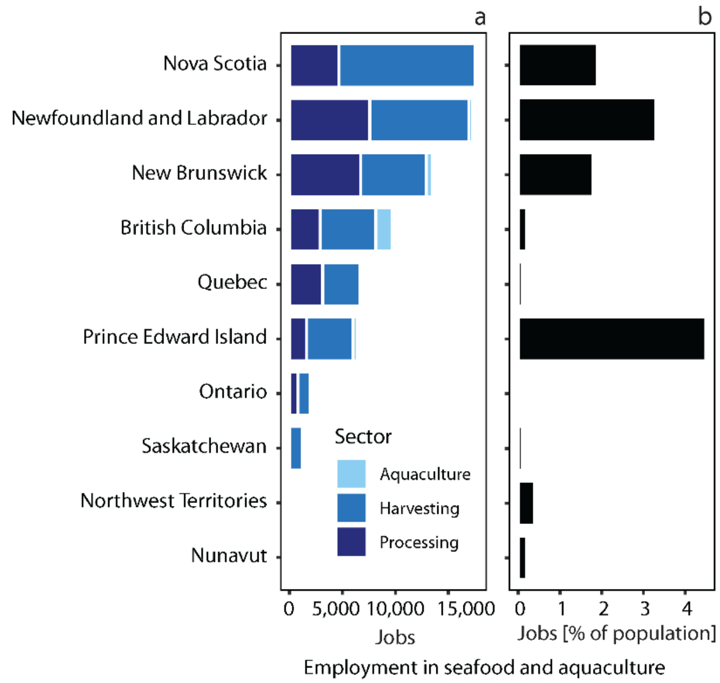

Figure 1.1 Employment in Canada's fisheries.
Annual direct employment (a) within Canada's fisheries and aquaculture sectors between 2017 and 2018 by province (b) and employment as a proportion of the population. (a) Colours depict employment in the seafood sector. Source: (DFO, 2020a)

Table 1.1 Landed value and volume of Canada's fisheries in 2018.
Landed values are in 000s of dollars, and volumes are in metric tonnes (t) by live weight. See the table for the proportions of the total of these values. Source: (DFO, 2020b)

Taxa	NS	*NB*	PEI	Quebec	NFLD	BC	Atlantic	Canada
Landed value (000 $CAD)								
Groundfish	78,751	1,443	646	12,710	112,030	204,763	205,581	410,344
Pelagics, other finfish	73,785	24,287	8,725	3,873	19,522	118,589	130,192	248,781
Shellfish	1,199,987	415,023	237,310	325,705	645,098	175,804	2,823,124	2,998,928
Total	1,352,524	440,754	246,682	342,288	776,650	499,155	3,158,897	3,658,053
Landed volume (t, live weight)								
Groundfish	39,837	151	70	2,694	44,000	141,487	86,752	228,239
Pelagics, other finfish	47,666	36,049	4,761	6,158	47,881	36,729	142,516	179,245
Shellfish	156,316	39,499	23,714	36,897	107,556	13,011	363,981	376,993
Total	243,818	75,700	28,545	45,749	199,437	191,227	593,249	784,477

Table 1.2 Proportional landed value and volume of Canada's fisheries in 2018.
The proportional contribution that the volumes and values of fisheries make to Canada's total. See the table for the raw values used to calculate the proportions. Source: (DFO, 2020b)

Taxa	NS	*NB*	PEI	Quebec	NFLD	BC	Atlantic
Landed value (% of total)							
Groundfish	19	0	0	3	27	50	50
Pelagics, other finfish	30	10	4	2	8	48	52
Shellfish	40	14	8	11	22	6	94
Total	37	12	7	9	21	14	86
Landed volume (% of total)							
Groundfish	17	0	0	1	19	62	38
Pelagics, other finfish	27	20	3	3	27	20	80
Shellfish	41	10	6	10	29	3	97
Total	31	10	4	6	25	24	76

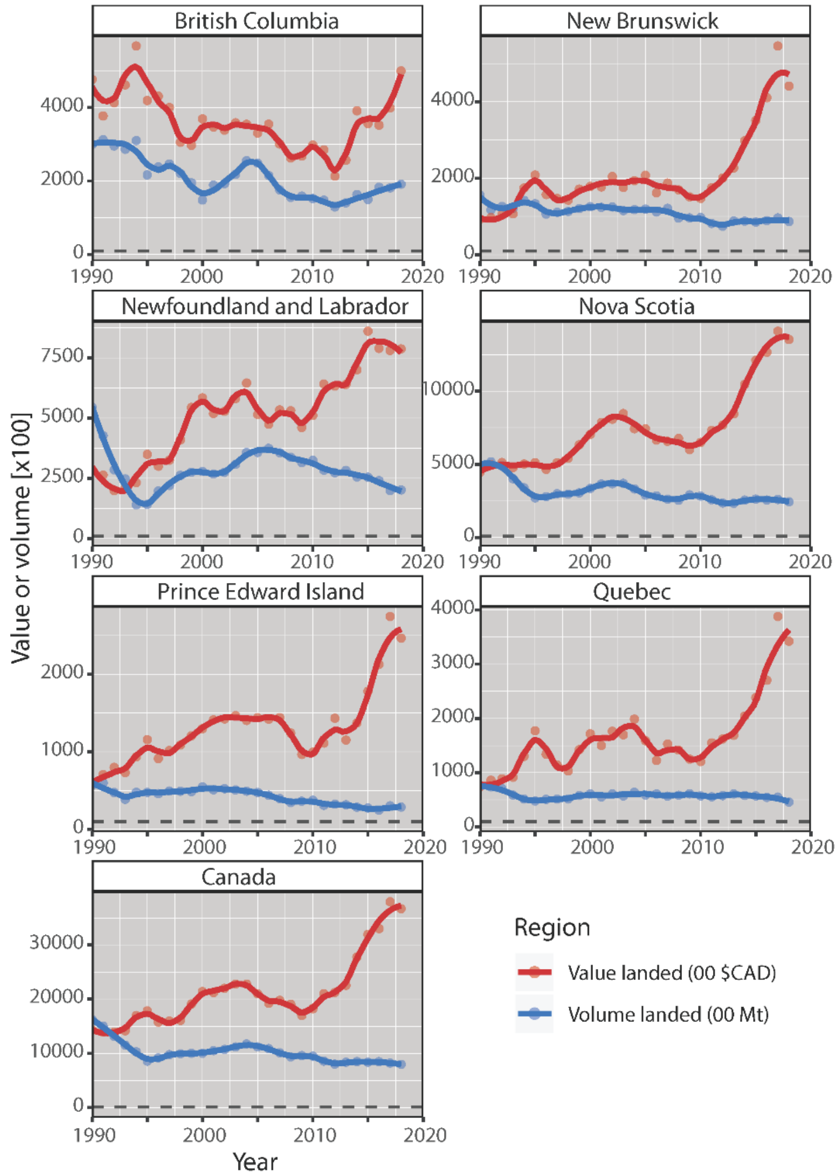

Figure 1.2 The landed volume and value of Canada's fisheries over time.

Points and lines depict the volume (00 t, live weight) and value (00 $CAD) of landed fisheries among provinces and nationally. Red is the landed value and blue the volume. Source: (DFO, 2020b)

The export value of fisheries is frequently higher than the landed values (Table 1.1) due to value-added processing. The fish and seafood sector is driven by exports, combined with agricultural products, and seafood was the fourth-largest Canadian export category in 2014. In 2018, 85% of Canadian seafood exports were destined for foreign markets, with 62% of Canada's landed fish, by value, destined for the United States (CAD $4.27B), 11% to China (CAD $1.17B), and 10% to the European Union (CAD $0.45B). In 2018, Canada's largest exports were lobster (CAD $2.2B), crab species (CAD $1.31B), salmon species (CAD $1.19B), shrimp (CAD $469M), scallop (CAD $163M), and herring (CAD $136M). Canada's most lucrative export species (e.g. lobster, crab, and shrimp/prawn) are driven by growing markets in China. The top exporting province in 2018 was Nova Scotia (CAD $2.03B).

Globally, Canada has dropped down the rankings of major seafood exporters. While Canada was the world's leading seafood exporter in 1987, by 2018 it had dropped to ninth place (FAO, 2020). This decline is driven by the collapse of the groundfish stocks and exports and by the increase in aquaculture production by nations such as Chile, Norway, and Thailand. Notwithstanding this trend, exports continue to be the largest market for Canadian seafood. In 2018, the total value of aquaculture in Canada was CAD $1.43B, representing 39% of the total value of landed fisheries. Since 2000, the total production of aquaculture has increased by a factor of 1.5, while total value has increased by a factor of 2.3[1]. Farmed salmon (family *Salmonidae*) account for the vast majority of Canada's total aquaculture production; in 2018, salmon constituted 64% of total aquaculture production and 78% of the total value.

In addition to the direct value of fisheries harvest and processing, healthy fisheries and ecosystems support a range of ocean-dependent activities. Healthy marine populations and ecosystems enhance the value provided by recreation and ecotourism operations such as sportfishing, wildlife watching, sea kayaking, and scuba diving. Further, healthy fisheries ensure that the livelihoods of fishers, processors, and other fisheries-dependent workers remain stable and profitable, benefiting entire communities.

The collapse of Atlantic cod (*Gadus morhua*) and other groundfish in Newfoundland (Northwest Atlantic Fisheries Organization [NAFO] Divisions 2J, 3K, 3L) provided a sobering real-world example of the economic and cultural importance of fisheries in the AOS and the potential consequences of suboptimal management (Frank *et al.*, 2005, 2011; Hutchings and Rangeley, 2011). From what was once the largest cod population in the world (Hutchings and Myers, 1993), cod biomass declined by more than 90% between 1962 and 1992, leading to the abrupt and prolonged closure of the directed fishery (Hutchings and Rangeley, 2011). Despite optimism that the fishery would rapidly reopen, the recovery has been slow, and the fishery has been closed for 28 years to date. The collapse and failed recovery led to a radically modified ecosystem and widespread economic effects. In what remains the largest layoff in Canadian history outside of the 2020 global pandemic, 35,000–40,000 people lost their source of livelihood (Hamilton and Butler, 2001; Hamilton *et al.*, 2004; Mather, 2013). The collapse has had a continued impact on the economy and demography of the region, with coastal communities in Newfoundland losing over 40% of their population (Palmer and Sinclair, 1997). In addition to the direct economic consequences of the cod fishery closure, there were additional costs associated with subsidizing the fishery throughout the 1980s when it was already in decline. Throughout the 1980s, the governments of Canada and Newfoundland invested nearly CAD $3B in the cod fishery, with the value of these investments commonly exceeding 40% of the total value of cod catch and production (Schrank *et al.*, 1995). The example of the cod illustrates how management approaches that neglect important drivers of population variability,

[1] https://www.dfo-mpo.gc.ca/stats/aqua/aqua-prod-eng.htm

particularly in the current era of accelerating climate change, can cause severe and long-lasting economic and cultural impacts.

1.3 Ecosystem functioning and service provision

In addition to the direct economic value of fisheries from landed catches, there are many less tangible but critically important services that healthy fisheries and ecosystems provide. Healthy, intact, biodiverse populations and ecosystems tend to be more biologically productive and dynamically stable, imbuing them with a greater ability to withstand stressors including, for instance, climate change, fishing, and pollution (Hilborn *et al.*, 2003; Worm *et al.*, 2006; Schindler *et al.*, 2010). Thus, the maintenance of healthy fisheries and ecosystems increases the likelihood that they will be resistant and resilient to disturbances and that their associated industries (e.g. fishing, tourism) will remain profitable. For example, by conducting a manipulative field experiment, Reusch *et al.* (2005) demonstrated that higher genetic diversity of the seagrass *Zostera marina* led to enhanced biomass production, plant density, and faunal abundance, despite near-lethal water temperatures due to extreme warming. The effects of genetic diversity were explained by complementarity and were found to have higher-order effects that were transmitted up the food web.

Furthermore, surveys from the Northern Line Islands have shown that uninhabited and unfished reefs show a greater capacity to resist and recover from major episodes of coral bleaching and disease, compared to those that are fished (Sandin *et al.*, 2008).

Overharvesting of predators, particularly large ones (a process known as trophic downgrading), can have cascading effects on ecosystems, leading to diverse and unanticipated impacts on, for instance, disease spread, invasive species, and biogeochemical cycling (Estes *et al.*, 2011). For example, in Alaska, predation by killer whales (*Orcinus orca*) has reduced the abundance of sea otters (*Enhydra lutris*), leading to overgrazing by urchins on kelp forests, leading to widespread and disproportionate effects throughout the ecosystems (Estes *et al.*, 1998; Steneck *et al.*, 2002). There are numerous examples where overharvesting has led to predator depletions and cascading ecosystem effects, altering ecosystem functioning and service provision (Frank *et al.*, 2005, 2011; Estes *et al.*, 2011).

Marine ecosystems also regulate the climate through their role as a major carbon (C) sink. The ocean has absorbed ~48% of all anthropogenic carbon emissions from 1800 to 1994 (Sabine *et al.*, 2004), with marine phytoplankton accounting for almost half of global net primary production (Field *et al.*, 1998). Coastal vegetated ecosystems such as salt marshes and seagrass meadows constitute the largest storage of C in the oceans and thus have disproportionately large roles in the global capture and storage of C (Donato *et al.*, 2011; Fourqurean *et al.*, 2012). There is also mounting evidence that preserving marine species and fisheries, particularly large-bodied predators, can significantly contribute to climate change mitigation through their direct and indirect influence on C cycling and sequestration (Atwood *et al.*, 2015). The biomass of all marine species is made up of carbon, and they thus serve as carbon reservoirs throughout their lifespans. Larger and more long-lived species, such as whales, sequester a greater amount of carbon for a longer duration. Upon death, the biomass within carcasses can be transported to the deep ocean, where they sustain deep-sea ecosystems and become sequestered over long time-scales in sediments. Marine predators can indirectly influence C cycling in ecosystems systems by modifying ecosystem structure, grazing rates, and ultimately primary producer and microbial dynamics. This is particularly true in coastal vegetated systems, which, despite their relatively small size, are among the largest C sinks in the oceans (Donato *et al.*, 2011; Fourqurean *et al.*, 2012). For instance, the abundance of tiger sharks (*Galeocerdo cuvier*) in a seagrass ecosystem in Australia induced shifts in the foraging behaviour of the dominant grazers such as dugongs (*Dugong dugon*) and green turtles (*Chelonia mydas*), affecting the biomass of seagrass beds and associated C stocks (Heithaus *et al.*, 2012). On Kiritimati Island, the reduction of predatory reef fishes through harvesting led to altered patterns of herbivory and reduced coral cover when compared to neighbouring Jarvis Island, which had no fishing, larger predator populations, and greater coral cover (Sandin *et al.*, 2008).

1.4 Key points

- Healthy and productive fisheries are integral to the economy, culture, and health of Canadians, particularly so in the Atlantic and Arctic regions.
- The fishing sector is a major contributor to the Canadian economy, particularly across Atlantic Canada. Three-quarters (76%) of the total seafood landed in Canada came from within the AOS, representing 86% of the total value of fisheries in Canada (Table 1.2).
- Fisheries provide coastal communities in Canada with an important source of cost-effective and high-quality protein, contributing to dietary health.
- Indigenous communities, particularly Inuit communities, are disproportionately food insecure relative to the rest of Canada. Food insecurity can be as high as 68.8% in Nunavut, 45.7% in Nunatsiavut, and 43.3% in the Inuvialuit Settlement Region (Rosol *et al.*, 2011), compared to the Canadian average of 9.2%.
- The volume of fisheries landings has been declining since 1990, while the value has been increasing. This pattern has been mostly driven by the expansion of invertebrate fisheries and the associated higher price per unit volume of invertebrate species, relative to groundfish or pelagic fishes. In 2018, invertebrate fisheries constituted 48% of the total landed fisheries by volume but 82% of the total landed value of all fisheries in Canada (Table 1.2).
- Fisheries in Canada are driven by exports. Canada has dropped in the global rankings of major seafood exporters. Canada was the world's leading seafood exporter in 1987. By 2018, it had dropped to ninth place (FAO, 2020). This decline is driven by the collapse of the groundfish stocks and exports and by the increase in aquaculture production by nations such as Chile, Norway, and Thailand.
- Sustainable fisheries can increase the health of marine ecosystems and populations and ensure that they continue to provide a wide range of critically important but less tangible services and benefits, such as nutrient cycling, climate regulation, tourism, and recreation.

2. Fisheries productivity in Atlantic Canada and the Eastern Canadian Arctic

2.1 The area of interest

At regional scales (Chassot *et al.*, 2007) and globally (Chassot *et al.*, 2010), marine fisheries yield is driven by the amount of primary production, 90% of which is generated by microscopic algae known as phytoplankton (Charpy-Roubaud and Sournia, 1990). In turn, phytoplankton growth and production are largely a function of the environmental conditions that drive mixing and upwelling, which in turn affect the amount of sunlight and nutrients (nitrate, phosphate, silicate) available in the upper ocean (Figure 2.1). The composition and size of the phytoplankton assemblages can also affect the flow of energy up the food web, with consequences for fisheries yield. In situations where phytoplankton assemblages comprise larger cells or species, primary production can be more rapidly and efficiently transferred up the food web, supporting a greater fraction of animal biomass (Boyce *et al.*, 2015a). Therefore, to fully understand fisheries dynamics and how factors such as climate change affect them, it is critical to also consider changes in plankton and biogeochemical conditions.

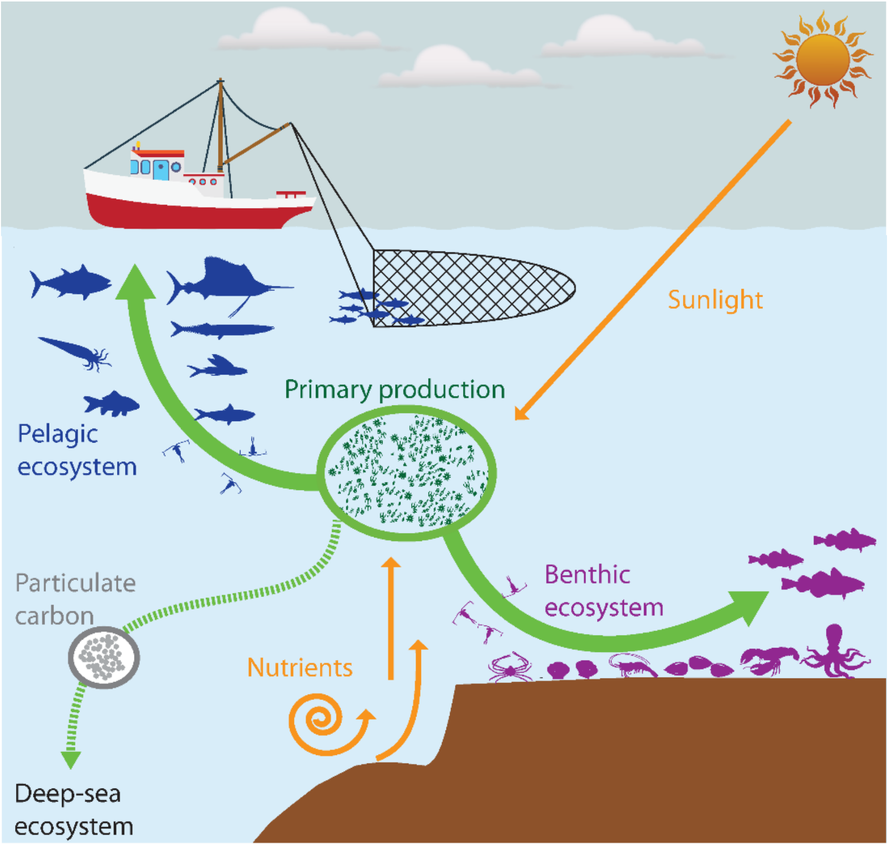

Figure 2.1 Primary production drives fisheries yield.
Fisheries biomass within pelagic (blue), benthic (purple), and deep-sea ecosystems is constrained by the amount of primary production generated by phytoplankton (green arrows), which is in turn driven by atmospheric and oceanographic factors (yellow arrows).

To explore fisheries dynamics in conjunction with the climatological and biogeographic factors that drive them, the focal area of this report was established in Atlantic Canada and the Eastern Canadian Arctic according to fisheries management units and bioregions. The geographic domain of the AOS was defined according to the NAFO management units within the Canadian exclusive economic zone (EEZ; subareas 0–4), and the four biogeographic regions defined by the Fisheries and Oceans Canada (DFO) that overlap with the NAFO units (Figure 2.2). The NAFO divisions enabled us to explore the dynamics of fisheries, while the bioregions enabled us to evaluate their relationship to biogeochemical characteristics. Accordingly, the environment, ecology, and fisheries management that are discussed throughout this document will primarily be focused on the Canadian AOS, although the dynamics of adjacent ecosystems (e.g. the Gulf of Maine) will also be explored.

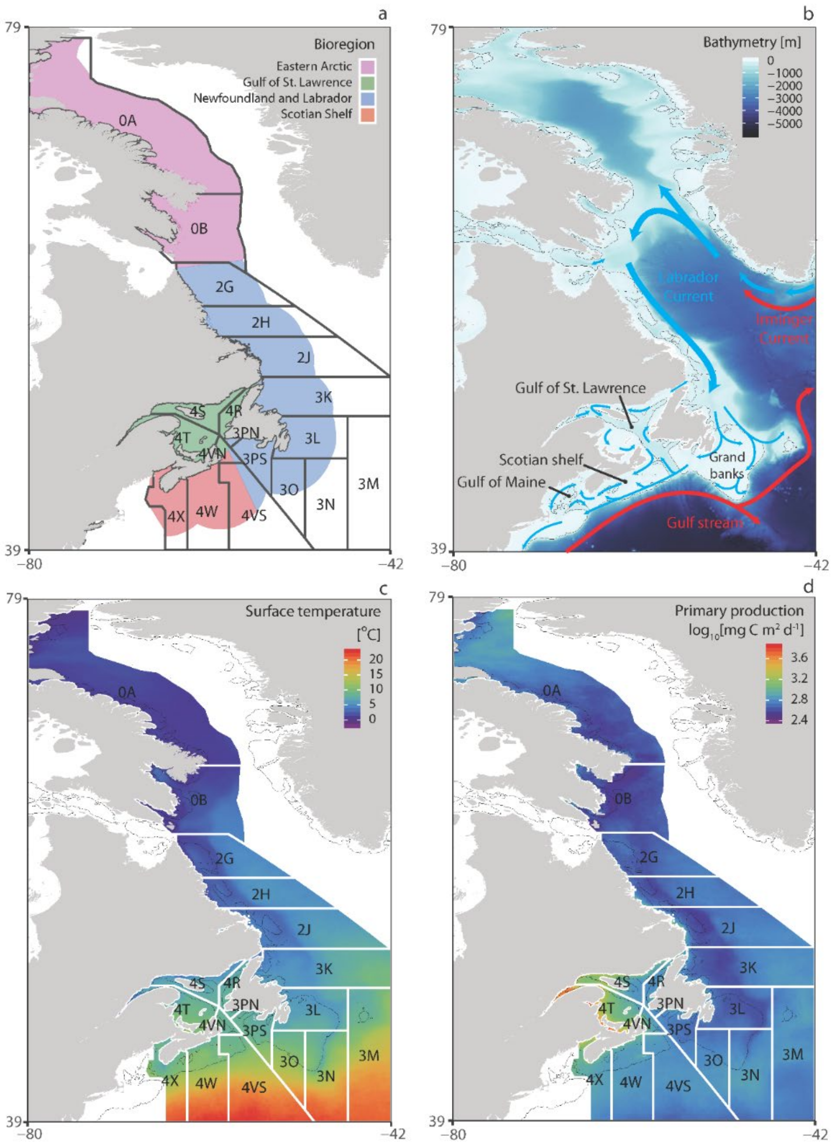

Figure 2.2 Biogeography of the area of interest.
(a) Colours depict the four biogeographic regions within the AOS with NAFO management divisions labelled. (b) Blue to white shading and contour lines show the bathymetry (m) across the AOS: dark blue depicts deeper and lighter shallower waters. The grey line is the 200 m isobath. The direction and temperature of the predominant surface currents are depicted as arrows: red depicts warm and blue cold currents. (c) Average annual surface temperature across the AOS: red depicts warmer and dark blue colder temperatures. (d) Average $\log_{10}$ annual primary production (mg C m^2 d^{-1}) across the AOS (2003–2012): red depicts higher and dark blue lower production. Details of the data sources for all maps are in Table 10.1.

2.2 Biogeographic overview

At the broadest scale, the biogeography of Canada's marine waters has been classified into 12 bioregions by DFO in the national framework for Canada's proposed network of marine protected areas (MPAs; DFO, 2009a). These bioregions are defined according to the geological, physical oceanographic, and biological properties that make them unique (Longhurst, 2007; Spalding *et al.*, 2007). Four of these bioregions overlap with our focal areas in Atlantic Canada and the Eastern Canadian Arctic: Eastern Arctic, Newfoundland-Labrador shelves, Scotian Shelf, and Gulf of St. Lawrence (Figure 2.12a). Collectively these four bioregions extend from 39°N to 78.1°N, a latitudinal range of 39.1°. The regions are subject to an exceptionally wide range of oceanographic conditions, including dynamic and complex tidal cycling and mixing (Figure 2.2b), large temperature variations (Figure 2.2c), strong and variable seasonal patterns of primary production (Figure 2.2d), and large terrestrial nutrient inputs via freshwater run-off. The continental shelves along the AOS are also extensive and contribute to the high productivity there. The Scotian Shelf extends up to 230 km offshore with an average depth of 90 m. In Newfoundland and Labrador, the coastal shelf extends roughly 150 km offshore, while the Grand Banks extends up to 480 km offshore, and the depth is between 25 m and 150 m deep.

The Gulf bioregion is commonly described as a semi-enclosed inland sea, with large freshwater inputs from the St. Lawrence River and warm Atlantic water in the deeper channels (Bernier *et al.*, 2018). The southern Gulf is dominated by warm shallow waters, which tend to be highly productive. In contrast, the northern Gulf is dominated by deeper channels, resulting in lower primary production (Bernier *et al.*, 2018). These large differences in primary production and bathymetry lead to distinct ecological communities in the north and south Gulf. Ice cover varies seasonally in the Gulf, with sea ice moving northward through the Labrador Current over the Newfoundland and Labrador shelves. The St. Lawrence estuary is dominated by colder freshwater outflow that tends to be well mixed, leading to higher primary productivity at the mouth of the river (Figure 2.2d).

South of the Gulf, the Scotian Shelf bioregion is primarily influenced by the mixing of the cold Labrador Current, cool outflowing currents from the Gulf of St. Lawrence, and the warm Gulf Stream (Figure 2.2b). This bioregion is seasonally ice-free; has higher species diversity, particularly at its southern extent; and has moderately high levels of primary production. The biogeographic structure of the shelf has been found to vary with the seasonal minimum bottom temperature and latitude, with ecological communities south of 44.6°N being distinct from those to the north (Stanley *et al.*, 2018).

To the north, the Newfoundland and Labrador bioregion is strongly influenced by the cool southward-flowing Labrador Current. As it flows southward along the Labrador shelves, it meets with the warm northeast-flowing Gulf Stream current, the two mixing to produce high primary production and productive fishing grounds (Figure 2.2b, d). Seasonal ice cover can be significant in this bioregion, particularly on the Labrador shelves, where the ice-free period can be as short as six months (June to November).

North of the Labrador shelf, the Eastern Arctic bioregion is defined by seasonal ice cover throughout much of the year and strong seasonal cycles of primary production. The seasonal cycle of primary production is characterized by a unimodal, high-amplitude peak in primary production in the summer when day length is long (>20 hours) and vanishingly low levels of production in winter when day length is short (<4 hours) and ice cover is extensive. Sea ice is a defining feature of Arctic marine ecosystems and the communities that rely on them. Sea ice provides habitat that is required for species to reproduce, hunt, and migrate and affects primary production rates, wave activity, and coastal erosion (Niemi *et al.*, 2019). The type, thickness, and extent of sea ice can have overarching effects on marine ecosystems and can affect climate and weather patterns.

Collectively, the extensive shelf areas and complex hydrodynamics and biogeography across these four bioregions create the local conditions that support the productivity of fisheries (Figure 2.2). This is seen in the emergent positive relationships that have been reported between primary production and fisheries yield across European seas (Chassot *et al.*, 2007) and globally (Chassot *et al.*, 2010). A similar positive relationship (r=0.61) is present across the AOS (Figure 2.3) and provides a useful foundation for understanding the effects of climate on fisheries.

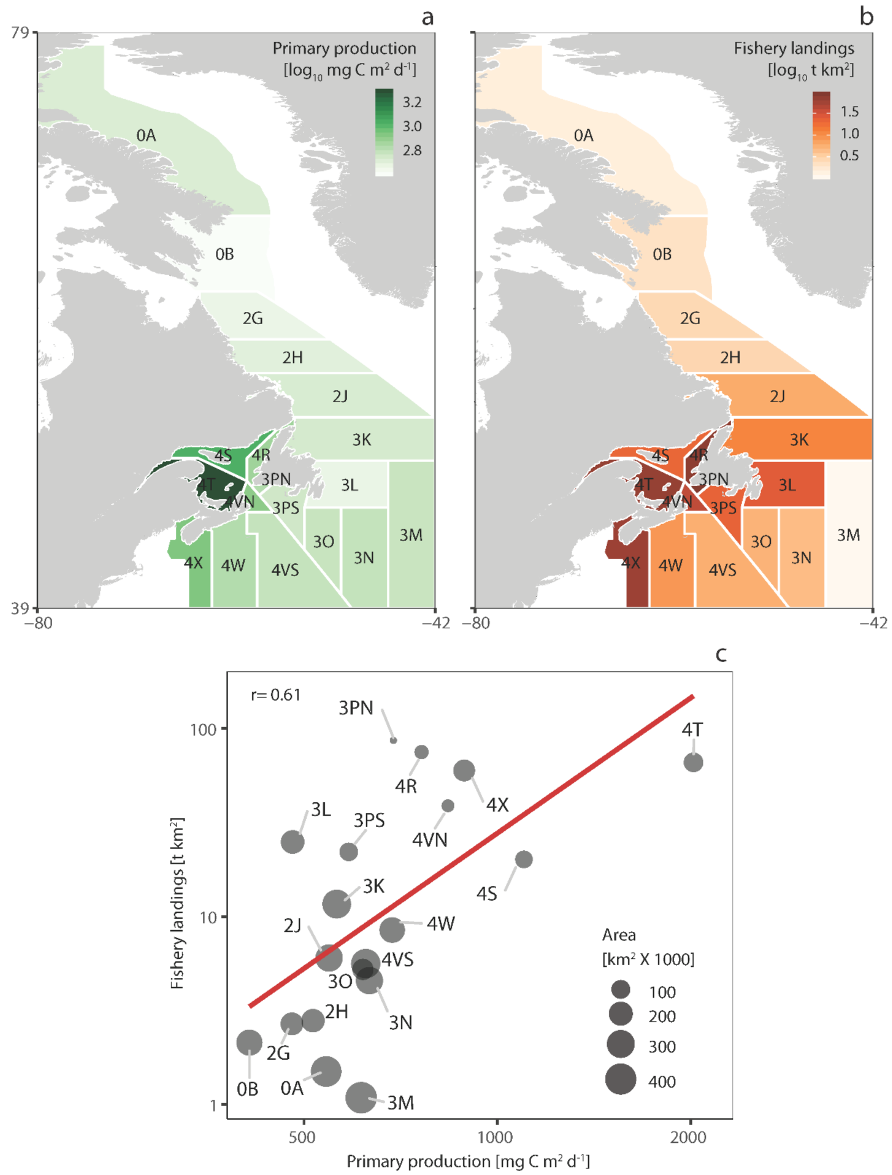

Figure 2.3 Fisheries are constrained by primary production.
(a) Colour depicts the log_{10} average primary production (2003–2012) across NAFO management divisions; dark green depicts high and light green low primary production. (b) Colour depicts the log_{10} total fisheries yield (1970–2018) within each NAFO management division per standardized unit area (km^2); dark red depicts high and light red low fishery landings. (c) Log_{10} relationship between average primary production and fish landed across NAFO divisions. The size of the points depicts the size (km^2) of each division. Data sources are listed in Table 10.1

2.3 Key points

- Marine fisheries yield is driven by the amount of primary production, which is a function of the environmental conditions that affect the amount of sunlight and nutrients (nitrate, phosphate, silicate) available in the upper ocean, such as mixing, upwelling, and the associated physical processes that affect them, such as temperature, wind, and ocean currents (Figure 2.1).
- A focal area was established in Atlantic Canada and the Eastern Canadian Arctic according to fisheries management units and bioregion to explore fisheries dynamics in conjunction with the climatological and biogeographic factors that drive them (Figure 2.2a).
- Collectively, AOS extends from 39°N to 78.1°N and is subject to an exceptionally wide range of oceanographic conditions, including dynamic and complex tidal cycling and mixing (Figure 2.2b), large temperature variations (Figure 2.2c), strong and variable seasonal patterns of primary production (Figure 2.2d), and large terrestrial nutrient inputs via freshwater run-off.

3. Fisheries: status, significant species, and trends

3.1 Overview

Over the past decade, several studies have reviewed the status of Canada's fisheries from different perspectives and made recommendations for improvement (Hutchings *et al.*, 2012; Bailey *et al.*, 2016; Baum and Fuller, 2016). A 2012 report by the Royal Society of Canada Expert Panel, *Sustaining Canadian Marine Biodiversity: Responding to the Challenges Posed by Climate Change, Fisheries, and Aquaculture*, assessed the status of Canada's fisheries management. The report concluded that the status of Canada's marine fish stocks is among the worst in the world and that when compared with similar industrialized nations, Canada was lagging in the incorporation of ecosystem indicators into scientific guidance (Côté *et al.*, 2012). The study presented a multispecies abundance index derived from 40 population of commercial fishes, which suggested that Canadian fish populations collectively have declined by 52% between 1970 and 2006. The analysis also reported that 28 of the 29 populations for which estimates were available were below biomass removals to achieve maximum sustainable yield (BMSY).

In 2016, Oceana produced a report evaluating the status and recovery potential for Canada's fisheries and had undertaken annual audits of the Canadian fishery from 2017 to 2020. The 2016 report highlighted Canada's relatively strong legal and policy instruments for fisheries management but also concluded that it had largely failed to effectively use these instruments to prevent overfishing and ensure recovery. The report implicated a long-standing lack of political will in using the existing management tools as a causal factor for the collapses and failed recoveries of many of Canada's fisheries. The 2019 Oceana audit of Canada's fisheries reviewed the status of 194 fish stocks and reported that 17% (n = 33) were in a critical state, 29% (n = 57) were healthy, but most (38%; n = 74) had insufficient information to assess their status. While ten stocks were at greater risk in 2019 relative to 2018, only two were at reduced risk. The report also stated that only 46% of stocks have upper stock reference points that are required for the establishment of stock rebuilding plans, and that only 18% of critical stocks had rebuilding plans in place. Also, in 2016, Bailey *et al.* (2016) reviewed the policy and management of Canada's ocean resources and concluded that it had deviated substantially from marine science. The study found that the capacity of the Canadian government to undertake and communicate ocean science had deteriorated, a situation that poses a serious threat to oceans public policy in Canada. This study and others have highlighted the strong fisheries and oceans law and policy tools but also the long-standing lack of political will to implement them, which have critical consequences for the status of Canadian fisheries (Hutchings *et al.*, 2012; Bailey *et al.*, 2016; Baum and Fuller, 2016).

Collectively, these existing reports have described in detail the declining status of many of Canada's fisheries, identified contributing factors, and suggested approaches to improving their health. This chapter builds on these reports and uses the most up-to-date data to summarize the major fisheries in the AOS and evaluate their current status. This was achieved through the use of officially reported NAFO fishery landings, DFO stock assessments from the RAM Legacy Stock Assessment Database (Ricard *et al.*, 2012; RAM

Legacy Stock Assessment Database, 2018), Committee on the Status of Endangered Wildlife in Canada status reports, and the DFO Sustainability Survey for Fisheries.

3.1.1 Major species

The NAFO landings database contains recorded fishery landings for all commercially harvested marine species within the NAFO regulatory areas since the 1960s. Since 1970, Atlantic herring and cod have together accounted for 44% of all fishery landings in the AOS (Figure 3.1). Additional important commercially harvested species include groundfish predators such as redfishes, American plaice, Greenland halibut, pollock, and haddock; forage species such as mackerel and capelin; and invertebrates such as queen crab, northern prawn, American lobster, and sea scallop. On a species-by-area basis, the largest landings have been of Atlantic herring in Division 4VWX (the western Scotian Shelf and Bay of Fundy), a stock that is under a rebuilding plan (DFO. and DFO, 2015; Boyce *et al.*, 2019).

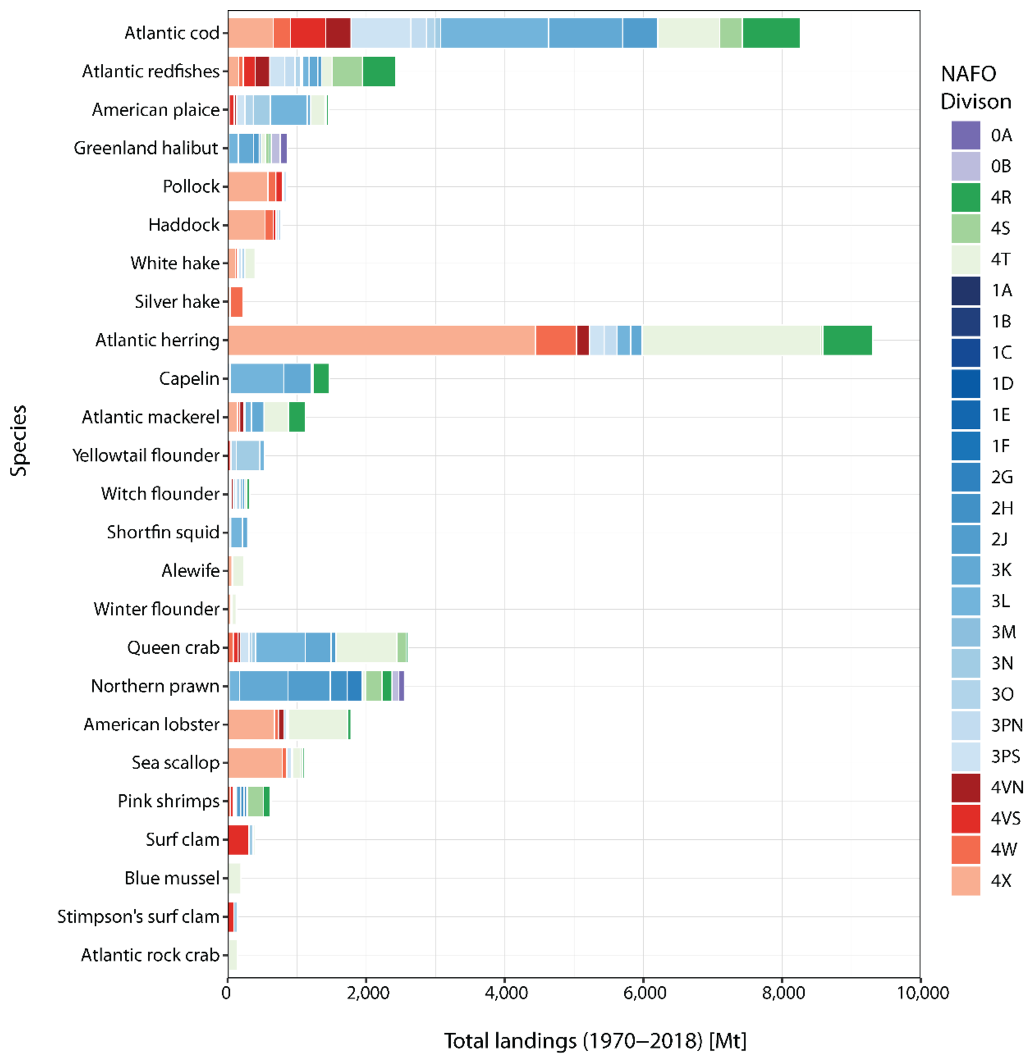

Figure 3.1 Officially reported commercial landings by species, bioregion, and NAFO division. Shaded bars depict the total reported commercial landings of the 25 top species by NAFO division (indicated by colour) between 1970 and 2018. Purple = Eastern Arctic, green = Gulf of St. Lawrence, blue = Newfoundland and Labrador, and orange = Scotian Shelf and Bay of Fundy. Species on the *y*-axis are organized by trophic level (T.L.), with high T.L. species in the upper axis and low T.L. species on the lower. Data sources are listed in Table 10.1.

The abundance and socio-economic importance of these species have also shifted over time. Large groundfish species such as Atlantic cod accounted for the majority of all landings before several populations collapsed in the early 1990s, leading to fisheries closures (Figure 3.2). The decline of Atlantic cod was particularly drastic, with the reduction of 2 million tonnes between 1960 and 1990 estimated to have been the greatest decline of any vertebrate in Canadian history (Hutchings and Rangeley, 2011), and from which it has yet to recover. Since the groundfish decline in the early 1990s, forage fishes and particularly invertebrates became of greater importance and constituted the majority of all fishery landings. Invertebrates now make up 65% of Atlantic Canadian fisheries landings, with lobster, shrimp, crab, and scallop being the most valuable (Baum and Fuller, 2016). Groundfish now account for only 12% of landings, with Greenland halibut (turbot) being Atlantic Canada's most lucrative groundfish fishery. Despite the documented overfishing of groundfish, in particular, the cumulative value of Canadian fisheries is at a record high due to the high value of the invertebrate fisheries (Baum and Fuller, 2016). For example, in 2018, invertebrate fisheries accounted for 48% of the total landings in Canada by volume, but 82% of the total landed value (Table 1.2), of which half was lobster. The disproportionate value of a few invertebrate species (e.g. lobster) could render the economic productivity fisheries in the AOS more vulnerable and less resilient to climate or ecosystem disruptions (Steneck *et al.*, 2011). However, it has been hypothesized that the marine ecosystems in the AOS are transitioning back to their pre-1990s state, in which groundfish was the focus of the fishery, with forage species and invertebrates being of lesser importance (Frank *et al.*, 2011).

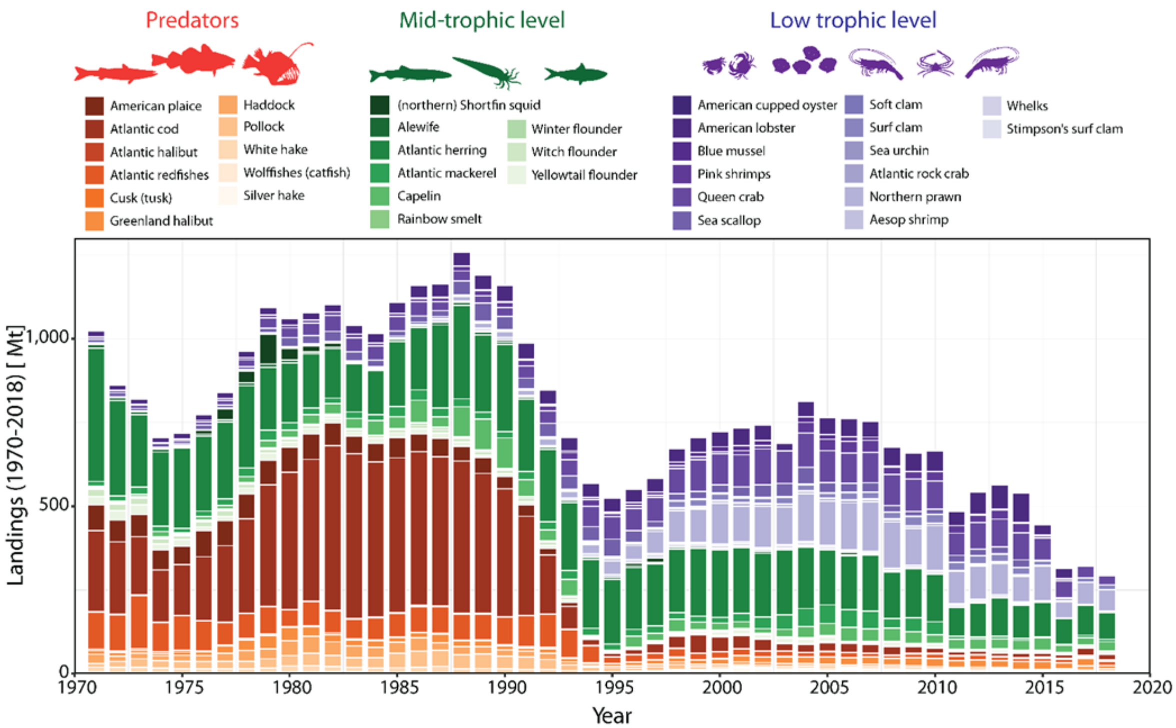

Figure 3.2 Officially reported commercial landings by species, functional group and year across the AOS.

Shaded bars depict the total reported commercial landings of the 35 top species by their functional group (indicated by colour) between 1970 and 2018. Orange depicts high trophic level (T.L.), green mid-T.L., and purple low T.L. species. Data sources are listed in Table 10.1.

3.1.2 Stock assessments

Fisheries assessments often represent the most detailed evaluations of the population dynamics of exploited marine species on which management decisions are made. Population models are typically applied to the most up-to-date data available to estimate time trends in the abundance and/or biomass of reproductive adults as well as recruitment rates and other key population parameters. Such assessments are data intensive and require information on fisheries landings as well as biological information on growth, maturity, mortality, size and demography, and stock-recruitment relationships (Hilborn and Walters, 1992). Time trends in abundance or biomass or commercially exploited marine fish and invertebrates within the AOS were explored using the RAM Legacy Stock Assessment Database (RAM database, described in Ricard *et al.* (2012)). The RAM database is a global open-source compilation of 1372 stock assessments. From the full database, 84 stocks were identified that were within the AOS and 47 that also contained time-series of abundance (spawning stock biomass [SSB], total biomass, or numbers; Table 3.1). The majority of the 47 assessments were available in the Scotian Shelf bioregion (62%), with fewer available in the Gulf (25%) or Newfoundland and Labrador (13%) regions. There were a greater number of high trophic level species that were assessed (15), relative to medium (2) or low (3) trophic levels. Despite this, the total number of stock assessments was actually less for high (26%) than for medium (38%) or low trophic level species (37%). Most of the 47 assessments contained estimates of fisheries landings (73%) with lower proportions containing time-series of SSB (33%), numbers (31%), total biomass (41%), recruitment (29%), or fishing (20%).

Table 3.1 Stock assessments across the AOS.

Inventory of stock assessments and associated time-series availability for species within the RAM database and across the AOS. Checks (✓) identify stocks where time-series are available and dashes (-) where they are not. For regions, S.S.: Scotian Shelf, NL: Newfoundland and Labrador, GSL: Gulf of St. Lawrence. The year denotes the most recent year of data in the assessment within the RAM database. SSB: spawning stock biomass, TB: Total biomass, TN: Abundance, R: Recruitment, F: Fishing mortality, T.C.: Total catch, T.L.: Total landings. Totals are the number of stocks that contain time-series. Data source is listed in Table 10.1.

Species	Trophic	Region	Year	Stock ID	SSB	TB	TN	R	F	TC	T.L.
Atlantic halibut	High	S.S.	2014	ATHAL3NOPs4VWX5Zc	✓	✓	✓	✓	✓	-	✓
Atlantic cod	High	NL	2014	COD3Ps	-		✓	-	-	✓	✓
Atlantic cod	High	GSL	2015	COD4TVn	✓	✓	✓	-	✓	-	✓
Atlantic cod	High	S.S.	2014	COD2J3KL	✓	✓	✓	✓	-	✓	✓
Atlantic cod	High	S.S.	2015	COD3Pn4RS	✓	✓	✓	✓	✓	-	✓
Atlantic cod	High	S.S.	2002	COD4VsW	✓	-	-	-	-	✓	-
Atlantic cod	High	S.S.	2009	COD4X5Yb	✓	-	✓	-	✓	-	✓
Atlantic cod	High	S.S.	2015	COD5Zjm	✓	-	✓	✓	✓	✓	✓
Greenland halibut	High	GSL	2015	GHAL4RST	✓	✓	✓	-	✓	-	✓
Haddock	High	S.S.	2014	HAD4X5Y	✓	✓	-	-	-	✓	✓
Monkfish	High	S.S.	2000	MONK2J3KLNOPs	-	✓	-	-	-	-	✓
Pollock	High	NL	2013	POLL3Ps	-	-	-	-	-	-	✓
Pollock	High	S.S.	2011	POLL4VWX	-	-	-	-	-	-	✓
Porbeagle shark	High	S.S.	2014	PORSHARATL	✓	-	✓	✓	-	✓	✓

Deep-water redfish	High	S.S.	2010	REDDEEP2J3K-3LNO	-	✓	-	-	-	✓	-
Deep-water redfish	High	S.S.	2010	REDDEEPUT12	-	✓	-	-	-	✓	-
Spiny dogfish	High	S.S.	2013	SDOG4VWX5	✓	-	✓	-	-	✓	-
Silver hake	High	S.S.	2015	SHAKE4VWX	-	✓	-	✓	✓	-	✓
Thorny skate	High	GSL	2010	TSKA4T	-	-	-	-	-	✓	✓
White hake	High	GSL	2013	WHAKE4T	✓	✓	✓	✓	✓	-	✓
White hake	High	S.S.	2013	WHAKE4RS	-	-	-	-	-	-	✓
White hake	High	S.S.	2005	WHAKE4VWX5	-	-	-	-	-	-	✓
Acadian redfish	Med	NL	2010	ACADRED2J3K	-	✓	-	-	-	✓	-
Acadian redfish	Med	NL	2010	ACADRED3LNO-UT12	-	✓	-	-	-	✓	-
Acadian redfish	Med	NL	2010	ACADREDUT3	-	✓	-	-	-	✓	-
American plaice	Med	NL	2012	AMPL23K	✓	✓	✓	✓	-	✓	✓
American plaice	Med	NL	2013	AMPL3Ps	-	✓	✓	✓	-	✓	✓
American plaice	Med	GSL	2012	AMPL4T	✓	-	✓	✓	-	✓	-
American plaice	Med	S.S.	2010	AMPL4VWX	✓	-	-	-	-	-	✓
Capelin	Med	GSL	2012	CAPE4RST	-	-	-	-	-	-	✓
Cusk	Med	S.S.	2007	CUSK4X	-	✓	-	-	-	-	-
Herring	Med	GSL	2003	HERR4RFA	✓	-	-	✓	✓	✓	-
Herring	Med	GSL	2004	HERR4RSP	✓	✓	-	✓	✓	✓	-
Herring	Med	GSL	2014	HERR4TFA	✓	✓	✓	✓	✓	✓	-
Herring	Med	GSL	2014	HERR4TSP	✓	✓	✓	✓	✓	✓	-
Herring	Med	S.S.	2010	HERR4S	-	-	-	-	-	✓	-
Herring	Med	S.S.	2012	HERR4VWX	✓	✓	✓	✓	✓	-	✓
Herring	Med	S.S.	2014	HERRNFLDESC	-	-	-	-	-	-	✓
American lobster	Med	GSL	2011	LOBSTERLFA23-26AB	-	-	-	-	-	-	✓
American lobster	Med	S.S.	2011	LOBSTERLFA15-18	-	-	-	-	-	-	✓
American lobster	Med	S.S.	2011	LOBSTERLFA19-21	-	-	-	-	-	-	✓
American lobster	Med	S.S.	2011	LOBSTERLFA22	-	-	-	-	-	-	✓
American lobster	Med	S.S.	2010	LOBSTERLFA27-33	-	-	-	-	-	-	✓
American lobster	Med	S.S.	2012	LOBSTERLFA3-14	-	-	-	-	-	-	✓
American lobster	Med	S.S.	2012	LOBSTERLFA34	-	-	-	-	-	-	✓
American lobster	Med	S.S.	2012	LOBSTERLFA35-38	-	-	-	-	-	-	✓
American lobster	Med	S.S.	2011	LOBSTERLFA41	-	-	-	-	-	-	✓
Mackerel	Med	SS-NL	2014	MACKNWATLSA3-4	✓	✓	-	✓	✓	-	✓
Redfish species	Med	S.S.	2000	REDFISHSPP3Pn4RSTVn	-	-	-	-	-	-	✓
Smooth skate	Med	NL	2012	SMOOTHSKA2J3K	-	-	-	-	-	✓	-

Smooth skate	Med	GSL	2010	SMOOTHSKA4T	-	-	-	-	-	✓	✓
Winter flounder	Med	GSL	2012	WINFLOUN4T	✓	-	✓	✓	✓	✓	✓
Witch flounder	Med	NL	2013	WITFLOUN3Ps	-	-	-	-	-	-	✓
Witch flounder	Med	GSL	2011	WITFLOUN4RST	✓	-	-	-	-	-	✓
Arctic surfclam	Low	GSL	2014	ARCSURF4RST	-	-	-	-	-	-	✓
Arctic surfclam	Low	SS	2010	ARCSURFBANQ	-	-	-	-	-	✓	-
Arctic surfclam	Low	SS	2010	ARCSURFGB	-	-	-	-	-	-	✓
Arctic surfclam	Low	SS	2011	ARCSURFQCW	-	-	-	-	-	-	✓
Green sea urchin	Low	GSL	2011	GURCH4RST	-	-	-	-	-	-	✓
Northern shrimp	Low	GSL	2012	PANDAL4RST	-	✓	-	-	✓	✓	✓
Northern shrimp	Low	S.S.	2012	PANDALSFA13-15	✓	✓	-	-	-	✓	-
Northern shrimp	Low	S.S.	2015	PANDALSFA2-3	✓	✓	-	-	-	✓	-
Northern shrimp	Low	S.S.	2012	PANDALSFA4	✓	✓	✓	✓	-	✓	-
Northern shrimp	Low	S.S.	2012	PANDALSFA5	✓	✓	✓	✓	-	✓	-
Northern shrimp	Low	S.S.	2012	PANDALSFA6	✓	✓	✓	✓	-	✓	-
Rock crab	Low	GSL	2010	ROCKCRABLFA23-26	-	-	-	-	-	-	✓
Rock crab	Low	S.S.	2012	ROCKCRABQCW	-	-	-	-	-	-	✓
Sea scallop	Low	NL	2010	SCALL3Ps	-	-	-	-	-	-	✓
Sea scallop	Low	GSL	2014	SCALL4T	-	-	-	-	-	-	✓
Sea scallop	Low	S.S.	2014	SCALLGB	-	✓	-	✓	-	-	✓
Sea scallop	Low	S.S.	2011	SCALLNBB	-	✓	-	-	-	✓	-
Sea scallop	Low	S.S.	2012	SCALLSFA16-20	-	-	-	-	-	-	✓
Sea scallop	Low	S.S.	2010	SCALLSPA1-6	-	-	-	-	-	-	✓
Sea scallop	Low	S.S.	2011	SCALLWSFA29	-	-	-	-	✓	-	✓
Snow crab	Low	NL	2013	SNOWCRAB3Ps	-	✓	✓	✓	-	-	✓
Snow crab	Low	GSL	2014	SNOWCRABSGSL	-	✓	-	✓	-	-	✓
Snow crab	Low	S.S.	2013	SNOWCRAB2HJ	-	-	✓	-	-	-	✓
Snow crab	Low	S.S.	2013	SNOWCRAB3K	-	✓	✓	✓	-	-	✓
Snow crab	Low	S.S.	2013	SNOWCRAB3LNO	-	-	✓	-	-	-	✓
Snow crab	Low	S.S.	2013	SNOWCRAB4R3Pn	-	-	✓	-	-	-	✓
Snow crab	Low	S.S.	2011	SNOWCRABSCMA12-17	-	-	-	-	-	-	✓
Softshell clam	Low	SS	2010	SSCLAMQCW	-	-	-	-	-	-	✓
Aesop shrimp	Low	S.S.	2010	STRSHRIMPSFA2-3	-	-	-	-	-	✓	-
Waved whelk	Low	S.S.	2011	WWHELKQCW	-	-	-	-	-	-	✓
				Total	**28**	**35**	**26**	**25**	**17**	**33**	**62**

To compare time-series of abundance that were available in different units, each of the 47 time-series of stock abundance was standardized to common units of percentage of the series maximum (%). Trends in population abundance for different species across the AOS were variable, with many stocks exhibiting large and/or frequent fluctuations in abundance over time (Figure 3.3). For each individual stock, the total standardized change in abundance over the series length was estimated using linear models. For each species, the average of these estimated changes was calculated across all stocks (all regions). This approach yields approximate, but not exact, estimates of the magnitude of abundance change over time for each stock and species, as neither the nonlinearity of many trends nor the temporal autocorrelation in the series was accounted for, both of which could affect the magnitude and statistical significance of the time trends (Pyper and Peterman, 1998). Notwithstanding the fluctuations in abundance for many series, declining abundance trends were apparent for most large predator species, including American plaice (−63%), Atlantic cod (−46%), cusk (−86%), deep-water redfish (−35%), Greenland halibut (−92%), porbeagle shark (−56%), spiny dogfish (−45%), white hake (−95), winter flounder (−39%) and witch flounder (−76). Likewise, increasing trends were evident for low trophic level species, including northern shrimp (41%) and sea scallop (35%), despite the short length of their abundance time-series.

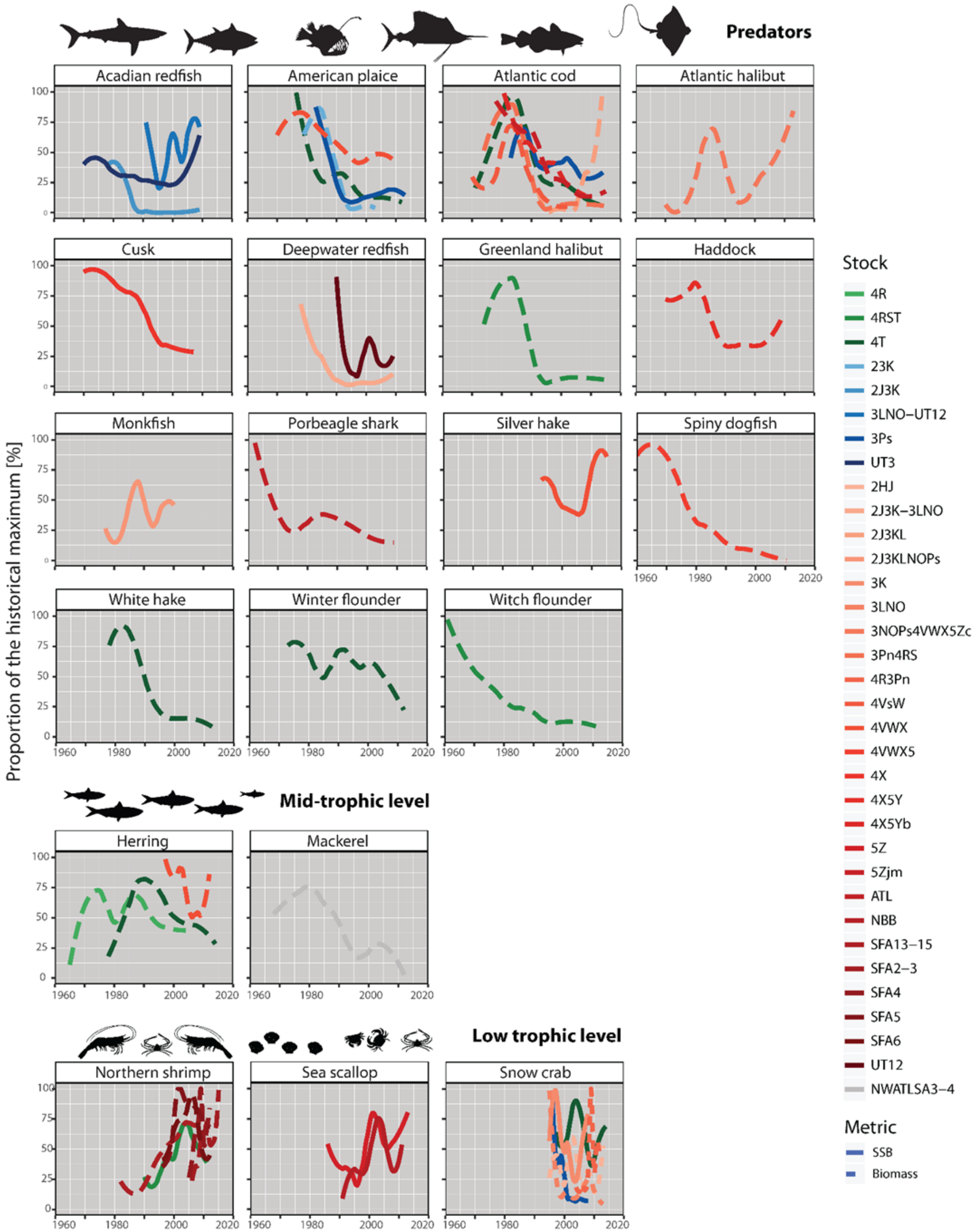

Figure 3.3 Stock assessment time trends within the AOS.

Time trends in estimated SSB (solid lines) and biomass (dashed lines) for all exploited species within the RAM stock assessment database located within the AOS. The bioregion and geographic identifier of the stocks are depicted in colours: Purple = Eastern Arctic, green = Gulf of St. Lawrence, blue = Newfoundland and Labrador, and orange = Scotian Shelf and Bay of Fundy. All time-series were standardized to units of percentage (%) of the time-series maximum. Lines are estimated from loess models (span = 0.25). Data sources are listed in Table 10.1.

3.1.3 Sustainability survey for fisheries

The Sustainability Survey for Fisheries is conducted annually as part of the DFO Sustainable Fisheries Framework. Upon completion of the fishing season, DFO scientists and managers complete the survey for the stocks in their regions, and the results are made publicly available. The 2018 survey was used, which is the most recent available and contains information for 179 Canadian stocks that were selected based on their economic, ecological, and cultural importance. The stocks are aggregated into seven species groups and seven geographic regions. The status of each stock is assigned to one of four categories by placing the estimated stock biomass level within the precautionary approach framework (DFO, 2009b). Stocks are classified as critical, cautious, healthy, or uncertain. A stock is categorized as critical if its mature biomass is less than the limit reference point (LRP), which is 40% of the BMSY. A stock is classified as cautious if its mature biomass is higher than the LRP but lower than the upper stock limit (USL), which is 80% of BMSY. A stock is classified as healthy if its mature biomass is above the USL. Two stocks that were freshwater species were removed, yielding 177 stocks.

Nationally, 113 of the 177 (64%) marine stocks were inside the AOS. Of these, almost half (44%) were classified as uncertain, 22% as cautious/critical, and only 34% as healthy. For stocks outside the AOS, the proportions of cautious/critical and healthy stocks were similar (28 and 38%, respectively), but the uncertainty in stock status tended to be lower (34%) than those in the AOS (44%). Removing marine mammals from the analysis (n = 19) yielded similar results, with the proportion of healthy stocks increasing (43%) and the proportion of uncertain stocks declining (27%) outside the AOS.

There was considerable regional variability in the status of the stocks within the AOS (Figure 3.4a). Only 15% of the populations in the Gulf region were healthy, whereas 69% were categorized as cautious or critical. Two regions in the AOS, Newfoundland and Labrador and the Eastern Arctic, had the most negative outcomes, with generally low proportions of healthy stocks (19–25%) and high degrees of uncertainty (58–75%). Of the four regions within the AOS, stocks within the Maritimes had the best outcomes, with 55% of stocks classified as healthy, and a relatively low degree of uncertainty (23%).

Within the AOS, there was also considerable variability in population status across species groups (Figure 3.4b). The proportion of stocks classified as healthy was generally low (0–58%), and uncertainty was medium to high (31–100%). Groundfish, small pelagic species, and salmonids, constituting most of the marine fishes, had a low proportion of healthy populations (0–28%), a higher proportion of cautious/critical stocks (33–46%), and a mid-to-high degree of uncertainty (31–67%). Stocks of crustaceans and molluscs, constituting the invertebrates, along with large pelagic species, were generally healthier (50–58%). Stock status was uncertain for most species groups but was especially so for marine mammals, for which three-quarters (73%) were classified as uncertain.

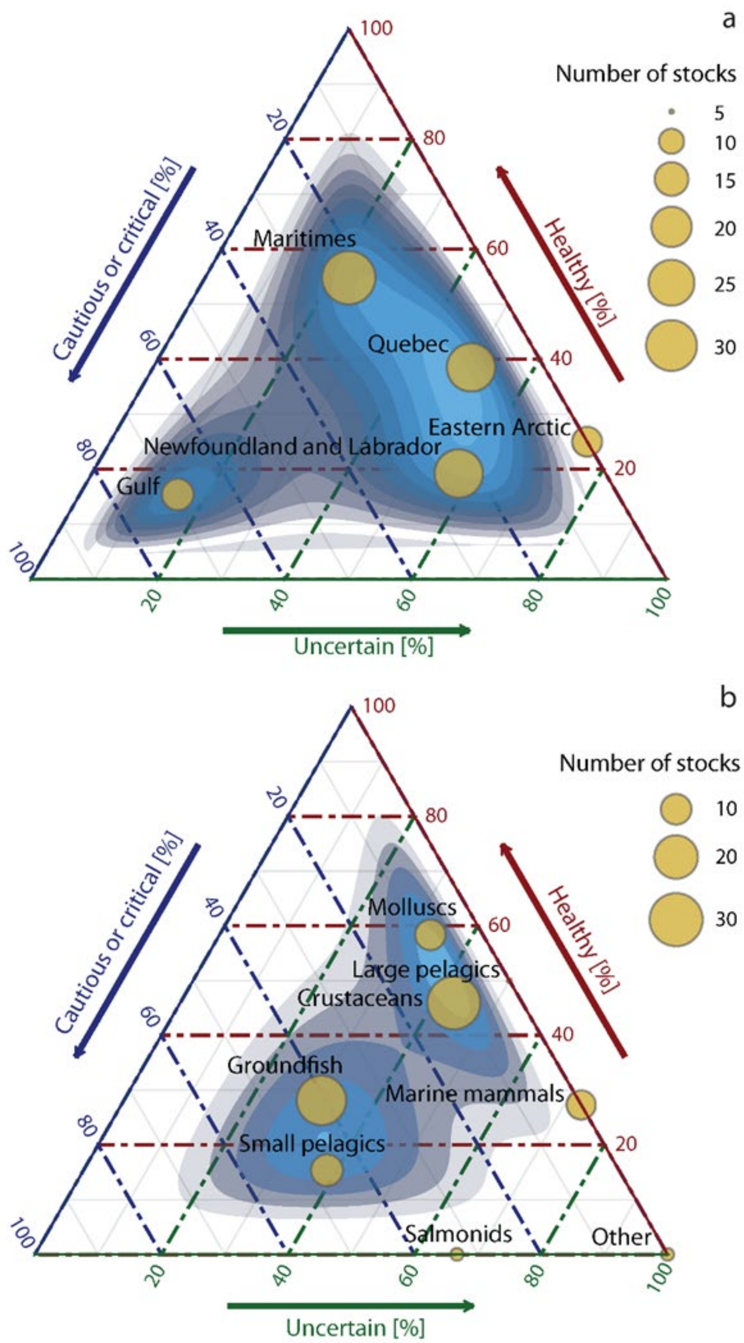

Figure 3.4 Sustainability survey of Canadian fisheries. Points and shading depict the proportion of exploited populations classified as healthy, cautious or critical, or uncertain by region (a) and species group (b). Points in the bottom left have a high proportion of cautious/critical stocks, in the bottom right have a high percentage of uncertain stocks, and in the upper corner have a high proportion of healthy stocks. The size of the symbol depicts the number of stocks in the region (a) or species group (b). Shading shows the kernel density of the distributions. Data source listed in Table 10.1.

3.2 Key points

- Previous reports have described the declining status of many of Canada's fisheries (Hutchings et al., 2012; Bailey et al., 2016; Baum and Fuller, 2016).
- In the AOS, Atlantic herring and cod together account for 44% of all fishery landings since 1970 (Figure 3.1).
- The largest landings by area in the AOS have been of Atlantic herring in division 4X (the western Scotian Shelf and Bay of Fundy), a stock for which there is currently serious concern and which is under a rebuilding plan.
- Following the groundfish collapse in the early 1990s, forage fishes and invertebrates became of greater importance and constituted the majority of all fishery landings. Invertebrates now make up 65% of Atlantic Canadian fisheries landings, with lobster, shrimp, crab, and scallop being the most valuable, while groundfish make up 12%.
- Ecosystems in the AOS may be transitioning back to their pre-1990s state, in which groundfish was the dominant group (Frank et al., 2011).
- Fishery stock assessments suggest declining abundance trends for most large predator species including American plaice (−63%), Atlantic cod (−46%), cusk (−86%), deep-water redfish (−35%), Greenland halibut (−92%), porbeagle shark (−56%), spiny dogfish (−45%), white hake (−95), winter flounder (−39%), and witch flounder (−76). Increasing trends were evident for low trophic level species, including northern shrimp (41%) and sea scallop (35%).
- The Sustainability Survey for Fisheries suggests that nationally, almost half (44%) of stocks within the AOS were classified as uncertain, 22% as cautious/critical, and only 34% as healthy (Figure 3.4a). Only 15% of the populations in the Gulf region were healthy, whereas 69% were categorized as cautious or critical. Newfoundland and Labrador and the Eastern Arctic had low proportions of healthy stocks (19–25%) and high degrees of uncertainty (58–75%). Stocks within the Maritimes had 55% of stocks classified as healthy and a relatively low degree of uncertainty (23%).

4. Observed climate effects on marine ecosystems and fisheries in Canada

4.1 Overview of climate effects on marine ecosystems

The biological impacts of climate change have now been documented across every ecosystem on Earth, affecting processes that scale from genes to entire ecosystems (Scheffers *et al.*, 2016). The multitude of climate change effects on marine species can be and have been initiated by shifts in the physical environment, including pH, oxygen, ice, ocean currents, precipitation, insolation, wind, freshwater fluxes, and temperature. In turn, these physical changes can directly or indirectly instigate tremendously varied, complex, and synergistic effects on marine species (Table 4.1). Direct climate impacts are transmitted via single pathways and include physiological effects that can be manifest as changing mortality, fecundity, energy use, spatial distribution, phenology, size structure, and demography. Indirect effects occur through second-order pathways and can include changing nutrient cycles and primary productivity; trophic interactions; habitat; and disease, parasitic, and viral transmissions. In nearshore areas, the climate-driven transformation of coastlines (e.g. erosion) and habitats by changing sea levels and storms can also affect species indirectly. Notwithstanding these varied pathways and effects, the most common and prominently documented response from fish stocks have been changes in distribution (Nye *et al.*, 2009, 2011; Cheung *et al.*, 2010; Pinsky *et al.*, 2013; MacKenzie *et al.*, 2014), phenology (Poloczanska *et al.*, 2013, 2016; Asch, 2015), and productivity (Cheung *et al.*, 2010, 2012; Britten *et al.*, 2016, 2017; Free *et al.*, 2019).

Fisheries will also be affected by climate-driven changes in key processes such as growth and recruitment. For example, it is expected that lower oxygen, warming, and associated changes in metabolism will lead to reductions in fish size (Shackell *et al.*, 2010; Cheung *et al.*, 2012) and associated reproductive output (Barneche *et al.*, 2018). Climate change is expected to amplify the variability, frequency, and intensity of fluctuations in critical fish life cycle events, in particular for pelagic stocks (Chavez *et al.*, 2003; Barange and Perry, 2009). Broadly, climate change is expected to increase fisheries catch potential in higher latitudes and to decrease in tropical regions due to the poleward redistribution of fish stocks in the northern hemisphere (Cheung *et al.*, 2010; Lotze *et al.*, 2019; Boyce *et al.*, 2020; Bryndum-Buchholz *et al.*, 2020). However, there is still significant uncertainty in projecting climate effects on fisheries (Cheung *et al.*, 2016b) and fisheries performance (Brander, 2007), particularly in the Arctic (Lotze *et al.*, 2019; Niemi *et al.*, 2019; Boyce *et al.*, 2020; Bryndum-Buchholz *et al.*, 2020). In short, climate change is affecting fisheries through a network of complex pathways, making any understanding of its effects on any particular species at specific locations highly challenging. Due to this complexity and existing knowledge gaps, the consequences of continued climate change for marine population or ecosystem productivity in Canada are largely unresolved (DFO, 2012a; Niemi *et al.*, 2019).

This chapter will provide a review of the climate change effects that have been observed thus far globally and across the AOS with an emphasis on common responses. Time trends in climate change indicators will be explored, focusing on those that are available in standardized units, at synoptic spatial scales, and over time-scales that are climate relevant. A critically important factor in evaluating climate change effects is the time-scales at which they are evaluated. Decadal and multi-decadal ocean basin–scale climate variabilities, such as the Atlantic Multi-decadal Oscillation and North Atlantic Oscillation, can create the appearance of short-term increasing or declining trends when they are, in fact, part of longer-term oscillations (Boyce *et al.*, 2010; Drinkwater and Kristiansen, 2018). For example, studies have found that continuous time-series of ~40 years are required to separate climate-driven phytoplankton changes from such natural variability (Henson *et al.*, 2010; Beaulieu *et al.*, 2013), although series of at least ~20 years have been suggested for the Canadian Arctic (Niemi *et al.*, 2019). This is particularly relevant for the Northwest Atlantic, which is one of the most dynamic regions of the global ocean, exhibiting large natural variability, making detection and attribution of climate change especially challenging (Hurrell *et al.*, 2006; Delworth *et al.*, 2016). To avoid erroneously attributing short-term changes to climate effects, the focus of this report will be on indicators of climate change that are publicly available over climate-relevant time periods (>40 years). These criteria mean that not all climate-relevant information can or will be directly evaluated.

Table 4.1 Biological responses to key climate change variables.
Table was adapted from Mora *et al.* (2013a).

Phenomenon	Warming	Acidification	Oxygen	Primary production
Growth, metabolism, condition, body size	Due to temperature-dependent metabolism (Clarke and Johnston, 1999), warming should reduce growth and size (Hunt and Roy, 2006; Sheridan and Bickford, 2011; Cheung *et al.*, 2013a), all else being equal. In some cold regions, warming could enhance individual growth (Drinkwater, 2005).	Acidification may reduce skeletogenesis (Byrne, 2011; Manno *et al.*, 2012) and increase metabolic costs of calcification (Wood *et al.*, 2008), although some taxa are resistant (Kroeker *et al.*, 2010) and some plants may benefit (Riebesell *et al.*, 2007) (but see (Hall-Spencer *et al.*, 2008)). CO_2 can increase in the blood, reducing growth (Michaelidis *et al.*, 2005; Poertner, 2008; Barton *et al.*, 2012).	Hypoxia should reduce growth and body size (Levin, 2003; Poertner and Knust, 2007; Daufresne *et al.*, 2009). Oxygen concentration also affects the calcification rates of corals (Wijgerde *et al.*, 2012).	Growth and body size decline with lowered productivity (Schmidt *et al.*, 2004; Kaariainen and Bett, 2006; Rex *et al.*, 2006; Darling and Cote, 2008; Ruhl *et al.*, 2008; Smith *et al.*, 2008). Changes in life history strategies of abyssal macrofauna may be driven by changes in surface productivity (Wigham *et al.*, 2003; Boyce and Worm, 2015).

Survival and abundance	Thermal tolerance limits could be exceeded by warming leading to excessive mortality (Mora and Ospina, 2001, 2002; McClain *et al.*, 2012; Pinsky *et al.*, 2019; Trisos *et al.*, 2020), especially if interacting with other stressors (Vaquer-Sunyer and Duarte, 2011). Warming reduces abundance (McClain *et al.*, 2012; Kelmo and Hallock, 2013; Koch *et al.*, 2013; Syamsuddin *et al.*, 2013) and may enhance disease prevalence (Cerrano *et al.*, 2000; Harvell *et al.*, 2002; Aronson *et al.*, 2003; Bruno *et al.*, 2007; Mora, 2008, 2009). Warming associated with increased disease transmission (Burge *et al.*, 2014; Vezzulli *et al.*, 2016). Warming associated with reduced recruitment capacity in fisheries (Pershing *et al.*, 2015; Britten *et al.*, 2016; Free *et al.*, 2019).	Acidification increases mortality in selected adult and juvenile (Kurihara *et al.*, 2004; Dupont *et al.*, 2008; Byrne, 2011; Ginger *et al.*, 2013) marine invertebrates (Byrne, 2011) and plants (Hall-Spencer *et al.*, 2008). Abundance can decline among producer species (Hall-Spencer *et al.*, 2008) (but see (Short and Neckles, 1999; Riebesell *et al.*, 2007). Acidification can cause tissue damage, making fish more vulnerable to infection (Frommel *et al.*, 2012).	Hypoxia causes mortality in most large eukaryote (Levin, 2003; Vaquer-Sunyer and Duarte, 2011), and anoxia could cause extinction in macro- and megafauna (WISHNER *et al.*, 1990; Gooday *et al.*, 2000; Levin, 2003; De Leo *et al.*, 2012; Kuroyanagi *et al.*, 2013). Hypoxia may enhance dominance by some taxa that are hypoxia tolerant (Purcell, 2012; Kuroyanagi *et al.*, 2013) or that are released from ecological interactions (Levin, 2003; Ekau *et al.*, 2010; Yasuhara *et al.*, 2012a).	Mortality of benthic invertebrates is generally higher with reductions in food supply (McClain *et al.*, 2012). Reduced productivity could reduce abundance (Billett *et al.*, 2001; Gooday, 2003; Vetter *et al.*, 2010; Tecchio *et al.*, 2011; McClain *et al.*, 2012; Yasuhara *et al.*, 2012a) and lead to dominance shifts from large to small taxa.

Geographic range and distribution	Warming could cause range shifts poleward and to deeper waters (Nesis, 1997; Perry *et al.*, 2005; Yasuhara *et al.*, 2009; Comeaux *et al.*, 2012), which in turn could affect the strength of ecological interactions (Narayanaswamy *et al.*, 2010), gene flow, and rates of evolution (Hill *et al.*, 2011). Warming also reduces habitat suitability for species (Shackell *et al.*, 2014).	Reduced calcium carbonate saturation constrains calcification and growth with adverse effects on calcifying species from shallow (Hoegh-Guldberg *et al.*, 2007; Tittensor *et al.*, 2010a) and deep-sea (Guinotte *et al.*, 2006) areas.	Some taxa may disappear from hypoxic waters (Levin, 2003; Prince *et al.*, 2010; Stramma *et al.*, 2010, 2012; Koslow *et al.*, 2011; Gilly *et al.*, 2013; Kuroyanagi *et al.*, 2013), but others may appear and thrive (Stramma *et al.*, 2010, 2012; Gilly *et al.*, 2013). Increased endemism among some benthic foraminifera in core regions of oxygen minimum zones (Schumacher *et al.*, 2007).	Certain species are unlikely to maintain their distribution in food limited areas of the seafloor (Tittensor *et al.*, 2011).
Species diversity composition	Theory suggests a positive relation between richness and temperature (Cronin and Raymo, 1997; Allen *et al.*, 2002; Currie *et al.*, 2004), which is confirmed in several marine studies (Cronin and Raymo, 1997; Mora and Robertson, 2005; Yasuhara *et al.*, 2009; Tittensor *et al.*, 2010b); although some regions and/or taxa fail to show a relationship (Yasuhara *et al.*, 2012b).	Acidification will likely lead to loss of species (Widdicombe and Spicer, 2008; Widdicombe *et al.*, 2009).	Diversity declines as oxygen declines for protists (Gooday *et al.*, 2000, 2009; Yasuhara *et al.*, 2012c), meiofauna (Yasuhara *et al.*, 2012c), macrofauna, and megafauna (Gooday *et al.*, 2000, 2009; Levin, 2003; Stramma *et al.*, 2010, 2012).	Richness shows a unimodal (Vetter *et al.*, 2010; Tecchio *et al.*, 2011; Tittensor *et al.*, 2011; McClain *et al.*, 2012) or no (Mora and Robertson, 2005; Yasuhara *et al.*, 2012b) relationship with proxies of the food supply. Productivity seasonality may negatively affect diversity (Gooday *et al.*, 1998; Corliss *et al.*, 2009). Eutrophication causes diversity decline (Yasuhara *et al.*, 2012c).

Functioning and service provision	Ecosystem malfunctioning could be extensive if keystone species are affected (Bellwood *et al.*, 2004; Hoegh-Guldberg *et al.*, 2007; Narayanaswamy *et al.*, 2010; Mora *et al.*, 2011) or if tolerances are exceeded simultaneously (Trisos *et al.*, 2020). Trophic cascades could also affect ecosystem structure and functioning (Frank *et al.*, 2005, 2011; Purcell, 2012; Boyce *et al.*, 2015b).	Acidification can affect nutrient cycling (Widdicombe *et al.*, 2009; Shi *et al.*, 2010), while reduced calcification can reduce sinking rates and carbon export fluxes to the seafloor via less mineral ballast (Hofmann and Schellnhuber, 2009).	Carbon cycling could shift from metazoans to benthic foraminifera (Woulds *et al.*, 2007) and microbiota (Woulds *et al.*, 2007; Diaz and Rosenberg, 2008) in suboxic and anoxic zones. Hypoxia can reduce colonization, recovery, and resilience (Woulds *et al.*, 2007).	Reduced food supply may lead to reduced fishery landings (Chassot *et al.*, 2007, 2010), can reduce carbon cycling (Ruhl *et al.*, 2008; Amaro *et al.*, 2010; van Oevelen *et al.*, 2011), modify food web structures (Tecchio *et al.*, 2011), and cause shifts from macrofaunal-to-microbial-dominated nutrient cycling (Smith *et al.*, 2008; van Nugteren *et al.*, 2009a, 2009b).

4.2 Climate effects on the physical–chemical environment

Climate change impacts are predominantly, though not exclusively, mediated through changes in temperature. Temperature effects are overarching, affecting important physical (e.g. sea ice formation, persistence, and extent, ocean mixing, currents), and chemical processes (e.g. deoxygenation, nutrient cycling) that drive direct and indirect climate effects on species. As temperature is a first-order proxy of climate change and observations of temperature are publicly available at long-term synoptic scales, it will be used as the main index of environmental climate change in this overview, although additional changes will also be discussed.

Changes in sea surface temperature (SST) were evaluated, using monthly observations from the MET Hadley dataset between 1900 and 2019 available on a global 1 × 1° grid (Table 10.1). When averaged across all months and examined globally, SST has increased linearly by an average of 0.67°C between 1900 and 2019. This warming trend is comparable to that estimated by the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (NOAA National Centers for Environmental information, 2020). The SST trends were spatially variable (range = −2.4–3.3°C; S.D. = 0.45°C), with most areas experiencing warming temperature trends. Within the AOS, warming has been more rapid (0.93°C; range = −0.6–2.1°C; S.D. = 0.47°C) than the global average since 1900. Almost all grid cells within the AOS exhibited warming, with a small number between Labrador and Baffin Island and at the northern extent of some divisions exhibiting cooling (Figure 4.1a). Average rates of surface warming in all AOS regions were more rapid than the global average, and all of the grid cells within the Gulf of St. Lawrence and the Scotian Shelf exhibited more rapid warming than the global average (Figure 4.1b). Warming trends in all regions were non-linear and driven by rapid SST increase since ~1970 (Figure 4.2). The most rapid warming since 1900 was observed on the Scotian Shelf (1.5°C) and in the Gulf of St. Lawrence (1.34°C), with the Eastern Arctic experiencing the slowest comparative warming (0.73°C). Independent satellite observations of SST also suggest that rapid warming has occurred in the AOS between 1985 and 2016 and that 2012 was an anomalously warm year (Bernier *et al.*, 2018). The trend of warmer oceans appears to be consistent across different regions within the AOS and is robust to the use of different input data sources. Notably, some of the most rapid warmings have occurred to the immediate south of the AOS in the Gulf of Maine. The average warming rate in this region (1.7°C) was almost twice as rapid as that across the AOS, and warming rates were less spatially variable (range = 0.95–2°C; S.D. = 0.3°C). Published studies have also highlighted the rapid pace of warming in the Gulf of Maine, particularly between 2005 and 2015 (Pershing *et al.*, 2015), while others report that this warming will continue at extreme rates throughout the Northwest Atlantic over the next century (Saba *et al.*, 2016).

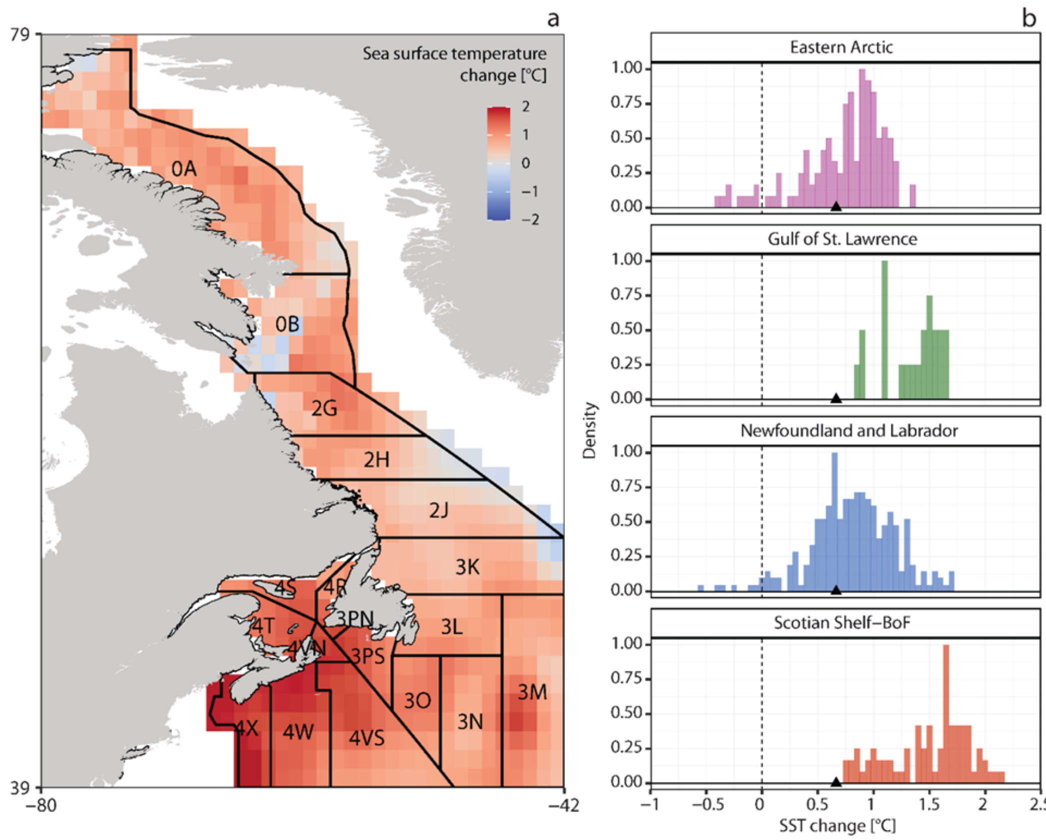

Figure 4.1 Long-term changes in SST across the AOS.

Total change in surface temperature (°C) over the past century (1900–2014) estimated using a linear model within each 1×1° cell within the AOS (a) and within each bioregion (b). (a) Temperature changes are depicted as colours: dark red show greater warming, and blue, cooling. (b) The density distribution of temperature changes within each bioregion region is shown as colours, with the black triangle showing the average global temperature change. Data source listed in Table 10.1.

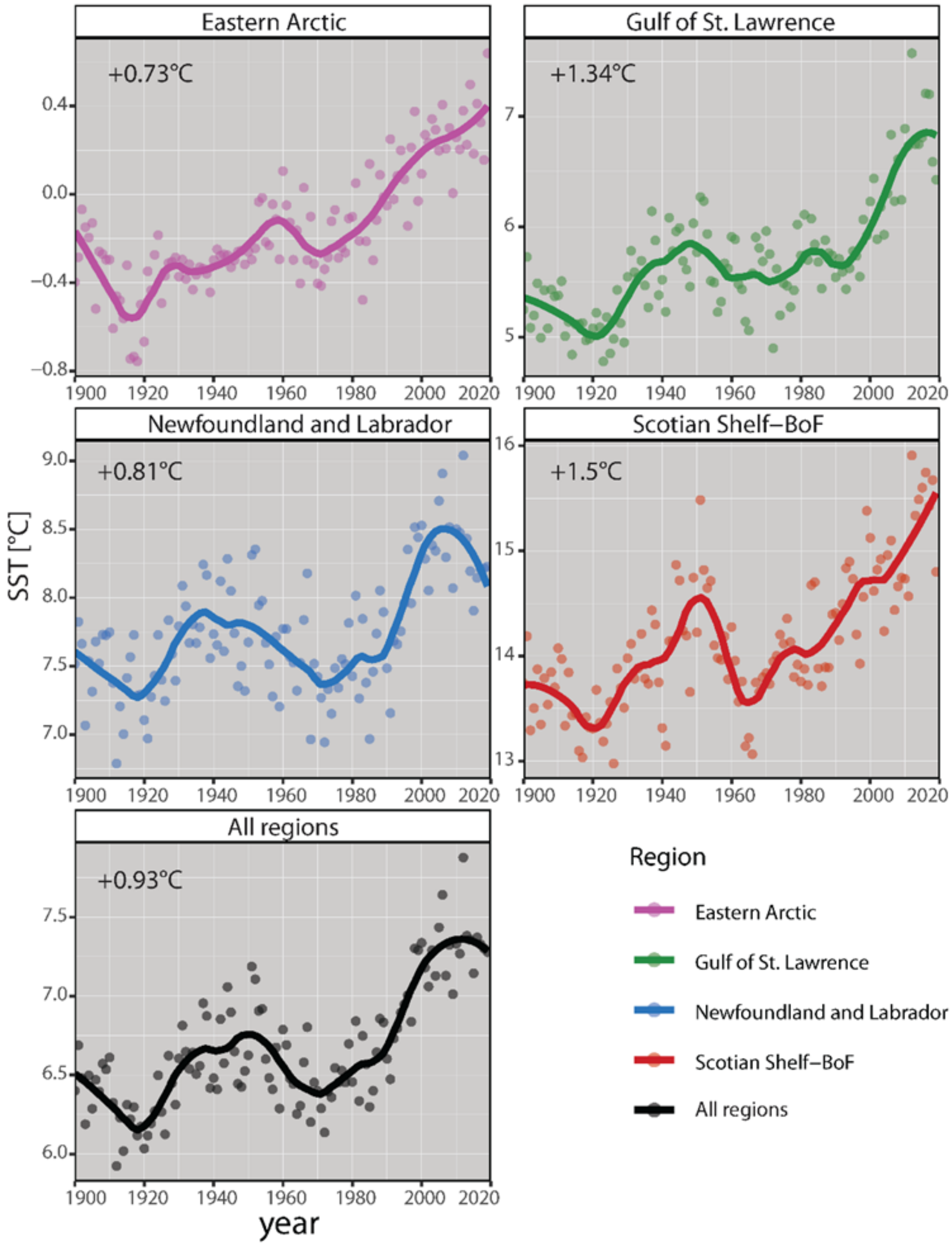

Figure 4.2 Long-term (1900–2014) surface temperature trends across the AOS.

Annually averaged surface temperature (°C) time-series across the regions within the AOS and for all regions combined. The regions are depicted as colours, and the AOS aggregate is in black. The total linear temperature change is shown in the top left of each panel. Data source listed in Table 10.1.

Table 4.2 summarizes many of the long-term changes in the biochemistry and population dynamics of marine species that have been attributed to climate change within the AOS. Ocean warming within the AOS has been associated with warmer winters since the 1800s and an associated reduction in ice volume and duration. Hutchings *et al.* (2012) reported that Arctic sea ice cover in both summer and winter has been declining since 1979, with September sea ice extent declining by 12% per decade and a projected ice-free Arctic in the fall of 2071. Sea ice thickness has also reportedly declined by 48% between 1980 and 2008

(Kwok and Rothrock, 2009). Linearly declining sea ice extent and thickness have also been reported between 1979 and 2011 for the Gulf of St. Lawrence (−3.9%) and Newfoundland and Labrador shelves (−3.1%), and sea ice extents reached their lowest historical levels in each of these two regions in 2010 and 2011, respectively.

These changes in sea ice have important consequences for mixing, nutrient availability, and oxygen levels. Warming of the ocean surface has been associated both globally and within the AOS to enhanced vertical stratification and reduced nutrient availability in surface waters (Behrenfeld *et al.*, 2006; Polovina *et al.*, 2008; Boyce *et al.*, 2010, 2014; Lewandowska *et al.*, 2014). For example, increased stratification has been reported on the Scotian Shelf between 1960 and 2008, with rapid increases in the 1990s (Petrie *et al.*, 2009a).

Changes in mixing patterns and altered nutrient inputs have also led to increasing hypoxia, a condition where oxygen (O_2) concentrations drop below 30% (Gilbert *et al.*, 2005; Hoegh-Guldberg and Bruno, 2010; Stendardo and Gruber, 2012; Bernier *et al.*, 2018). Hypoxia has been associated with mass mortality events in marine species and is known to have adverse effects on the growth, reproduction, and distribution of species. Dissolved oxygen has reportedly declined in almost all regions of the North Atlantic between 1960 and 2009 (Stendardo and Gruber, 2012). Hypoxia has been increasing in the Gulf of St. Lawrence, with hypoxic conditions being common since 1984 and reaching an annual average low of 18% saturation in 2016 (Bernier *et al.*, 2018). Gilbert *et al*. (2005) reported a 48% reduction in dissolved O_2 at depth in the St. Lawrence Estuary since the 1930s, in association with a 1.7°C warming. There have also been reports of low O_2 levels on the Scotian Shelf (Petrie and Yeats, 2000) and northeastern Newfoundland Shelf (Kiceniuk and Colbourne, 1997).

As the atmospheric carbon dioxide (CO_2) concentration increases, an increasing amount of carbon is absorbed by the oceans, leading to decreases in pH and ultimately to increasing acidification. Acidification in the Northwest Atlantic is reportedly increasing faster than in most other oceans, with adverse effects on species such as plankton molluscs, crustaceans, and corals that form calcium carbonate skeletons. Greater acidification has also been reported in coastal areas near large estuaries and cold-water currents, compared to deeper offshore waters of warmer origin (Peck and Pinnegar, 2018). Acidification is especially relevant in the Arctic because the solubility of CO_2 is greater in colder waters, and to a shoaling of the aragonite saturation horizon as a function of depth (Fabry *et al.*, 2008), leading the onset of under-saturation to occur earlier. Declines in pH and calcium carbonate have been reported in the Arctic and may be partly driven by increasing freshwater influx from melting ice caps (Steinacher *et al.*, 2009). Acidification has also been found to cause tissue damage in larval Atlantic cod, leading to increased susceptibility to infection (Frommel *et al.*, 2012). Notwithstanding this, the impacts of acidification on North Atlantic finfish are generally poorly understood (Peck and Pinnegar, 2018).

Table 4.2 Observed climate change trends within the AOS.

Phenomenon	General observed pattern	References
Range expansion or contraction	- By 2060 55% of species projected as losing thermal habitat, 21% gaining, and 24% remaining constant	(Cheung *et al.*, 2013b; Pinsky *et al.*, 2013; Shackell *et al.*, 2014)
Latitudinal range shifts	- Northward range shifts - 'Borealization' of Arctic, 'tropicalization' of temperate ecosystems - A shift in the spatial distribution of larvae for 43% of taxa in the northeastern US; mostly northward	(Nye *et al.*, 2011; Shackell *et al.*, 2012; Pinsky *et al.*, 2013; Walsh *et al.*, 2015; Morley *et al.*, 2018)
Depth distribution	- A shift towards inhabiting deeper, colder waters	(Shackell *et al.*, 2012; Pinsky *et al.*, 2013; Morley *et al.*, 2018)
Species invasions	- New arrivals from US waters on the Scotian Shelf associated with latitudinal range shifts - New arrivals in the Arctic from the south, with effects on low diversity ecosystems there	(MacKenzie *et al.*, 2014; Bernier *et al.*, 2018)
Seasonal	- A shift in seasonal timing of larval occurrence for 49% of taxa in the northeastern US shelf - Earlier melting of sea ice in the year	(Edwards *et al.*, 2004; Walsh *et al.*, 2015; Niemi *et al.*, 2019)
Trophic	- Increased zooplankton grazing - Increased predation of ectotherms relative to endotherms - A shift towards resource control of marine ecosystems	(Frank *et al.*, 2006, 2007; Petrie *et al.*, 2009b; Boyce *et al.*, 2015b; Grady *et al.*, 2019)
Size structure	- Reduction in size of primary and secondary producers	(Drinkwater, 2005; Li *et al.*, 2009; Shackell *et al.*, 2010; Sheridan and Bickford, 2011; Cheung *et al.*, 2013a)
Temperature	- Warming almost everywhere - Rapid warming in the Gulf of Maine, Gulf of St. Lawrence, Scotian Shelf	(Hutchings *et al.*, 2012; Saba *et al.*, 2016; Greenan *et al.*, 2019)
Freshwater flux	- Increased at high latitudes from hydrological cycle intensification	(Durack and Wijffels, 2010; Durack *et al.*, 2012)
Melting sea ice	- Melting Arctic ice and Greenland ice sheet, leading to a freshening of the Arctic - Spatially variable changes in sea ice type (old versus seasonal), thickness, and extent in the Arctic	(Bamber *et al.*, 2012; Hutchings *et al.*, 2012; Stroeve *et al.*, 2012; Bernier *et al.*, 2018; Niemi *et al.*, 2019)
Stratification	- Increased, especially at low latitudes - Associated with nutrient limitations at low to mid latitudes	(Behrenfeld *et al.*, 2006; Polovina *et al.*, 2008)
Acidification	- Increasing, especially in the Gulf and Arctic - Negative effects on calcifying species	(Doney *et al.*, 2009; Steinacher *et al.*, 2009; Wanninkhof *et al.*, 2015; Bernier *et al.*, 2018; Peck and Pinnegar, 2018; Niemi *et al.*, 2019)
Deoxygenation	- Widespread increases, especially in the Gulf of St. Lawrence	(Hoegh-Guldberg and Bruno, 2010; Stendardo and Gruber, 2012; Stramma *et al.*, 2012; Bernier *et al.*, 2018; Niemi *et al.*, 2019)
Primary production	- Spatially variable, but generally declining, especially at lower latitudes - Complex responses in the Arctic including changes from ice algae to phytoplankton; moderate declines in some areas but increases in others	(Gregg *et al.*, 2003; Behrenfeld *et al.*, 2006; Boyce *et al.*, 2010, 2014; Niemi *et al.*, 2019)
Disease transmission	- Increased, especially in the Arctic	(Frommel *et al.*, 2012; Burge *et al.*, 2014; Vezzulli *et al.*, 2016)

4.3 Climate effects on plankton

There is a notable lack of long-term standardized time-series that are needed to resolve climate change–associated processes (Boyce *et al.*, 2010, 2014; Boyce and Worm, 2015), particularly in the Arctic (Boyce *et al.*, 2010, 2014; Niemi *et al.*, 2019). Notwithstanding this, DFO has reported an overall decline in phytoplankton concentration in the AOS between 1999 and 2016, associated with altered nutrient concentrations (Bernier *et al.*, 2018). This decline broadly coincides with regional estimates that chlorophyll concentrations have declined across the Northwest Atlantic (−0.6% yr^{-1}; 1911–2010) and Arctic (−0.4% yr^{-1}; 1899–2005) oceans over the past century, associated with long-term warming and reduced vertical mixing and nutrient delivery (Boyce *et al.*, 2010, 2014). However, the biogeochemical response to warming has been more complex in the Arctic. In several areas, including Cumberland Sound (Eastern Arctic), warming has led to the loss of old ice, thus reducing the concentration of algae that grow on ice underside (ice algae), leading to increased concentrations of open-water algae (phytoplankton), with consequences for nutrient fluxes and ecosystem structure (Niemi *et al.*, 2019).

Outside of the Arctic, changes in the cyclic seasonal development (phenology) of phytoplankton have been reported within the AOS between 1999 and 2016, with large variability in the magnitude and timing of the spring bloom and a gradual decline in the bloom duration (Bernier *et al.*, 2018). The decline in spring bloom duration in the AOS is comparable to reports that, when spatially averaged, the duration of the phytoplankton growing season has declined at temperate–polar latitudes (35–65°N) between 1998 and 2007, coincident with surface temperature changes (Racault *et al.*, 2012). Such shifts in the timing of seasonal phytoplankton development have also been linked to the larval survivorship and subsequent productivity of haddock (*Melanogrammus aeglefinus*) and shrimp (*Pandalus borealis*) in the AOS (Platt *et al.*, 2003; Koeller *et al.*, 2009). In the Arctic, warming and earlier melting of sea ice have led to a longer growing season with unknown impacts on marine species (Niemi *et al.*, 2019).

Ocean warming has also been associated with changing plankton species composition and a reduction in the average size of plankton. Ocean warming, stratification, and reduced nutrient concentrations have led to increases in picophytoplankton (<0.2 um) and species groups that are better adapted to thriving under these conditions. For example, Li *et al.* (2009) reported that freshening and increasing stratification in the Canadian Arctic has led to increasing picophytoplankton (<2 µm diameter) and declining nanoplankton (2–20 µm diameter) abundances between 2004 and 2008. Warming in the Arctic is also leading to shifts in the amount of primary production in ice algae relative to phytoplankton (Niemi *et al.*, 2019). Climate-driven shifts in major phytoplankton species groups, including diatoms, dinoflagellates, and coccolithophores, have also been reported across the North Atlantic in response to climate-driven stratification and nutrient limitation (Cermeno *et al.*, 2008; Hinder *et al.*, 2012; Barton *et al.*, 2016). Barton *et al.* (Barton *et al.*, 2016) analyzed the thermal preferences of 87 phytoplankton species in the North Atlantic and reported that ocean warming was contributing to rapid poleward and eastward shifts in most species. Similar to phytoplankton, warming has been associated with an increase in small warm-water zooplankton and a reduction in the large energy-rich copepod *Calanus finmarchicus*

(Bernier *et al.*, 2018). *C. finmarchicus* has been declining across the AOS since 2009, with the largest declines reported on the Scotian Shelf. Alternatively, smaller copepods such as *Pseudocalanus* spp. have increased, particularly in the Gulf of St. Lawrence and the Newfoundland Shelf (Bernier *et al.*, 2018). Such shifts can have large effects on the flow of energy through marine ecosystems, with consequences for fisheries. As a consequence of size-based predation and trophic transfer efficiency, a smaller fraction of the energy in smaller plankton is transferred to upper trophic levels (Boyce *et al.*, 2015a). This means that more production is cycled in the microbial loop that is transferred to upper trophic levels to support fisheries (Azam and Malfatti, 2007; Boyce and Worm, 2015). Likewise, the size structure and composition of plankton communities have strong effects on the amount of particular organic matter that is exported to support deep-sea ecosystems and fisheries.

4.4 Climate effects on bacteria and viruses

Climate effects on bacteria and viruses are less well understood, but their effects on marine ecosystems and fisheries are likely to be profound (Cavicchioli *et al.*, 2019). It has been estimated that 90% of marine biomass comprises microbes, including bacteria and viruses. The abundance and diversity of such microorganisms underlie their critical importance on marine species and ecosystems. It is likely that hosts and parasites will track species as they shift poleward under climate change. Warming has already been associated with an increase in the prevalence of disease outbreaks and bleaching in coral ecosystems (Altizer *et al.*, 2013; Bourne *et al.*, 2016), and some disease outbreaks coincide with periodicities in the El Niño Southern Oscillation; (Randall and van Woesik, 2017). Climate change may also render some species more susceptible to infection. For example, ocean acidification was reported to cause tissue damage in Atlantic cod larvae, weakening their immune systems and making them more susceptible to bacterial invasion (Frommel *et al.*, 2012). Warming in the Arctic is projected to lead to increased disease transmission between species in the Eastern and Western Arctic ecosystems, with cascading effects on ecosystem structure and fisheries. Disease outbreaks can also lead to mass mortality of keystone species such as sea stars and urchins, leading in turn to cascading ecosystem effects (Harvell *et al.*, 2019). Climate change–associated increases in storm surges and sea level rise are projected to lead to an expansion of the geographic and seasonal ranges of bacteria (Burge *et al.*, 2014). For example, a poleward range shift of outbreaks of *Vibrio* has already been reported in the North Atlantic, the North Sea, the Baltic Sea, and Alaska associated with shifting temperature and salinity (Burge *et al.*, 2014; Vezzulli *et al.*, 2016). Harmful algal blooms that can lead to fishery closures and reduced productivity are projected to increase in frequency and extent with climate change (Howard *et al.*, 2013).

4.5 Climate effects on fisheries

Resolving the emergent effects of climate change on fisheries is exceedingly challenging due to the multiple pathways by which they can be manifest, as well as the presence of coincident impacts such as exploitation, which can obscure climate effects. Climate effects can be manifest on species directly by affecting metabolic rates or indirectly by modifying prey availability. Notwithstanding these challenges, studies have documented a range of fisheries responses to climate change, which are summarized below.

4.5.1 Distributional shifts

Several studies have documented distributional shifts in response to climate changes, with shifts being more rapid in marine systems than in terrestrial ones, due to the greater connectivity there. Where climate-driven shifts have been reported, species have generally shifted into either deeper or more northerly waters, presumably in search of more thermally suitable habitat (Dulvy *et al.*, 2008; Pinsky *et al.*, 2013; Cheung *et al.*, 2016a), although directional shifts can also be more complex (Pinsky *et al.*, 2013). Regional-scale distributional shifts have been increasingly documented in the North Atlantic and Arctic oceans, including the northeastern US (Nye *et al.*, 2011; Pinsky *et al.*, 2013), North Sea (Perry *et al.*, 2005), and Denmark Strait (MacKenzie *et al.*, 2014). For example, Nye *et al.* (Nye *et al.*, 2009) reported poleward shifts in 17 of the 36 commercial fish stocks between 1968 and 2007 in US waters that were associated with ocean warming. The general trend of warmer-adapted species moving into more northerly habitats has been termed 'tropicalization' in temperate systems and 'borealization' in the Arctic. For example, DFO has recently noted an increasing number of exotic warm-water species being reported in the summer research vessel survey, particularly in more southerly regions (Bernier *et al.*, 2018) (Figure 4.3). Climate change has also been associated with an expansion of bluefin tuna outside of their usual range and into the subpolar waters near Greenland (MacKenzie *et al.*, 2014). Reduced sea ice duration in the Arctic has also led to more frequent occurrences of killer whales in the Eastern Arctic and associated changes in the behaviour of other whales as they seek to avoid them (Niemi *et al.*, 2019). Range expansions have also been observed for Pacific salmon and harp seals across the Arctic (Niemi *et al.*, 2019). It is unknown to what extent the introduction of new species, as well as the emigration of others, will restructure marine ecosystems in the AOS and what the consequences for fisheries will be.

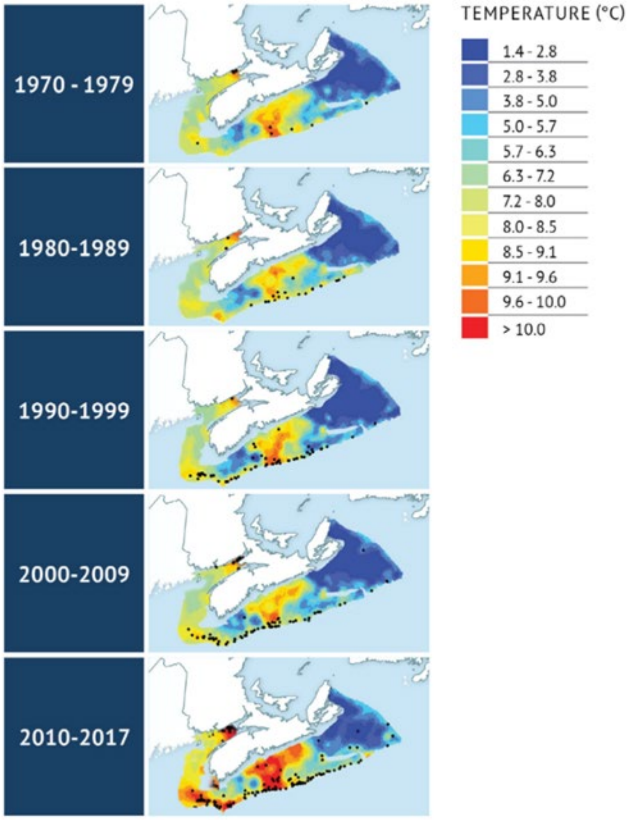

Figure 4.3 Climate-driven species redistributions.
Points depict the occurrence of novel species in the DFO summer bottom trawl survey within each decade (1970–2017). Colours depict the average bottom water temperature. The figure is from Bernier *et al.* (2018).

4.5.2 Phenology

For many species, including marine fish, migrations and life history processes such as spawning are closely associated with cyclic seasonal variation (phenology) in climate and primary productivity. In particular, delayed timing of seasonal plankton blooms has been hypothesized to strongly affect the survivorship of larval fish, with effects on adult productivity (Cushing, 1969, 1990). For example, Platt *et al.* (2003) reported that the survivorship of larval haddock on the Eastern Scotian Shelf was strongly influenced by the timing of the spring phytoplankton bloom, with reduced survivorship occurring when the spring bloom was delayed. In a separate study, Koeller *et al.* (2009) reported that shrimp (*Pandalus borealus*) egg hatching times were significantly related to the seasonal spring timing of phytoplankton and bottom water temperature. Similar but community-wide shifts in seasonal spawning times have been reported for fish in the northwest Pacific Ocean between 1951 and 2008, in association with seasonal changes in temperature (Asch, 2015).

4.5.3 Size structure

As it has been for plankton, increasing temperature has been associated with changing growth rates and reduced size of fish and invertebrates. Shackell *et al.* (Shackell *et al.*, 2010) reported a 60% decline in average body mass of predatory fish and invertebrate species between 1970 and 2008, coincident with increasing temperature and stratification and size-selective harvesting (Figure 4.4). Such changes in size, which are often exacerbated by size-selective fishing (Pauly *et al.*, 1998; Frank *et al.*, 2019), have wide-ranging effects on the growth and energy use of these species as well as on trophic interactions and ecosystem structure.

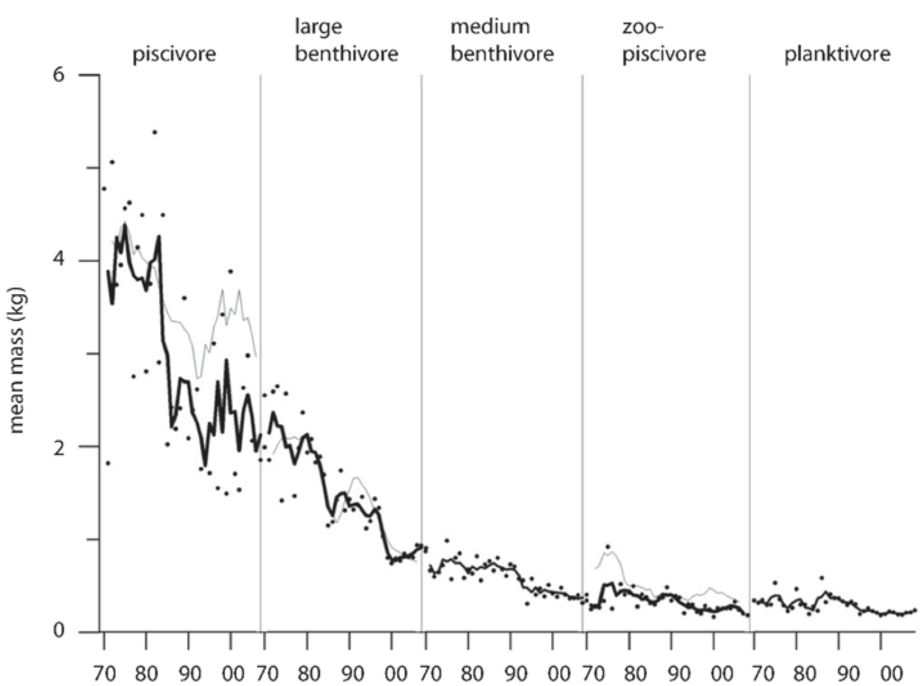

Figure 4.4 Reduced size of marine species on the western Scotian Shelf. Average mass (kg) for fish functional groups (1970–2008). Points are annual values, and lines are the 3-year moving averages. Grey lines are the mass at age six as weighted by species biomass within the functional groups. The figure is from Shackell *et al.* (2010).

4.5.4 Predation

There is substantial evidence that temperature has overarching effects on predator–prey (trophic) interactions in marine food webs globally (Boyce *et al.*, 2015b) and across the North Atlantic and Arctic oceans (Frank *et al.*, 2006, 2007; Petrie *et al.*, 2009b). However, understanding how changing temperature influences trophic dynamics and the emergent dynamics of single species is notoriously difficult, as effects can operate via multiple direct and indirect pathways and can be time lagged. For example, Shackell *et al*. (Shackell *et al.*, 2010) reported that while aggregate predator biomass remained constant over time, reductions in their average size eroded their predation efficiency and led to 300% increases in the biomass of their prey between 1990 and 2008. Temperature has also been found to affect predator–prey interactions by differentially altering the metabolic demands of species. For example, Grady *et al.* (2019) recently reported that the per capita prey encounter rates, capture efficiencies, and maximum capture rates of cold-blooded ectotherms (e.g. most fish and invertebrates) would change with warming, whereas those of warm-blooded endotherms (e.g. mammals, some tunas, sharks, and billfish) would remain constant. As an emergent consequence of this metabolic effect, ectotherms would benefit, consuming a larger share of the available prey than would endotherms. Similarly, the metabolic rate of secondary producers has been found to increase with temperature more rapidly than primary producers (e.g. phytoplankton), again creating an energetic advantage for zooplankton and other consumers as temperatures increase (O'Connor *et al.*, 2009; Lewandowska *et al.*, 2014). Resolving the biological effects of warming on marine species is one of the key uncertainties and limitations to projecting the impacts of climate on marine species and ecosystems (Taucher and Oschlies, 2011; Lotze *et al.*, 2019).

4.5.5 Synergistic effects

The interplay among climate change, fisheries, and additional stressors can be highly interactive and context specific. The drivers of marine ecosystems rarely vary in isolation, and several factors may additively or synergistically act to amplify or attenuate the impact of a single driver (Crain *et al.*, 2008; Poertner, 2010; Gruber, 2011). For example, in the Arctic, climate change is leading to changes in sea ice extent, thickness, and duration, which in turn are causing cascading and interactive changes throughout the ecosystem with effects on the reproductive success, migration, seasonal development, and fitness of species there (Niemi *et al.*, 2019). Because sea ice acts as a mirror and increases surface albedo, warming and sea ice loss can also accelerate warming and climate change impacts in the Arctic (Perovich and Richter-Menge, 2009). Warming and melting sea ice are also leading to increased ship traffic and opportunities for human settlement and marine resource use in the Arctic, with probable impacts on ecosystems and fisheries. Increased ocean acidification has also been found to interact with warming to increase coccolithophore abundance but reduce calcite production, with consequences for fisheries (Feng *et al.*, 2009). Climate effects on ecosystems and species can also be more severe when overlaid by additional stressors including, for instance, fishing, pollution, and nutrient loading. For example, Ottersen *et al.* (Ottersen *et al.*, 2006) reported that extensive fishing could render fish populations less resistant to the negative effects of short-term climate variability on occasional poor year classes. Alternatively, studies have reported that systems that have high species and/or functional diversity may be more resistant and resilient to stressors such as climate change and fishing (Worm *et al.*, 2002, 2006; Worm and Duffy, 2003). These findings have applied relevance to fisheries management. Studies across the AOS suggest that diverse ecosystems that are less heavily impacted by climate and other stressors may be able to sustainably withstand higher levels of exploitation (Shackell and Frank, 2007; Fisher *et al.*, 2008; Petrie *et al.*, 2009b). Despite having similar exploitation rates, several groundfish species collapsed in the Eastern Scotian Shelf in the early 1990s while those on the adjacent western Scotian Shelf did not. The greater capacity of the western Scotian Shelf to resist the deleterious effects of exploitation was attributed to higher species diversity and to warmer waters, allowing compensatory species to increase more rapidly there (Shackell and Frank, 2007).

To explore how stressors are distributed globally and across the AOS, spatial patterns in the cumulative human impact index (HII) developed by Halpern *et al.* (Halpern *et al.*, 2008); Table 10.1) were evaluated. The index synthesizes 17 global datasets of human drivers of ecological change to estimate spatial patterns of human impacts. Across the AOS, the HII indicated that the most impacted areas were located in nearshore waters, particularly in the Gulf of St. Lawrence and Newfoundland and Labrador (Figure 4.5a). Virtually all of the grid cells in the Gulf of St. Lawrence, Newfoundland and Labrador, and Scotian Shelf were more heavily impacted than the global average (Figure 4.5b). Likely due to its inaccessibility, sparse population, and less productive fisheries, the Eastern Arctic was less impacted by human activities than the other bioregions. However, due to the rapid warming and projected expansion of commercial fishing activities, human impacts in the Arctic are expected to increase (Lotze *et al.*, 2019; Boyce *et al.*, 2020; Bryndum-Buchholz *et al.*, 2020).

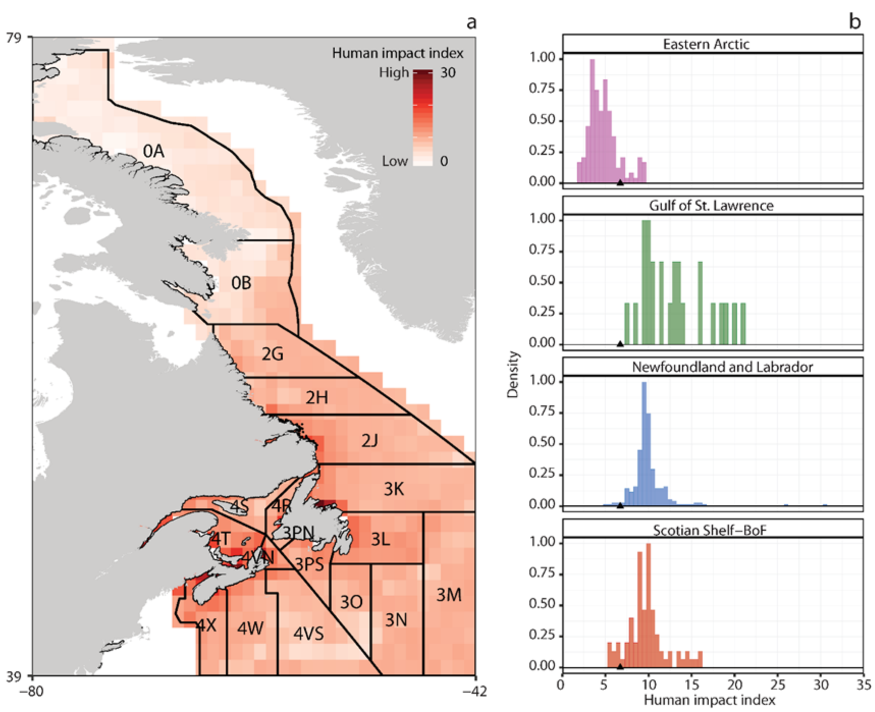

Figure 4.5 Cumulative human impacts across the AOS.
Cumulative HII estimated by Halpern *et al.* (Halpern *et al.*, 2008) within each 1° cell within the AOS (a) and within each bioregion (b). (a) Cumulative impacts are depicted as colours: dark red shows the most heavily impacted areas. (b) The density distribution of impacts within each bioregion is shown as colours, with the black triangle showing the global average.

4.6 Increasing magnitude and frequency of extreme events

In addition to the changes in the mean state discussed thus far, climate change has been associated with increases in the frequency and intensity of climate extremes (Meehl and Tebaldi, 2004; IPCC *et al.*, 2012; Thompson *et al.*, 2013; Oliver *et al.*, 2018). For example, Oliver *et al.* (2018) have reported that the average frequency and duration of marine heatwaves have significantly increased by 34% and 17%, respectively, since 1925, with socio-economic and ecological consequences. Notable marine heatwaves have also occurred in several locations, including the Northwest Atlantic in 2012 (Chen *et al.*, 2014). These warming extremes have been associated with widespread ecological and socio-economic effects, including habitat loss (Wernberg *et al.*, 2016; Hughes *et al.*, 2017), reduced primary production (Bond *et al.*, 2015), mass mortality events (Oliver *et al.*, 2017), range shifts (Wernberg *et al.*, 2016), altered community structure, and fisheries disruption (Caputi *et al.*, 2016; Cavole *et al.*, 2016; Oliver *et al.*, 2017).

Climate change has also been associated with improbable events, termed 'black swans,' in animal populations (Anderson *et al.*, 2017b). Anderson *et al.* (2017b) examined 609 animal populations and reported that black swan events occurred in ~4% of populations and were associated with climate effects, severe winters, predators, parasites, or synergistic drivers. These extreme events primarily occur as population crashes (86%) rather than increases.

4.7 Key points

- Climate change affects fisheries through a multitude of direct and indirect pathways, creating winners and losers, but originating with changes in the physical environment (Table 4.1).
- Both globally and across the AOS, a range of climate change effects have been reported, including warming; reduced mixing and surface nutrient supply; modified freshwater flux; widespread deoxygenation; acidification (e.g. in the Gulf of St. Lawrence); loss of sea ice (e.g. in the Eastern Arctic); reduced primary production (except in the Arctic); reduced size structure; altered community composition; altered species ranges and depth distributions; increased disease transmission; modified growth, metabolism, and condition; and seasonal development (see Table 1.1).
- Surface temperature is a first-order indicator of climate change and is publicly available at synoptic scales over long time-scales.
- Climate effects on marine microorganisms, including bacteria, viruses, and plankton, and their impacts on fisheries is poorly resolved, but likely to be profound (Cavicchioli *et al.*, 2019).
- The magnitude of climate change effects can be context dependent. More severe climate effects can occur when overlaid by additional stressors, whereas greater climate resistance and resilience have been observed in highly diverse ecosystems.

- Climate change is associated with increasing magnitude and frequency of extremes both in the environment and in animal populations.
- Climate change is reconfiguring ecosystems and altering population dynamics in ways that are not yet fully understood but which certainly have implications for the productivity and management of fish populations.

5. Future changes in marine ecosystems and fisheries in Canada

5.1 An overview of climate projection and forecasting

The use of models to understand and project climate change impacts on species and ecosystems under different fishing and warming scenarios is rapidly growing (Carozza *et al.*, 2019; Eyring *et al.*, 2019; Free *et al.*, 2019; Lotze *et al.*, 2019; Boyce *et al.*, 2020; Bryndum-Buchholz *et al.*, 2020). Climate projections are increasingly appearing in documents such as the Intergovernmental Panel on Climate Change (IPCC) reports (IPCC, 2014, 2019). International organizations such as the Food and Agriculture Organization of the United Nations (FAO), and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) now use climate projections to inform decision-makers of how climate-driven ecological changes may affect biodiversity and food production (Barange *et al.*, 2018; IPBES, 2019). Climate projections and forecasts are also beginning to be incorporated into applied ocean management settings (Hobday and Hartog, 2014; Maxwell *et al.*, 2015; Hobday *et al.*, 2016; Barange *et al.*, 2018; Greenan *et al.*, 2019).

Global climate projections of marine systems are generated by global climate models (GCMs), Earth system models (ESMs), and marine ecosystem models (MEMs). GCMs resolve physical and atmospheric processes in the oceans (e.g. temperature, salinity), and ESMs can also resolve physical and biogeochemical processes (e.g. nutrients, phytoplankton). Using the output from ESMs, MEMs resolve ecological processes and can project the impacts of climate changes on a range of marine species from plankton to top predators (Figure 5.1). Through networks such as the Coupled Model Intercomparison Project (CMIP) and the Fisheries and Marine Ecosystem Model Intercomparison Project (Tittensor *et al.*, 2018b, 2018a), projections from GCMs, ESMs, and MEMs are freely available as standardized global projections that can be combined to assess the range of uncertainty and increase the accuracy of climate projections (Mora *et al.*, 2011; Bryndum-Buchholz *et al.*, 2018; Lotze *et al.*, 2019; Schewe *et al.*, 2019; Boyce *et al.*, 2020).

However, despite their widespread availability and use, the projection skill from these coarse-resolution global models can be poor in nearshore waters and inland waterways when assessed against observed data (Laurent *et al.*, n.d.; Loder *et al.*, 2015; Lavoie *et al.*, 2019) and are not yet suitable for management purposes. A review of six ESMs by Loder *et al.* (2015) reported that the models were able to reproduce large-scale patterns in surface temperature and salinity across the North Atlantic well, but did not capture detailed features such as the position of the Gulf Stream. A recent study in review by Laurent *et al.*

(n.d.) compared 29 coarse-resolution global ESMs against a regional model for the northwest North Atlantic shelf ocean and reported that the regional model reproduced observations of chlorophyll, nitrate, and temperature significantly better than the ESMs. It has been hypothesized that the coarse resolution (~1°) of the global models may be a contributing factor and that a resolution of 0.1° to 0.25° may be required to more reliably represent these dynamic nearshore features (Loder *et al.*, 2015; Yool *et al.*, 2015; Saba *et al.*, 2016). To accomplish this, local or regional-scale projections (5–100 km^2) have been developed independently or coarse resolution (100–300 km^2) global models have been downscaled (Saba *et al.*, 2016). Such local or regional models often incorporate regionally specific dynamic nearshore processes and operate at finer spatial and temporal scales than do global models, contributing to better performance when assessed against historical observations. However, the drawback of regional models is the lack of synoptic spatial coverage, the computational requirements to run them, and the large volume of projected output. Few such models exist within the AOS. The Bedford Institute of Oceanography North Atlantic Model is a climate model at 1/12° resolution across the North Atlantic between ~7°N and 75°N (Brickman *et al.*, 2016; Wang *et al.*, 2018). This model provides projections of physical ocean variables for 2055 and 2075 under representative concentration pathway (RCP) scenarios 4.5 and 8.5. The NOAA Geophysical Fluid Dynamics Laboratory Climate Model 2.6 (CM2.6) has also been used to project changes in physical variables such as temperature across the North Atlantic (Saba *et al.*, 2016; Greenan *et al.*, 2019). However, local or regionally scaled ESMs or MEMs that can project plankton and/or animal biomass at space–time scales needed for fisheries are not yet available in the AOS.

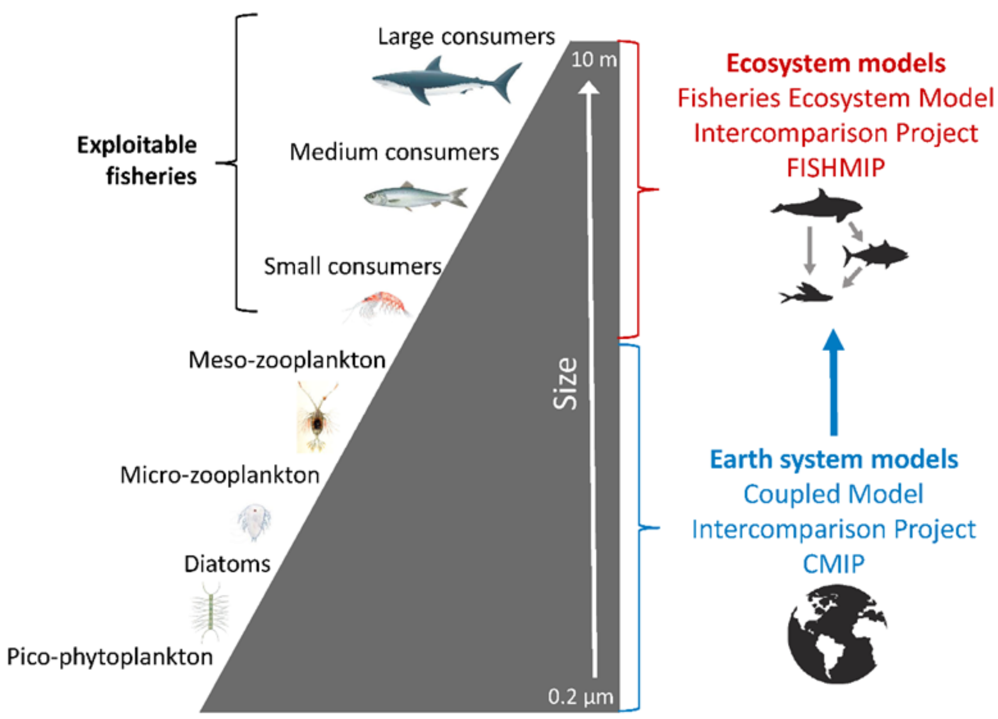

Figure 5.1 Projecting climate impacts on marine ecosystem biomass.
Schematic depicts how ESMs and MEMs enable climate projections of different marine species groups.

Despite this, a range of approaches, such as species distribution modelling and mass-balanced ecosystem modelling, have been developed to project the effects of climate on species and ecosystems at different spatial, temporal, and taxonomic scales (Jones *et al.*, 2012; Shackell *et al.*, 2014; Stortini *et al.*, 2015; Cheung *et al.*, 2016b; Greenan *et al.*, 2019).

The following chapter will evaluate projected future trends across the AOS using publicly available climate projections from model intercomparison projects, which represent the gold standard for model comparison (Tittensor *et al.*, 2018a; Lotze *et al.*, 2019; Boyce *et al.*, 2020; Bryndum-Buchholz *et al.*, 2020).

5.2 Methods

Future changes in fisheries potential across the Northwest Atlantic Ocean and AOS were evaluated using publicly available ensemble climate projections of temperature, net primary productivity (NPP), and plankton and marine animal biomass obtained from coarse-resolution global ESMs and MEMs. Projections from such models should be interpreted with particular caution in regional and/or nearshore settings, particularly in the Northwest Atlantic (Bopp *et al.*, 2013; Loder *et al.*, 2013, 2015). Measures were taken to increase confidence in the validity of the climate projections. First, future trends were estimated as ensemble climate projections from model intercomparison programs. These programs force an ensemble of climate models in a standardized manner, enabling their output to be compared and integrated; they currently represent the highest standard in climate impact studies and provide increased confidence in the validity of climate change projections (Mora *et al.*, 2011; Bopp *et al.*, 2013; Eyring *et al.*, 2019; Lotze *et al.*, 2019; Boyce *et al.*, 2020; Bryndum-Buchholz *et al.*, 2020). Studies have found that by integrating across several model projections, the multi-model average is more reliable than individual projections (Mora *et al.*, 2013a). Second, a newly developed approach, using longitudinal models, was used to estimate ensemble rates of change and their statistical significance (Boyce *et al.*, 2020). The approach is suited to situations where several possibly heterogeneous time-series describe a shared process over time and are thus suited to ensemble modelling. This approach allows the standard error and statistical significance of the ensemble trend to be robustly estimated, which had not previously been the case.

Projected time-series of surface temperature, NPP, and zooplankton carbon biomass between 2006 and 2100 were obtained from the CMIP Phase 5 (CMIP5). Projections were obtained from several published and validated GCMs and ESMs and were forced with a standardized set of inputs (Table 10.2). Projected time-series of marine animal biomass between 2006 and 2100 were obtained from the Fisheries and Marine Ecosystem Model Intercomparison Project (Tittensor *et al.*, 2018b, 2018a), which is part of the Inter-Sectoral Impact Model Intercomparison Project. Projections were obtained from six published and validated global MEMs that are described in Tittensor *et al.* (2018): APECOSM (Maury, 2010), BOATS (Carozza *et al.*, 2016), DBEM (Cheung *et al.*, 2011), DPBM (Blanchard *et al.*, 2012), EcoOcean (Christensen *et al.*, 2015), and the macroecological model (Jennings and Collingridge, 2015). All MEMs were forced with standardized outputs from two ESMs from the CMIP5: NOAA's Geophysical Fluid Dynamics Laboratory Climate Model (GFDL-ESM2M); (Dunne *et al.*, 2012, 2013) and the Institute Pierre Simon Laplace Climate Model (IPSL-CM5A-LR); (Dufresne *et al.*, 2013). All projections were made under RCP2.6, a high-mitigation, low-emission scenario, and RCP8.5, a business-as-usual or worst-case pathway that assumes a continuous increase in emissions until 2100 (Riahi *et al.*, 2011; van Vuuren *et al.*, 2011).

All projections were standardized to relative change (% of the 2006–2016 average) to account for differences in the subsets of marine animals included in the models (Tittensor *et al.*, 2018b). Model projections were combined into ensemble averages to increase the accuracy of the projections (Mora *et al.*, 2011; Bryndum-Buchholz *et al.*, 2018; Lotze *et al.*, 2019; Schewe *et al.*, 2019). Multi-model projections of SST, NPP, zooplankton biomass, and animal biomass were combined using longitudinal models to robustly evaluate the average rates of future change and their uncertainty (standard error and statistical significance; Boyce *et al.*, 2020).

The time of emergence (ToE) of surface temperature and O_2 were used to evaluate projected climate changes in the context of natural variability. The ToE estimates the year in which projected SST or O_2 would exceed the boundaries of its natural, pre-industrial range and was developed and provided by Henson *et al.* (2017). To explore species-specific climate projections that are not provided by the global MEMs, a study using species distribution modelling across the northwestern Atlantic was reviewed (Shackell *et al.*, 2014).

5.3 Ensemble climate projections of temperature, plankton, and animal biomass

Under a business-as-usual, or worst-case emission scenario (RCP8.5), global climate projections to 2100 are similar in direction to those observed in the past. Globally, the oceans are projected to become warmer, to have lower rates of primary production and less marine animal biomass (Mora *et al.*, 2013a; Boyce and Worm, 2015; Lotze *et al.*, 2019; Boyce *et al.*, 2020). Hutchings *et al.* (2012) reported that the global ocean would warm by 2.6°C relative to the 1995–2005 average, with more rapid warming at higher latitudes. Several studies (see (Boyce and Worm, 2015) for a review) have projected global declines in phytoplankton concentration and primary production until 2100, with large spatial variability in the direction and magnitude of changes. Warming is projected to lead to increasing phytoplankton concentrations in the Arctic and Southern oceans and an increase of smaller phytoplankton (Boyce and Worm, 2015). Ensemble projections have recently reported that total marine animal biomass (excluding zooplankton) would decline by 17% (±11% S.D.) under RCP8.5 with an average 5% decline per 1°C warming (Lotze *et al.*, 2019), despite large but uncertain increases at high-latitude locations (Boyce *et al.*, 2020). Under a strong emission mitigation scenario (RCP2.6), projections in temperature, plankton biomass, and animal biomass were similar in direction but of more modest magnitude.

Projected climate changes are more rapid within the AOS than the globally average rates. Under a worst-case emission scenario (RCP8.5), significant ($p < 0.05$) changes in SST, NPP, zooplankton biomass, and animal biomass were projected across the AOS, with spatial variability in the direction, magnitude, and certainty of changes (Figure 5.2). Significant surface warming trends were apparent across all cells within the AOS, with more rapid warming projected north of 45°N (Figure 5.2a). These projections broadly agree with the analyses of ensemble climate projections by Loder and van der Baaren (2013), who reported projected warming of 1–5°C across the AOS, excluding the Arctic, by 2062. Along with this warming trend, the average annual Arctic sea ice extent has been projected to decline by about 15% per degree of global warming (NRC, 2011).

Spatial patterns of projected changes in NPP and zooplankton biomass were similar, suggesting declines across most of the AOS but larger statistically significant declines on the Eastern Scotian Shelf, in Newfoundland and Labrador, and in the high Eastern Arctic (Figure 5.2b–c). Of the cells exhibiting statistically significant changes within the AOS, 96% showed declining NPP, and 99% showed declining zooplankton biomass. These trends broadly agree with global projections of an overall decline in primary production and phytoplankton biomass over the 21st century, with increases at higher latitudes and large spatial variability (reviewed in Boyce and Worm, 2015).

Under RCP8.5, declining animal biomass is projected across most of the southern AOS (<~60°N) with large increases projected in the Arctic (Figure 5.2d). Approximately half (46%) of statistically significant animal biomass trends were declining. Despite differences in methodology, these projections of animal biomass broadly agree with recent reports that under RCP8.5, marine animal biomass will decline from 1971 to 2099 by an average of 7.7% within the entire Canadian EEZ, but with substantial spatial variability (±29.5%); (Bryndum-Buchholz *et al.*, 2020). Biomass in the Atlantic EEZ was projected to decline by 25.5% (± 9.5%), and in the Arctic to increase by 26.2% (± 38.4%). Despite projected increases in cumulative animal biomass in the Arctic, individual species will be adversely affected. For instance, climate change is projected to threaten the persistence of polar bear populations across the Arctic, with severe warming leading to possible extinction by 2100 (Molnár *et al.*, 2020).

Under RCP8.5, all projected SST changes within the AOS were statistically significant (<0.05), whereas only 79% of NPP, 79% of zooplankton biomass, and 56% of animal biomass changes were significant. Under a strong mitigation scenario (RCP2.6), changes in all variables were more modest, and the proportion of significant changes declined: 28% of SST, 36% of NPP, 34% of zooplankton biomass, and 28% of animal biomass trends were statistically significant. Most of the non-significant changes were driven by conflicting projections across ESMs and MEMs.

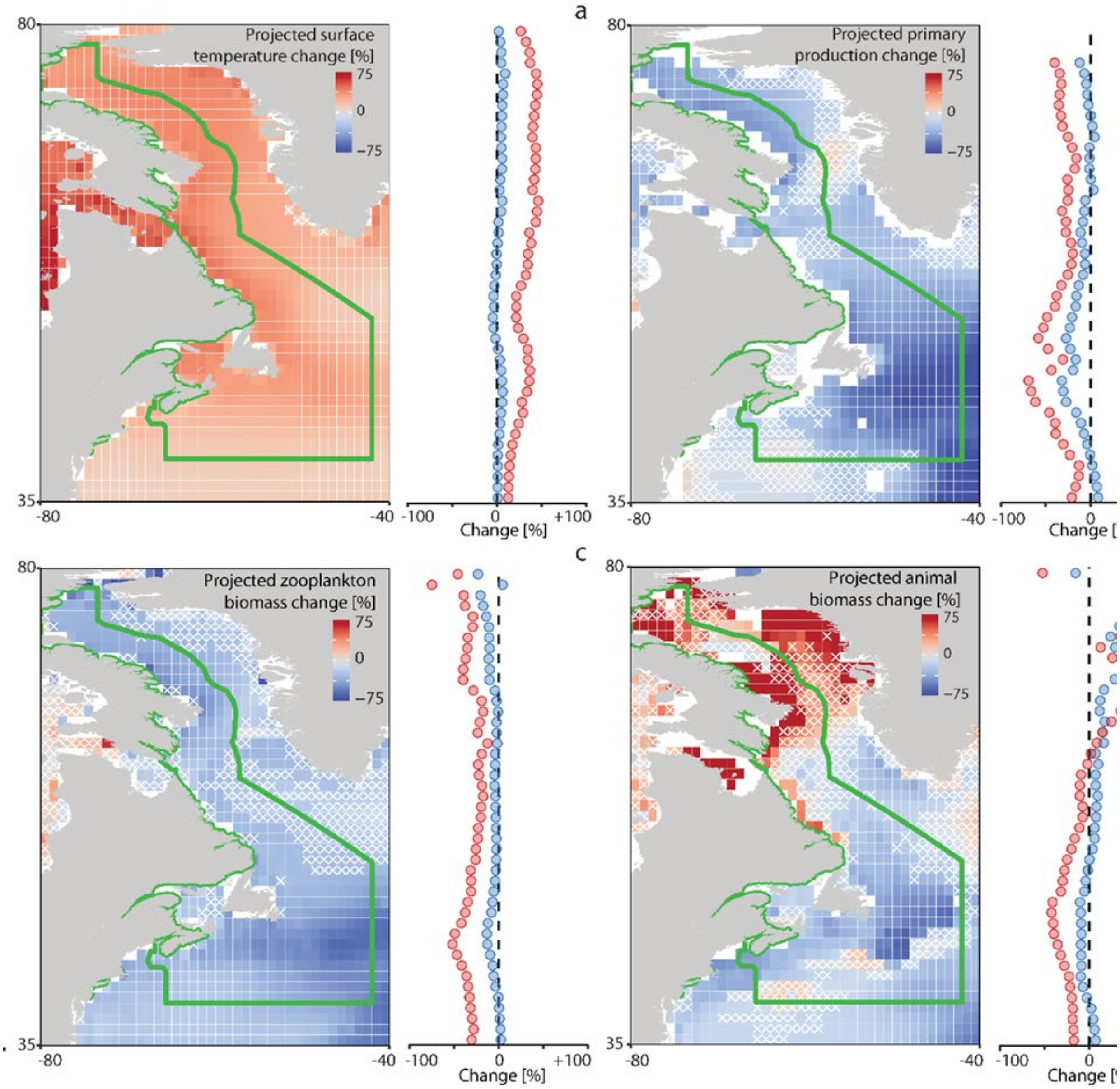

Figure 5.2 Climate projections under RCP8.5 across the AOS.
Maps of projected future change in SST (a), NPP (b), zooplankton biomass (c), and animal biomass (d) between 2006 and 2100, relative to the reference period (2006–2016) under a worst-case RCP8.5 scenario. Red depicts increase and blue decline. Cells with white 'x' depict non-significant changes (p>0.05), which are those that contained insufficient data for analyses. Plots to the right of the maps show the average rate of change along latitude. Red points are projection under RCP8.5, while blue is under RCP2.6. Projected changes were estimated using longitudinal models. Data sources list in Table 10.2.

When averaged across bioregions, these multi-model climate projections under RCP8.5 showed increasing SST and declining NPP, zooplankton biomass, and animal biomass in the Scotian Shelf–Bay of Fundy, Newfoundland and Labrador, and Gulf of St. Lawrence (Figure 5.3). In the Eastern Arctic, rapid SST increases were accompanied by rapid declines in NPP and zooplankton biomass, but non-linear increases in animal biomass.

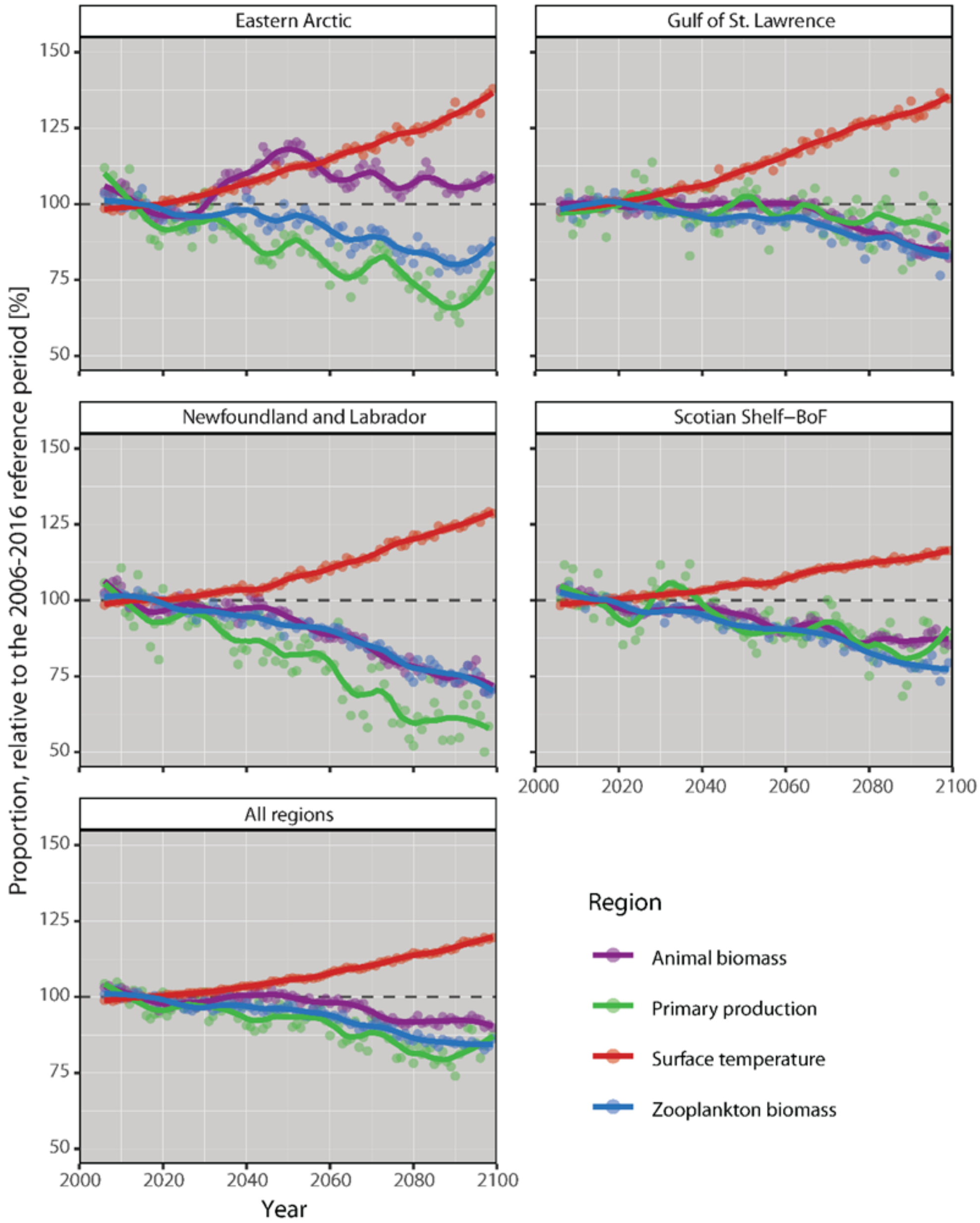

Figure 5.3 Projected time-series under RCP8.5 within and across AOS bioregions.

Multi-model averaged time-series of projected SST (red), NPP (green), zooplankton biomass (blue), and animal biomass (purple) across the regions within the time-series are relative to the reference period (2006–2016) under a worst-case RCP8.5 emission scenario. Data sources list in Table 10.2.

5.4 Projected timing of climate emergence from natural variability

Whereas the direction and magnitude of projected climate changes are important, their impact on species and fisheries will depend on whether these changes will exceed the bounds of natural variability and the tolerances of individual species. Species' responses to environmental change will depend in part on their capacity to adapt to or acclimate to it, which is in part determined by the range of natural variability they inhabit as well as their capacity to respond to it (Williams *et al.*, 2007; Doney *et al.*, 2012; Trisos *et al.*, 2020).

Accordingly, the time at which climate emerges from the natural variability (ToE) provides an estimate of when species will be exposed to novel and potentially harmful climate conditions (Mora *et al.*, 2013b; Henson *et al.*, 2017; Trisos *et al.*, 2020). Under RCP8.5, the surface temperature rapidly emerges from natural variability in many locations across the AOS, particularly in the Gulf of St. Lawrence, Scotian Shelf, and parts of the Eastern Arctic, and 5% of cells within the AOS have already emerged from natural variability (Figure 5.4a). Oxygen concentrations, on the other hand, have already exceeded the bounds of natural variability in 23% of cells within the AOS, including many in the Gulf of St. Lawrence, Eastern Arctic, and Newfoundland and Labrador (Figure 5.4b). Six per cent of cells within the AOS are projected to emerge from their natural variability in both SST and O_2 by the year 2050, most of them in the Gulf of St. Lawrence and Eastern Arctic (Figure 5.4c).

Recently a study extended the ToE approach and estimated the timing at which temperatures were projected to exceed the upper thermal tolerances for >30,000 species across marine and terrestrial systems (Trisos *et al.*, 2020). The study reported that the tolerances for many species would be exceeded nearly simultaneously, potentially causing abrupt ecosystem-wide changes, beginning as soon as 2030 in tropical oceans under RCP8.5. While most rapid exposures were reported for the tropics, the results also suggested that some of the most rapid ecological change would occur in the Scotian Shelf and nearshore Newfoundland and Labrador (Trisos *et al.*, 2020; figure 2).

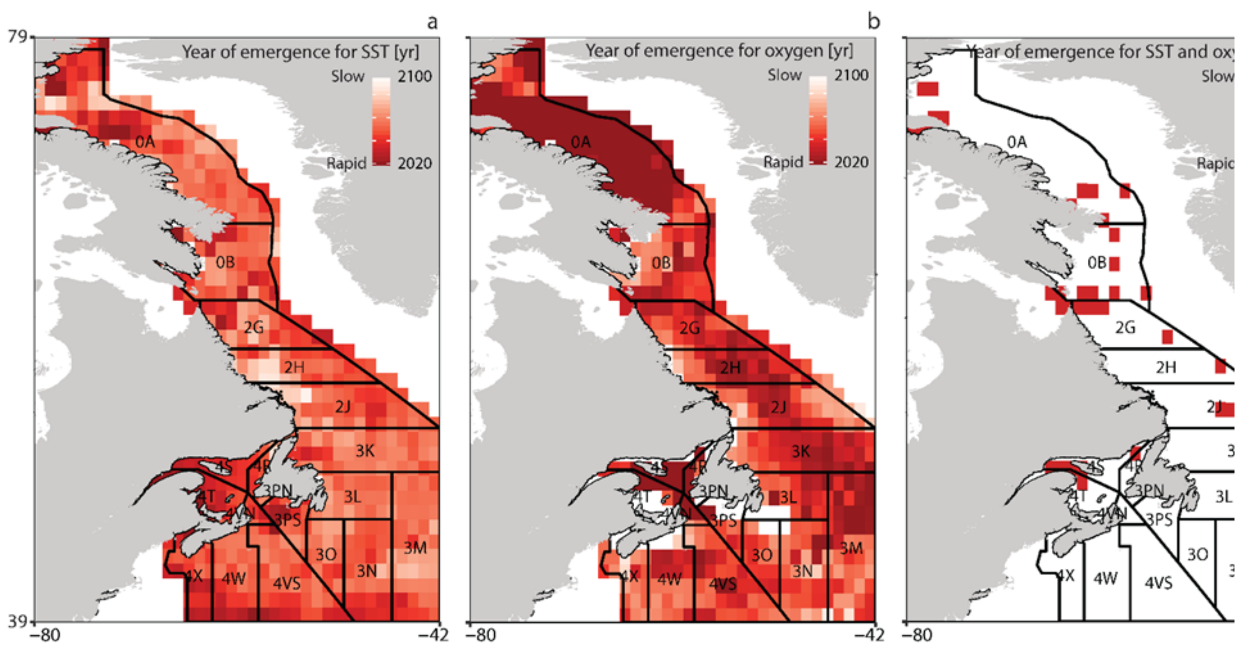

Figure 5.4 Projected time of emergence from natural variability under RCP8.5 across the AOS.

Multi-model averaged year in which the average SST (a) and oxygen (b) are projected to exceed the bounds or their pre-industrial range of variability under RCP8.5. Dark red depicts cells that already have emerged or are more rapidly emerging from natural variability. (c) Locations where both SST and oxygen are projected to exceed natural variability before the year 2050. Data from Bruno *et al.* (2018).

5.5 Climate projections of species distribution

Not all of the global ESMs and MEMs used here cannot project changes at the species level (Tittensor *et al.*, 2018b). However, Shackell *et al.* (2014) developed a species distribution modelling approach to predict changes in the thermally suitable habitat of 46 marine species in the Northwest Atlantic (~35°N to ~48°N) under short- (2030) and long-term (2060) warming scenarios. The study suggested that by 2060 most species (55%) in the Canadian EEZ would lose thermal habitat, with 21% gaining and 24% remaining constant. In the US, 65% of species would lose thermal habitat, with 20% gaining and 15% remaining constant. In Canada, highly commercial species were projected to gain thermal habitat, while those in the US would lose; this trend was driven by lobster, which dominated the combined value in Canada. As a group, planktivores such as herring, sand lance, and capelin were predicted to lose significant habitat in both Canada and the US. This is troubling, as these forage species are critically important keystone species in many marine food webs and support a range of valuable higher trophic level fisheries. The changes in thermal habitat were more modest when projecting over the shorter term (2030s). An important caveat to the use of such correlative approaches is the inability to account for the effects of species interactions that may alter the distribution patterns predicted by climate alone.

5.6 Climate change impacts in relation to fisheries productivity and ecosystem stressors

Analyses were undertaken to understand what the historical and projected future climate-driven changes in marine ecosystems reported here could mean for Canadian fisheries and whether they may interact with other stressors. Spatial patterns of projected climate-driven changes in marine animal biomass (Figure 5.2d) were evaluated against historical and present-day patterns of reported fisheries landings and ecosystem stressors (Figure 4.5) across the AOS. When averaged within each NAFO division, the historical time trends in total reported fishery landings (1960–2018) were positively related to the statistically significant projected future trends in animal biomass (2006–2100) under both the RCP8.5 worst-case ($r = 0.74$) and RCP2.6 strong mitigation ($r = 0.8$) scenarios (Figure 5.5a). These relationships were largely unchanged when using all projected trends in animal biomass rather than only those that were statistically significant under RCP8.5 ($r = 0.69$) and RCP2.6 ($r = 0.75$). This indicated that areas experiencing the greatest decline in fishery landings over the past ~60 years would also experience the largest climate-driven losses of animal biomass over the next ~80 years.

The analyses suggested that NAFO divisions that currently support the highest total fishery landings (2000–2018) are projected to lose the greatest biomass of marine animals due to climate change under both emission scenarios (Figure 5.5b). The relationships between landings and projected biomass changes were negative under both RCP8.5 ($r = -0.68$) and RCP2.6 ($r = -0.7$) and became only minimally weaker when using all projected trends rather than only those that were significant ($p<0.05$). These relationships suggest that fisheries across the AOS will be disrupted by ongoing climate change and that the magnitude will depend strongly on emission mitigation. Under both scenarios, fisheries will either need to track the spatial redistribution of fisheries biomass or experience declines in total landings. Either way, a major disruption of the fishing industry is likely, particularly under the RCP8.5 worst-case emission scenario. These patterns between climate-driven changes in biomass and fishery dynamics have also been reported globally, suggesting that under a worst-case scenario, disruptions to fisheries will extend outside of the AOS, with widespread socio-economic implications.

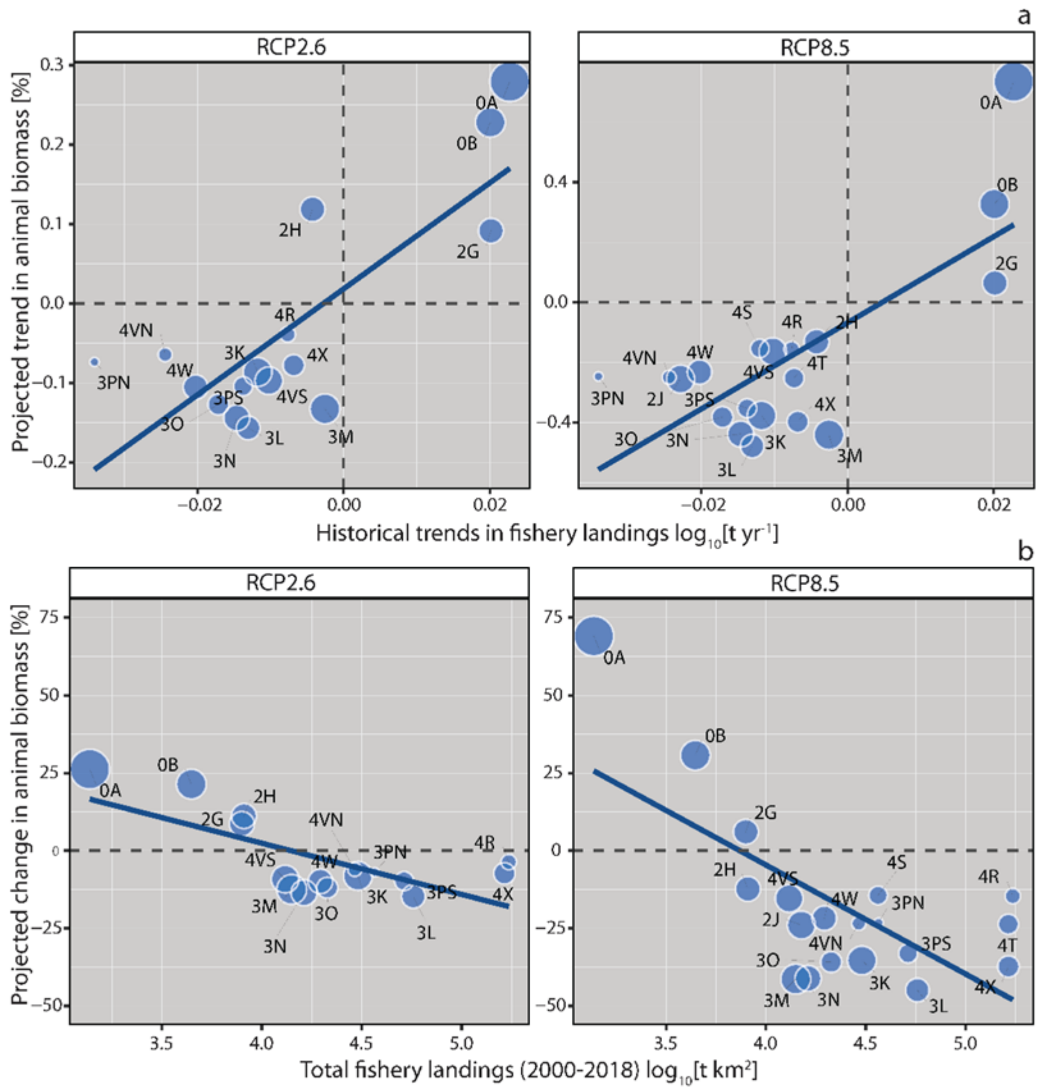

Figure 5.5 Future changes in animal biomass in relation to historical fishery landings across the AOS.

(a) Multi-model projected future changes in animal biomass (2006–2100), as a proportion of present levels in relation to the total fishery landings (2000–2018) in each NAFO division. (b) Multi-model projected future trends in animal biomass (2006–2100), as a proportion of present levels in relation to the historical trends in total fishery landings (1960–2018) in each NAFO division. (a–b) Left panels are projections under the RCP2.6 strong mitigation scenario, and the left is under the RCP8.5 worst-case scenario. Symbol sizes depict the area of the NAFO divisions. Lines are the best-fitting regression lines. Data sources list in Table 10.1 and Table 10.2.

Spatial patterns of the future climate-driven changes in marine animal biomass were evaluated against present-day patterns of cumulative HIIs (Figure 4.5). Negative relationships were found between the HII and statistically significant future changes in animal biomass within each 1° cell across the AOS, under both RCP8.5 (r = −0.74) and RCP2.6 (r = −0.69); the relationships were slightly weaker when using all future trends rather than only those that were significant (Figure 5.6). Since the models used to project animal biomass do not account for non-climate stressors, these relationships suggest that the projected declines in animal biomass may be underestimates as additional stressors (e.g. pollution) may amplify them.

An index of cumulative climate change was calculated by integrating the historical and projected future trends reported here with the HII (see Appendix C: Cumulative climate change across the AOS for details). The index is dimensionless, with higher values denoting locations where climate changes have been more rapid or human impacts have been larger. While cumulative climate changes were found across the entirety of the AOS, they were largest in the Eastern Arctic, followed by the Gulf of St. Lawrence, Scotian Shelf–Bay of Fundy, and Newfoundland and Labrador (Figure 5.7a). In particular, NAFO divisions 0A (high Arctic), 4T (Southern Gulf of St Lawrence) and 4X (western Scotian Shelf and Bay of Fundy) had the greatest cumulative climate changes, while 2G and 2H (northern Labrador) had the lowest. Examining these cumulative climate changes in relation to fishery productivity (Figure 5.7b) and status (Figure 5.7c) could be useful in identifying regions and/or species that are most in need of climate-relevant management responses. For example, areas subjected to large climate changes that also support the most currently productive fisheries (e.g. NAFO divisions 4X, 4T) or that have high stock-status uncertainty (e.g. Eastern Arctic) could potentially be focal areas for the incorporation of climate and ecosystem considerations. Alternatively, areas subjected to large climate changes that currently have low fishery landings (e.g. divisions 0A, 0B) could be identified as priority areas to prepare for new fisheries and opportunities and to apply precautionary and adaptive management. Whereas climate and ecosystem considerations should be incorporated into all Canadian fisheries, locations that have lower relative climate impacts and that are less intensively fished (*e.g.* divisions 2G, 2H) could potentially be of lower priority.

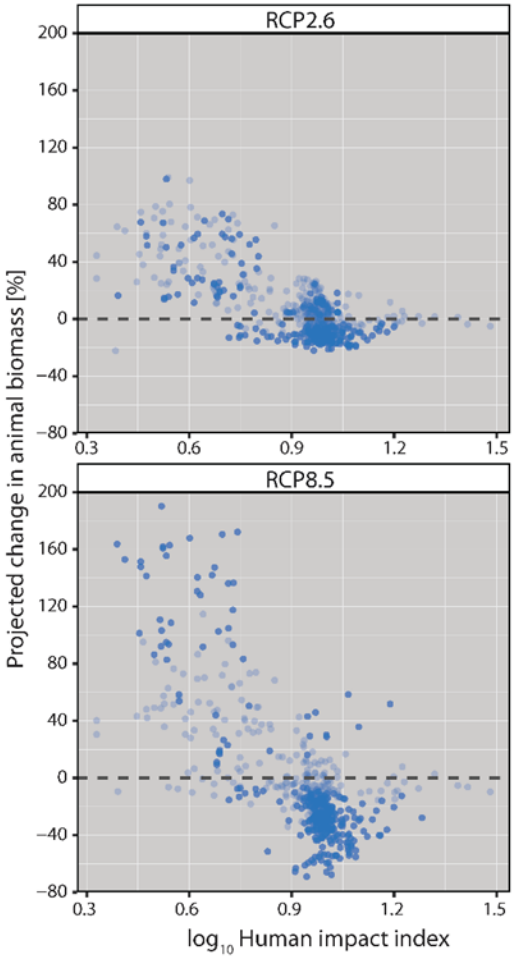

Figure 5.6 Future changes in animal biomass in relation to present-day patterns of human impacts across the AOS.

Multi-model projected future changes in animal biomass (2006–2100), as a proportion of present levels in relation to the average HII in each 1° grid cell across the AOS. The top panel contains projections under the RCP2.6 strong mitigation scenario, and the bottom under the RCP8.5 worst-case scenario. Dark blue points are projected trends that were statistically significant ($p<0.05$), and light blue ones, non-significant. Data sources list in Table 10.1 and Table 10.2.

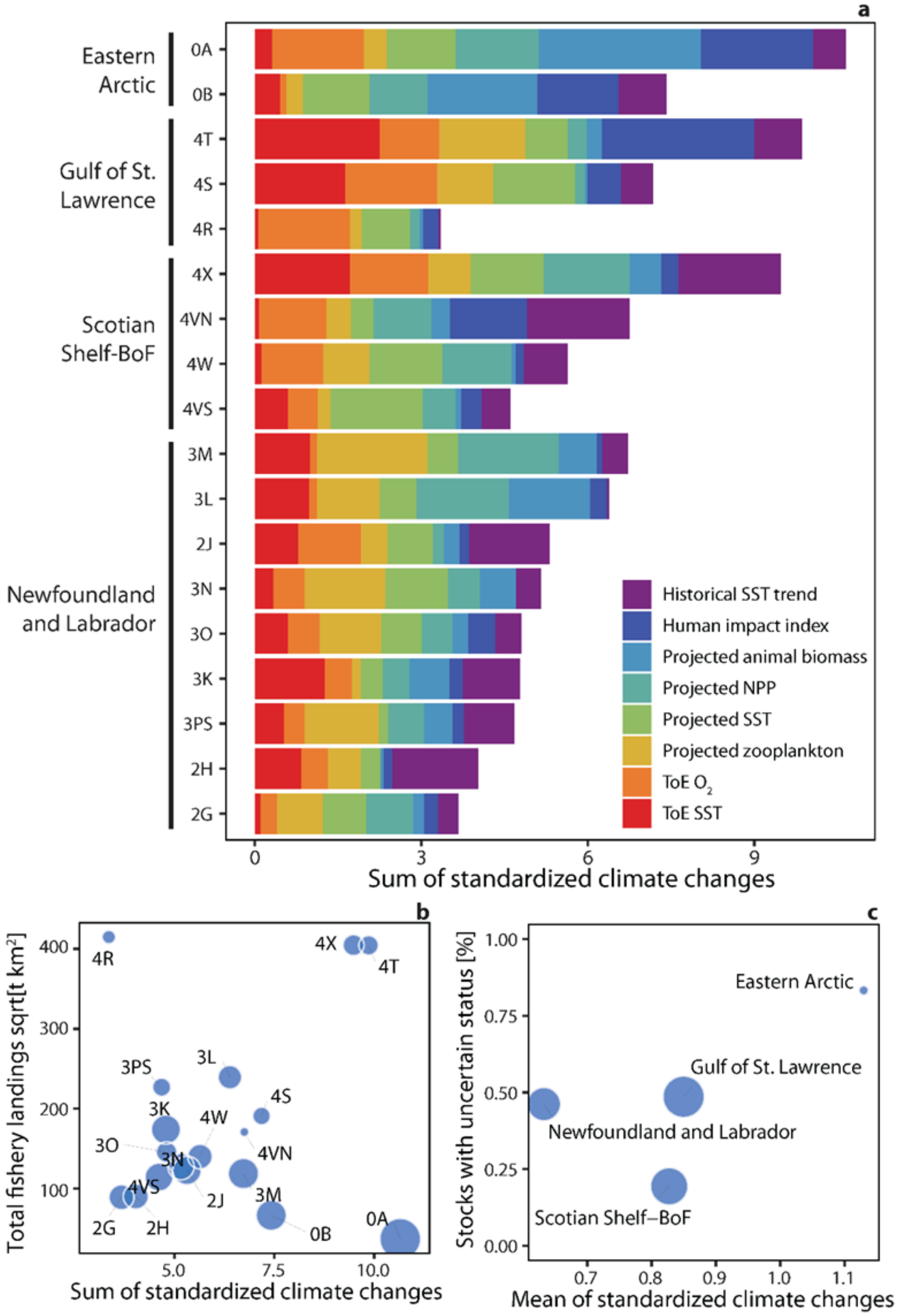

Figure 5.7 Cumulative climate impacts in relation to fisheries productivity and status across the AOS.

a) Sum of standardized historical and future climate changes across NAFO divisions and bioregions within the AOS. Colours depict the climate change variable. (b) Sum of the standardized climate changes against the total reported fishery landings within each division. (c) Mean of standardized climate changes against the proportion of all stocks that have uncertain status. Symbol sizes depict the geographic area (b) and the number of stocks (c). Data sources list in Table 10.1 and Table 10.2.

5.7 Key points

- Climate projections across the AOS under a worst-case emission scenario indicate widespread surface warming and deoxygenation, and declining NPP, zooplankton biomass, and animal biomass (but increasing in the Eastern Arctic).
- Novel climate conditions in surface temperature and dissolved oxygen have already emerged from the background of natural variability in many locations within the AOS.
- Climate-driven changes in the AOS are projected to be abrupt and to occur in the next 20–30 years, with the most rapid changes projected on the Scotian Shelf and nearshore Newfoundland and Labrador.
- Fifty-five per cent of species in the AOS south of 45°N are projected to lose thermal habitat by 2060, and 21% to gain habitat.
- Across the AOS, geographic patterns in the historical trends in total reported fisheries landings (1960–2018) closely mirror those of projected future changes in animal biomass (2006–2100).
- Under both emission scenarios, climate-projected declines in animal biomass would be more severe in NAFO divisions that currently support the largest fishery landings, a trend that has also been reported globally.
- Globally and across the AOS, climate-driven declines in animal biomass will be more severe in areas that are presently more impacted by cumulative human impacts (e.g. pollution), suggesting that climate effects on fisheries may be aggravated by additional stressors.

6. Incorporating climate change into fisheries management: approaches and best practices

6.1 Summary

Evaluating the best practices to integrate climate change considerations into fisheries management can be facilitated by thinking about the process of fisheries management and what it entails. This report adopts the broad definition of fisheries management established by the FAO as "the integrated process of information gathering, analysis, planning, consultation, decision-making, allocation of resources and formulation and implementation, with enforcement as necessary, of regulations or rules which govern fisheries activities in order to ensure the continued productivity of the resources and the accomplishment of other fisheries objectives" (FAO, 1997). Following this definition, a generalized outline is presented, which depicts the main steps and processes that are used to manage most marine fisheries (Figure 6.1). Regardless of the overarching management objectives, principles, and priorities (red in Figure 6.1), be they, for instance, climate change integration, an ecosystem approach to fisheries (EAF), or the precautionary approach to management, the steps in the integrated management process are broadly similar and vary only in the details of how each step is carried out. In brief, these steps include data and information gathering (yellow in Figure 6.1), quantitative stock assessments, knowledge generation and advice (green in Figure 6.1), decision-making (turquoise in Figure 6.1), and implementation of tools and actions (blue in Figure 6.1). The extent to which real-world fisheries are managed can substantially differ from this idealized process depending on many factors. For instance, the uptake of scientific information into management advice can be influenced by, for instance, governance models, political regimes, the geographic region, information management cultures of science and management domains, and personal and institutional interests and the interests of various stakeholders (Delaney and Hastie, 2007; Wilson, 2009; Soomai *et al.*, 2011; Cossarini *et al.*, 2014) in such a way that management decisions can be less science based.

Guided by the overarching management mandates and priorities for the fishery and guidance from decision-makers, various data and information sources are used, in combination with quantitative tools, to address key requirements and/or questions posed by decision-makers about the state of the fishery and which actions are to be taken to achieve the desired outcomes. Enforcement could be an additional step but is excluded here as it is less relevant for climate change integration. The type of data and quantitative tools used and the knowledge produced could vary substantially depending on the information that is requested by decision-makers. For example, whereas EAF could require ecosystem monitoring data and multispecies assessment models (Koen-Alonso *et al.*, 2019), dynamic management may instead require high-resolution remote sensing data and mathematical forecasting models (Dunn *et al.*, 2011, 2014; Lewison *et al.*, 2015). The structure of the decision-making process can also vary but generally involves the translation of science and advice into the implementation of management actions and tools. The last step involves the administration of various management actions and tools outlined by decision-makers to achieve the desired outcomes. While the details of these steps can vary, they are, for the most part, generalizable across most fisheries, and differ only in the type of data, quantitative tools, knowledge and advice required, decision-making structure, and administration tools used. Importantly, this schematic explicitly acknowledges that the choice of decision-making system and administrative actions taken will very likely depend on the data and information collected and the way that they are quantitatively processed. Thus, implementing climate and/or ecosystem considerations in fisheries management will necessitate changes across several stages of this integrated process.

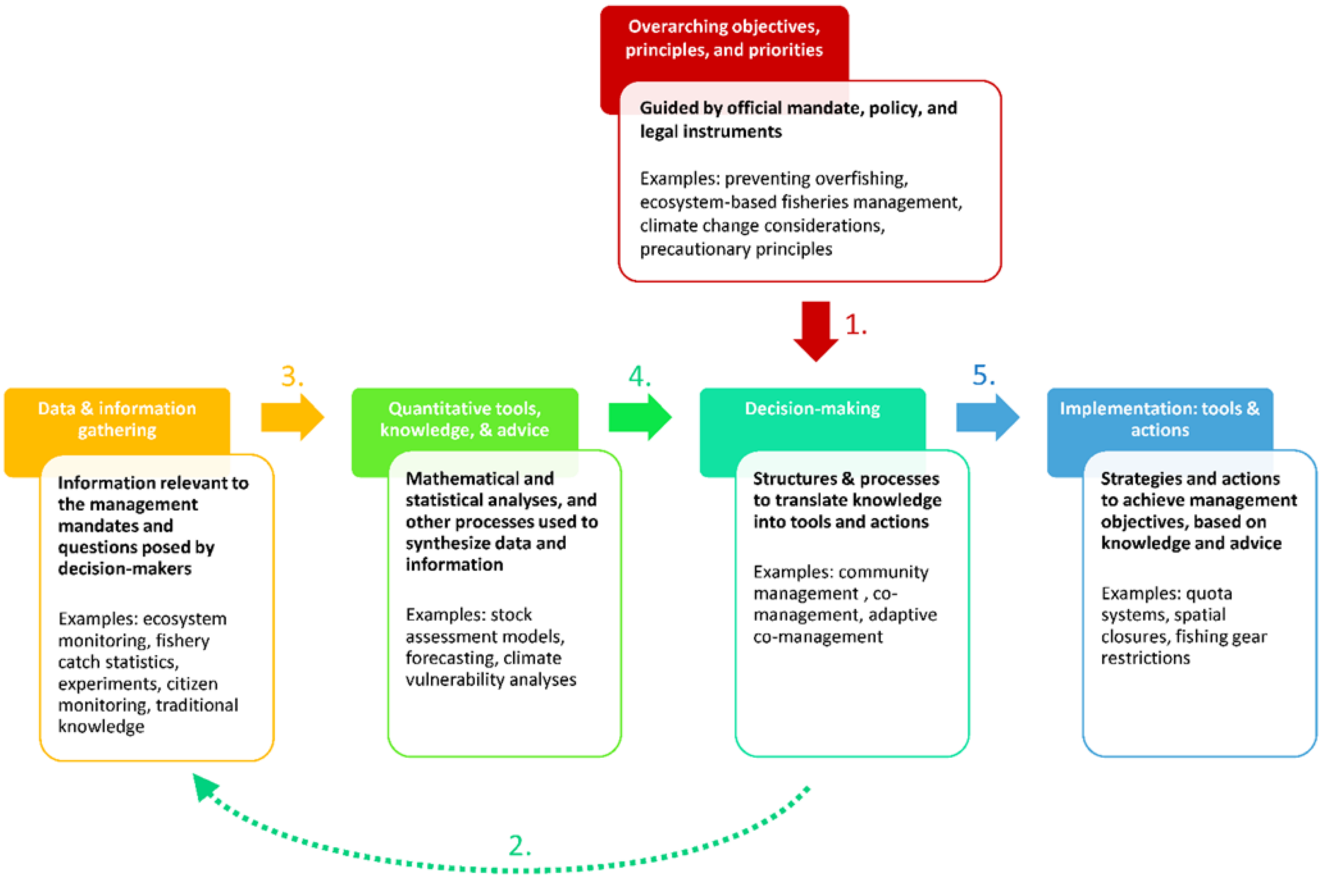

Figure 6.1 A generalized outline of the processes of fisheries management.
Colours and boxes depict the main steps and processes involved in managing fisheries. Arrows represent how these processes are connected and the order in which they occur. Guided by the overarching objectives, principles and priorities (red) and decision-makers (turquoise) request information and pose questions that lead to information (yellow) being synthesized into advice (green). Lastly, decision-makers (turquoise) translate knowledge and advice into management tools and actions (blue).

From the previous chapters, it should be clear that without adequately incorporating climate change considerations, the effectiveness of fisheries conservation and management will likely deteriorate, leading to reduced fisheries performance and missed opportunities as well as risks to vulnerable stocks (e.g. Figure 5.7). In response to this, many fisheries agencies around the world are developing tools and approaches to incorporate climate change considerations into their fisheries management frameworks. One of the overarching objectives of these efforts is identifying climate-informed reference points (Link *et al.*, 2015; Busch *et al.*, 2016). Reference points are critical thresholds used in the decision-making process, including, for example, single-species estimates of maximum sustainable yield (MSY), multispecies fishing rates, and thresholds for ecosystem-level indicators. In Canada, they are also critical to the implementation of the precautionary approach to fisheries management (DFO, 2006a). Currently, most assessments estimate reference points using stock assessment models that assume that future natural variability will reflect the range of conditions that have been observed in the past. However, as this report has shown, climate change is creating novel conditions (e.g. Figure 5.4), and reference points based on historical dynamics may not be accurate (Pershing *et al.*, 2015; Britten *et al.*, 2016, 2017). There is no uniform consensus about how to optimally identify climate-informed reference points or how to ensure that fisheries management strategies are robust to climate change. However, most emerging approaches require a high level of observational data and knowledge and feature common principles that are centred on understanding if, how, and why climate change will impact species, which species will be at risk, and how conditions will change in the future; incorporating risk and uncertainty, ecosystem considerations, precaution, flexibility and responsiveness, and proactivity; and enhancing capacity and resilience. This chapter will review these various aspects and principles with the implicit understanding that no single approach is suitable for all fisheries or circumstances. The information is summarized under the four primary categories outlined previously: data and information gathering; quantitative stock assessments; knowledge generation; and advice, decision-making, and implementation and actions. A fifth category (management principles) outlines high-level concepts and principles that can pervade all steps in the management process and increase the climate readiness of fisheries management.

6.2 Overarching management objectives, principles, and priorities

Overarching management principles and approaches are often mandated in policy and legislation but can also be informally incorporated into the management process as a means of achieving these policy objectives. For example, whereas climate change is not explicitly mentioned in Canada's Fisheries Act, incorporating climate considerations into management will be essential to meet its mandated objectives of ensuring healthy and sustainable fisheries. However, a common feature of overarching management principles and objectives is that they often supersede and encompass several steps in the management process. The following section explores overarching objectives, principles, and priorities that could facilitate climate change integration into the fisheries management process.

6.2.1 Minimizing abatable stressors and promoting healthy fisheries

The cumulative impacts of individual abatable non-climate stressors, including pollution, overfishing, bycatch, and habitat alteration, can reduce the resistance and resilience of species and ecosystems to climate change. When stressors occur simultaneously, they can additively or synergistically act to amplify or attenuate the impact of a single stressor (Crain *et al.*, 2008; Poertner, 2010; Gruber, 2011), potentially increasing the severity of climate effects on ecosystems and species. Reducing abatable stressors and instituting effective and sustainable fisheries management can, in many instances, counter the deleterious effects of climate change on fisheries productivity (Le Bris *et al.*, 2018).

6.2.2 An ecosystem approach to fisheries

As this report has demonstrated, climate change will cause direct effects on species and populations as well as a multitude of indirect effects that will cascade through the ecosystem, impacting fisheries resources through complex pathways. As such, incorporating climate change considerations into fisheries management will also require an EAF and adopting the principles therein (e.g. Koen-Alonso *et al.*, 2019). In brief, the FAO states that "the purpose of an ecosystem approach to fisheries is to plan, develop and manage fisheries in a manner that addresses the multiplicity of societal needs and desires, without jeopardizing the options for future generations to benefit from a full range of goods and services provided by marine ecosystems." Therefore, "an ecosystem approach to fisheries strives to balance diverse societal objectives, by taking account of 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." EAF is conceptually similar to ecosystem-based fisheries management (EBFM) but is broader in its scope, considering not only management but a range of additional activities including, for instance, development, planning, and food safety (Garcia *et al.*, 2003).

6.2.3 Precautionary approaches

Climate change will introduce new sources of uncertainty to fisheries science and management in situations where climate patterns and their effects on species are not well understood. Erring on the side of precaution when uncertainty regarding the stock status and climate impacts is high would provide a buffer against this uncertainty. Measures could include lowering quotas or instituting moratoria until the uncertainty is reduced to sufficient levels.

6.2.4 Enhancing ecological stability

There is evidence that targeted management actions aimed at facilitating particular species or ecosystem functions (e.g. resilience) can be effective at minimizing the adverse effects of climate change, and in some instances, amplifying the positive effects (Le Bris *et al.*, 2015, 2018). For example, Le Bris *et al.* (2018) found that management initiatives to conserve large female lobsters in the Gulf of Maine have led to higher resilience to ocean warming and productivity of the lobster population there when compared to populations in adjacent southern New England, where large individuals were less strictly conserved (Le Bris *et al.*, 2018). Without conservation measures to protect large lobsters and female reproductive lobsters, lobster abundance in the Gulf of Maine would have increased by 242% rather than 515%, as oceans warmed between 1985 and 2014 (Le Bris *et al.*, 2018). Additional studies also suggest that preserving large females can increase resilience to exploitation (Le Bris *et al.*, 2015) and reduce fluctuations caused by climate variability (Hsieh *et al.*, 2006). These results contribute to a growing body of research suggesting that protecting large individuals and predators, in particular, can enhance the resilience of populations to stressors, such as climate change and exploitation (Britten *et al.*, 2014; Le Bris *et al.*, 2015). For example, the selective removal of large-bodied northern cod in Atlantic Canada compromised the resilience of the population, precipitating the collapse that followed several years of high exploitation and poor environmental conditions (Drinkwater, 2002). Britten *et al.* (Britten *et al.*, 2014) reported long-term declines in large predator fish abundance due to overharvesting in a Mediterranean coastal fish community that was associated with reduced stability (resistance, resilience, reactivity) in the ecosystem. Harvest strategies based on fundamental biological principles, such as maintaining large individuals and predators in the population, can therefore dampen negative effects of perturbations such as climate change (Baum and Worm, 2009; Ferretti *et al.*, 2010; Britten *et al.*, 2014; Le Bris *et al.*, 2015; Gendron *et al.*, 2019).

Biodiversity at genetic, species, and ecosystem scales has also been widely associated with increased resilience and productivity in marine ecosystems (Johnson *et al.*, 1996; Frank *et al.*, 2006, 2007; O'Gorman *et al.*, 2008; Petrie *et al.*, 2009b; Boyce *et al.*, 2015b; Lefcheck *et al.*, 2015). Worm *et al.* (Worm *et al.*, 2006) reported that declining species diversity had been associated with increased resource collapse and exponential declines in population recovery potential, stability, and water quality. In contrast, restoring biodiversity increased ecosystem productivity fourfold and decreased variability by 21% (Worm *et al.*, 2006). Likewise, the erosion of spatial subpopulations has also been associated with reduced stability and persistence of populations, rendering them more susceptible to anthropogenic and environmental stressors (Ciannelli *et al.*, 2013). Thus, avoiding species collapses and associated ecosystem restructuring and preserving biodiversity diversity are key elements in ensuring that fisheries are best positioned to withstand the deleterious effects of climate change.

6.3 Data and information gathering

6.3.1 Ecosystem monitoring

As previous chapters have emphasized, climate change can affect species through a multitude of direct and indirect pathways that can propagate through ecosystems. Integrating climate change considerations will, therefore, require a broad, ecosystem-level consideration (Table 4.1). Collecting frequent information related to environmental conditions, including human impacts, and changes in predator and prey abundances and incorporating this into fisheries management will be increasingly important as climate change continues. Frequent field observations of climate change–relevant biophysical factors and habitat features, including water temperature, plankton, chemistry, hydrography, and others, are necessary to understand how climate effects are being manifest in marine ecosystems and to enable early-warning detection systems. Such observations form the basis from which relationships between climate change and fisheries can be formed and understood (Figure 2.1).

Monitoring has been vital to the effectiveness of traditional fisheries stock assessment approaches and will become even more so under climate change, as the spatial distribution, phenology, migration patterns, and trophic interactions of exploited species may be shifting. Data sources that are long term will also be needed that can disentangle natural variability from climate change and its impacts on fisheries. While progress has been made within government agencies (Pepin *et al.*, 2020), it is clear that a broader source of knowledge can improve efforts to adapt to climate change. These requirements have also led to the increased use of additional or non-traditional data sources such as digital data rescue, environmental DNA (eDNA; Baillie *et al.*, 2019), citizen science monitoring, and traditional ecological knowledge (TEK) being used in fisheries management (Fairclough *et al.*, 2014; Dunmall and Reist, 2018; Fulton *et al.*, 2019). For example, "Send Us Your Skeletons" is an Australian citizen science program that asks recreational fishers to donate fish skeletons that are then used to estimate age structures and conduct stock assessment analyses (Fairclough *et al.*, 2014). Redmap (Range Extension Database and Mapping project) is another Australian citizen science program that allows citizens to log uncommon marine species in order to identify geographic range shifts[2]. Technological advances (e.g. smartphones, social networking, internet access) have increased the rate and scale of information transfer, making such citizen monitoring/science programs a more cost-effective and feasible option, particularly where traditional monitoring is less feasible, such as in the Arctic (Dunmall and Reist, 2018). For example, "Arctic Salmon"[3] is a successful citizen science program that monitors salmon species across the Canadian Arctic (Dunmall *et al.*, 2013). The program was developed by DFO in 2000, out of community interest in monitoring the increasing harvest of Pacific salmon (*Oncorhynchus* spp.) in the Northwest Territories. Through increased communication and outreach, the program was expanded to the entire Canadian Arctic in 2011, and the mandate was expanded to explore the geographic origins of harvested salmon, interactions with local fisheries, and the identification of salmon species. Through the program, harvesters can voluntarily report their salmon catch, provide samples for scientific study, and receive a financial reward for their contribution. The project has led to an increased understanding of salmon population dynamics, as well as how climate change is impacting salmon and Arctic ecosystems. The program has demonstrated the potential value of citizen science, TEK, and co-management in addressing data and knowledge limitations, particularly in large, remote areas. A similar community-based monitoring program also exists in the Arctic to track the health of beluga whales in the Tarium Niryutait Marine Protected Area and was expanded to also monitor environmental variables including water temperature, salinity, and ice thickness (Niemi *et al.*, 2019). Likewise, the LEO Network[4] was created by the Alaska Native Tribal Health

[2] https://www.redmap.org.au/
[3] http://www.arcticsalmon.ca/
[4] https://www.leonetwork.org/en/#lat=28.4904&lng=80.9845&zoom=7

Consortium in 2012 as a tool to help the tribal health system and local observers to share information about climate and other drivers of environmental change in Canada and elsewhere.

6.4 Quantitative stock assessments, knowledge generation, and advice

6.4.1 Climate-considered stock assessment models

Uncertainty pervades fisheries management at the best of times, but climate change is introducing additional sources of uncertainty, such as changing spatial distributions and productivity patterns, that will need to be considered when making management decisions. As climate change continues to create novel and extreme climate and ecosystem conditions, estimating baseline conditions and reference points for fisheries, which form the basis for most fisheries management decisions, will become increasingly challenging and uncertain. Consequently, assessment models will need to change to reflect increasingly variable and novel climate conditions (Melnychuk *et al.*, 2014; Britten *et al.*, 2016, 2017) as well as new and possibly unknown sources of uncertainty. Fortunately, assessment methods are available that are better suited to such circumstances, and that can evaluate dynamic changes in biological parameters and the robustness of different harvest strategies to a broad range of assumptions and uncertainties (Chin *et al.*, 2010; Hobday *et al.*, 2011; Le Bris *et al.*, 2018).

Non-stationary stock-recruitment parameters and biological reference points

Whereas traditional assessment methods often assume that population parameters (e.g. mortality, growth) and fishery attributes (e.g. selectivity, catchability) are temporally stationary, there is growing evidence that such attributes can vary over time in response to, for instance, temperature (McCarty, 2001; Walther *et al.*, 2002; Genner *et al.*, 2004), regime shifts (Holbrook *et al.*, 1997), the level (Pondella II and Allen, 2008) and nature (Hilborn and Walters, 1992) of exploitation, ecosystem factors (Tyrrell *et al.*, 2011; Neira and Arancibia, 2013), and stock distribution (PETERMAN and STEER, 1981). Through a meta-analysis of 224 fish stocks, Szuwalski et al. (2015) reported that recruitment frequently varied over time and was often more strongly driven by the environment than SSB. Britten *et al.* (2017) evaluated 276 fish stocks using hierarchical models of dynamic stock productivity and found that 68% of these exhibited non-stationary trends in their intrinsic rate of population growth (r). The practical consequences of failing to account for productivity variation due to climate or other factors is that estimates of biomass available for harvest can be biased, leading to over- and under-exploitation. For example, prior to the collapse and fishing moratorium of Atlantic cod in the Gulf of St. Lawrence in the early 1990s, catches remained high even as realized surplus production became negative (Britten *et al.*, 2017). Through the use of time-varying estimation of r, long-term declines in surplus production and sustainable yield were identified (dashed lines in Figure 6.2), whereas static methods did not (Figure 6.2). In this situation, the use of static models led to systematic over- and underestimates of biomass, and to periods of silent over- and underfishing (red and grey shading in Figure 6.2b). Consequently, fisheries models with time-varying parameters are increasingly used, particularly as an approach to incorporating climate variability and change (SCHNUTE, 1994; Peterman *et al.*, 2000; King *et al.*, 2015; Britten *et al.*, 2017).

Approaches to achieving this vary in complexity and are situational but, in general, seek to more dynamically adjust stock-recruitment parameters and biological reference points as the environment and stock status changes. For example, species in the eastern Bering Sea experience alternating regime shifts driven by the Pacific Decadal Oscillation (Hare and Mantua, 2000) and reference points for snow crab (*Chionoecetes opilio*) are estimated only after a climate shift has occurred (Szuwalski and Punt, 2013). In California, Pacific sardines (*Sardinops sagax*) have been found to be more productive when ocean temperatures are near 17.5°C (JACOBSON and MACCALL, 1995), and simulations indicate that lower harvest rates during cold periods could have mitigated the sardine collapses that occurred in the 1950s (Lindegren *et al.*, 2013). Based on these findings, ocean temperature has been incorporated into the harvest rule for sardines such that a larger fraction of the available stock is allowed to be harvested in warmer rather than colder years, though never more than 15% or less than 5% (Pinsky and Mantua, 2014). In other situations, time-varying parameters (e.g. growth, recruitment, mortality) are incorporated using more complex analytical methods with parameters allowed to vary over time according to a random walk process or Kalman filter (SCHNUTE, 1994; Peterman *et al.*, 2000; Britten *et al.*, 2017).

Such time-varying approaches rarely incorporate climate or ecosystem information directly. Instead, they statistically estimate the time-variation in biological parameters that may be related to changing climate, ecological conditions, exploitation regimes, or other factors. Thus, they can facilitate the examination of biological and fisheries characteristics at climate-relevant scales, regardless of the actual impacts (if any) of climate change. In this respect, they are immensely appealing; they can potentially evaluate fishery changes dynamically, regardless of the factors driving them. They are also relatively cost-effective and straightforward to implement. With sufficient monitoring data and technical knowledge, dynamic assessment models could be rapidly implemented across most fisheries (Britten *et al.*, 2017). Despite these advantages, time-varying estimation approaches are also limited in some important respects. For example, climate-driven shifts in species distribution or phenology would likely be identified as, for instance, declining productivity when in fact productivity has merely been displaced spatially or temporally. Interpreting and communicating management recommendations under dynamic reference points can also be challenging and counterintuitive due to the complex interplay between a stock's status (e.g. SSB), relative to a dynamic productivity regime. For instance, declining SSB trends may trigger a reduction in quota if it falls under the fixed limit reference point, yet if the environmental productivity regime and corresponding limit reference points have also increased, the quota can potentially be increased even though SSB is in decline. Evaluating climate changes and its impacts may identify important biological changes that are not captured by time-varying estimation routines. Additional information, including, for instance, spatial indicators of changing distribution, may therefore be particularly important to supplement time-varying estimation approaches. It is also unclear how reliable such time-varying approaches are when time-series are short or when biological parameters change in a dynamic and simultaneous manner. While simulation analyses have shown that such time-varying approaches can outperform those that are time invariant, their performance in real-world settings has not been rigorously evaluated. The usefulness of dynamic models would be strengthened by coupling them with detailed ecosystem monitoring data and knowledge of climate effects. Ideally, such time-varying estimation approaches can be combined with those that also directly incorporate climate and ecosystem considerations while evaluating risk and uncertainty, such as management strategy evaluation (MSE; see below).

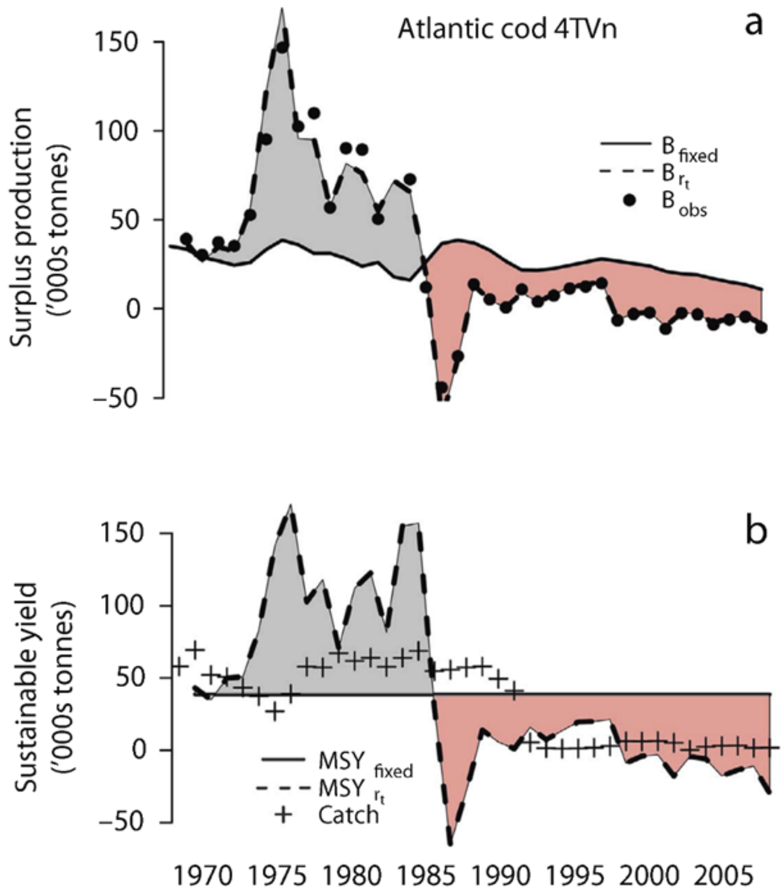

Figure 6.2 Example of non-stationary productivity in Atlantic cod from the Southern Gulf of St. Lawrence in Canada, NAFO Division 4TVn.

(a) The annual surplus production (circles are observed values, B_{obs}; the solid line is the biomass predicted from a model with fixed *r*, denoted B_{fixed}; and the dashed line is the biomass predicted from the non-stationary model, B_{rt}). (b) The theoretical maximum sustainable yield (crosses are recorded catches). Grey shading indicates when productivity is higher than would be predicted based on a static productivity model (potential underfishing), and red shading indicates lower-than-expected productivity that would promote overfishing. Source: (Britten *et al.*, 2017)

Multispecies stock assessment models

Due to the complex pathways by which climate impacts individual species, incorporating climate change considerations into management will also require the inclusion of EAF principles. In addition to broader ecosystem-scale monitoring, stock assessment modelling approaches that incorporate such data will be important to supporting EAF. Multispecies models that can incorporate species interactions in the dynamics of ecosystems simultaneously have existed since the early 1980s and are becoming important tools used to support EAF (Plagányi, 2007) and to understand the impacts of perturbations on ecosystem structure and population dynamics. Such models vary in their approaches and levels of complexity. Whole ecosystem models such as Ecopath with Ecosim (Christensen and Walters, 2004) or Atlantis (Fulton *et al.*, 2004), are time-consuming and labour intensive to construct, as they require detailed information of abundances, predation rates, and other biological parameters for individual species that are often acquired through diet studies or the literature. Whole ecosystem models are useful in understanding possible mechanisms governing ecosystem dynamics and testing management scenarios (Fulton *et al.*, 2014; Weijerman *et al.*, 2016) but are less appropriate for supporting tactical management advice (Trijoulet *et al.*, 2019). To support EAF and provide fisheries management advice, statistical multispecies stock assessment models are a more appropriate and common approach. Such models are of intermediate to moderate complexity, and are question-driven, focusing only on components of the ecosystem that are relevant for addressing management questions (Plaganyi *et al.*, 2014). Multispecies assessment models range from simple deterministic Multispecies Virtual Population Analysis models (Tsou and Collie, 2001) to more complex multispecies statistical catch-at-age models (Jurado-Molina *et al.*, 2005; KINZEY and PUNT, 2008; Curti *et al.*, 2013). For example, the Globally applicable Area-Disaggregated General Ecosystem Toolbox (Gadget) is a flexible statistical framework developed to dynamically model complex marine ecosystems within a fisheries management context (Howell and Begley, 2004; Plagányi, 2007; Pérez-Rodríguez *et al.*, 2017). Gadget has been used to incorporate EAF into fisheries around the world (Taylor and Peck, 2004; Lindstrøm *et al.*, 2009; Andonegi *et al.*, 2011; Bartolino *et al.*, 2011; Elvarsson *et al.*, 2018). Another multispecies model, the Climate Enhanced Age-based model with Temperature-specific Trophic Linkages and Energetics (CEATTLE), is used in the annual Bering Sea walleye pollock (*Gadus chalcogrammus*) assessment (Holsman *et al.*, 2019b). CEATTLE includes temperature-dependent weight-at-age functions and temperature-specific predation interactions to evaluate fishing impacts and mortality under different climatic scenarios. Such multispecies models can be applied both as stock assessment models and as operating models in MSEs (read below). Where an ensemble of multi-species or food-web models are available, multi-model approaches can be adopted to reduce the uncertainty associated with single model projections and obtain more comprehensive predictions.

Incorporating multispecies dynamics via such models is important to fisheries management and for understanding climate and exploitation impacts on ecological dynamics. For example, it has been widely shown that predation is, in many cases, a more significant driver of mortality than fishing (Bax, 1998; Jennings *et al.*, 2001; Pérez-Rodríguez *et al.*, 2017) and that failing to consider trophic interactions can lead to overestimates of yield per recruit (Pinnegar *et al.*, 2008) and reduced predictive ability. However, despite this and the increasing availability of multispecies models, their use in fish stock assessments remains rare (Trijoulet *et al.*, 2019). The inclusion of multispecies models in fisheries management is likely hindered by the higher degree of ecosystem data and technical expertise required to run them. For instance, such models often require detailed diet, demographic, and other data for multiple species (Trijoulet *et al.*, 2020). Further, defining optimal yield in a multispecies setting is more complex than for single species, and it is not often possible to maximize the yield of several species simultaneously (Gaichas *et al.*, 2012; Moffitt *et al.*, 2016). Notwithstanding, EBFM approaches based on multispecies assessment models have been reported to mitigate adverse climate change impacts on fisheries in the near-term and may thus be an effective climate adaptation strategy in many situations (Holsman *et al.*, 2020).

Management strategy evaluation

MSE is a quantitative modelling approach that embodies the principles of uncertainty and risk management in the estimation of climate-considered reference points and harvest strategies. The approach is now capable of incorporating climate forecasts and ecosystem-based considerations. MSE has been used in marine management since the early 1990s but is now becoming more widely used as an approach to implement management procedures that, through simulation, can be shown to be robust to a range of uncertainties associated with data limitations and other factors (Goethel *et al.*, 2019). MSE is a flexible modelling framework that allows scientists and stakeholders to assess the robustness of different management actions to a range of uncertainties related to the species, ecosystem, model architecture, or other factors. A defining feature of MSE is the quantification of uncertainty and the robustness of the management strategy to this uncertainty. The approach relies on operating models, which are analogous to stock assessment models, and this similarity may contribute to the rapidity and ease with which MSEs are being adopted in fisheries (e.g. Punt *et al.*, 2014, 2016). However, MSEs offer advantages over traditional stock assessment models. As shown by Plagányi *et al.* (2013), rather than relying on a single assessment model, MSE approaches can be used to consider an ensemble of plausible models, thereby enabling consideration of some critical biological uncertainties (e.g. nature of the stock-recruitment relationships, level of natural mortality), as well as those related to the likelihood and consequences of climate change and other factors.

To achieve ecosystem and multispecies objectives, MSE can be implemented using multispecies models that incorporate species interactions and the effects of changing environment on them (Sainsbury *et al.*, 2000; Smith *et al.*, 2007; Dichmont *et al.*, 2008; Plagányi *et al.*, 2013; Merino *et al.*, 2019). Similarly, uncertainties related to past or future climate changes can be evaluated within MSE by inputting observed or forecasted climate time-series under different emission scenarios (Merino *et al.*, 2019). MSEs vary in complexity and realism. They range from fully coupled biophysical models of regional ecosystem responses to climate change to climate-informed single- or multispecies projection models. Fully coupled ecosystem models estimate species interactions in space and time using ecological principles of bioenergetics, size-based dynamics, predation, and the probability of prey encounter. Examples of these include size-spectrum models, food web models, and individual-based models. Climate-informed single- or multispecies models use time-series of physics, prey availability, predation, and bioenergetics to inform functional responses, model parameterizations, covariates, and model structure to make future projections. For example, A'mar *et al.* (2009) used MSE to explore the effect of incorporating climate change factors dynamically in the management of walleye pollock (*Gadus chalcogrammus*) in the Gulf of Alaska. This approach allows specific climate change metrics that are deemed to be important to population structure to be quantitatively included in the estimation of population dynamics and subsequent management strategy optimization. Whereas the benefits of including temperature or other climate factors in MSE models for walleye pollock and other gadoids is reportedly low, the approach has been effective in other marine fisheries. For example, MSE studies have been used to determine how the stock-recruitment relationship for Pacific sardine (*Sardinops sagax*) changes with SST. Based on this, the average SST during the most recent three years is used to establish the proportion of the sardine population biomass that will be used as the acceptable biological catch for the next year (PFMC, 2007).

This power and flexibility may be the reason why MSE is often touted as a solution to meeting current objectives in fisheries management, such as incorporating climate change, ecosystem-based considerations, and the precautionary principle (Goethel *et al.*, 2019). Attesting to this, the use of MSE is growing (Punt *et al.*, 2016; Goethel *et al.*, 2019). MSEs have been routinely used to manage fisheries in South Africa for over 20 years (Punt *et al.*, 2016) and are currently used to set quotas for several species, including anchovy (*Engraulis encrasicolus*), sardine (*Sardinops sagax*), Cape hake (*Merluccius paradoxus*), rock lobster (*Jasus lalandii*), and horse mackerel (*Trachurus trachurus capensis*); (Punt *et al.*, 2016). MSE has also been used to manage a range of species including, for instance, southern bluefin tuna (*Thunnus maccoyii*; Polacheck, 1999), sockeye salmon (*Oncorhynchus nerka*; Cunningham *et al.*, 2019), and rock lobster (Starr *et al.*, 1997), and to evaluate a bycatch management rule for seabirds (Tuck, 2011). In Canada, MSEs have been used to manage sablefish (*Anoplopoma fimbria*) in the Pacific (Cox and Kronlund, 2008), and Greenland halibut (*Reinhardtius hippoglossoides*; Butterworth and Rademeyer, 2010) and pollock (*Pollachius virens*) in the Northwest Atlantic (Rademeyer and Butterworth, 2011).

Risk-based approaches

Recently, Duplisea *et al.* (2020) introduced a risk-based approach to incorporating climate change considerations into fisheries management in Canada. Through the framework, accounting for climate change in advice involves what the authors refer to as "climate change conditioning of science advice" (CCCA), in which climate change variables are identified and related to the risk assessment component of advice through assumed modelled response dynamics. The CCCA approach requires information on how the environment affects the productivity dynamics of a resource and takes climate change into account when estimating the probability that an objective is being met, such as a population being above its target. The CCCA approach is based on the risk equivalency, the concept of making management decisions of equal risk, despite differences in, for instance, data availability, resource dynamics, knowledge, assessment methods, and advisory contexts. Risk equivalency is intended to lead to a standardized application of risk in decision-making. The equivalency operates by factoring in 'buffers' to the advice such that with increasing risk, the recommended level of activity decreases. The approach introduced by Duplisea *et al.* (2020) seeks to adapt DFO's precautionary approach framework such that guiding reference points are conditioned for the effects of climate change on population parameters (non-stationarity in production). Environmental variable(s), together with a baseline environmental reference(s), are used to track environmental trends and thus condition the risk of resource use on the deviation of the environment from its baseline. However, such baselines are notoriously difficult to estimate and interpret due to natural environmental variability and cycles, a lack of long-term observations, and non-stationary dynamics (Baum and Myers, 2004; Saenz-Arroyo *et al.*, 2005; Bunce *et al.*, 2008; Knowlton and Jackson, 2008). Estimating such baselines would require long time-series that are notably lacking for many climate and/or fisheries variables in Canada and elsewhere. The authors suggest that information regarding baseline conditions can be derived from experiments of independent studies, yet it is not immediately apparent how this would work. The risk posed by climate change is ultimately represented by a risk profile—often visualized as the human activity to be managed (e.g. fishing) versus the probability of meeting a management objective (e.g. B/BMSY). The risk profile and associated climate conditioning factor are either estimated or approximated by comparing different model scenarios with different assumptions about resource dynamics dependence on the baseline climate conditions. Should the climate conditioning factor be >1, maintaining risk equivalency would require reducing the level of human activity accordingly and vice versa.

Although risk-equivalency approaches have been applied in the management of Australian fisheries and in the US (Fulton *et al.*, 2016), they are less common than other approaches discussed previously, and their efficacy has yet to be rigorously evaluated. One clear advantage of such an approach is that the effects of uncertainty introduced by climate change on fisheries are couched in risk-based advice, which is already common in DFO management advice. Further, with good knowledge about the effects of climate change on the dynamics of a stock and good long-term data, implementing CCCA appears to be a feasible approach. However, such situations are far from the norm, and it is not clear how CCCA would proceed in these situations. Many fisheries in Canada and elsewhere are data deficient, and obtaining reliable long-term time-series needed to derive baseline conditions would be extremely challenging, particularly in overfished systems and where synoptic observations were required. Similar to MSE (discussed next), CCCA evaluates climate change in terms of risk, but it is not clear what advantages CCCA offers over the more widely used and perhaps flexible MSE.

6.4.2 Climate vulnerability of fisheries

Understanding whether and how strongly climate change will affect a fishery is of fundamental importance to the management of that fishery. Climate change can have a range of impacts on exploited species, ecosystems, and coupled human communities across a range of scales. Our current scientific understanding suggests that these effects will not be uniform or consistent across species or ecosystems—there will be winners and losers, and some areas will experience gradual change while in others, change will be abrupt (Table 4.1 & Table 4.2). Further complicating matters, some species may experience positive effects of climate change in one habitat and life history stage of their development and a negative effect in another habitat or life stage. Climate change vulnerability assessments seek to understand how different species, and in some instances, coupled socio-economic systems, will respond to climate change (*e.g.* Pacifici *et al.*, 2015; de los Ríos *et al.*, 2018; Foden *et al.*, 2019). There is a general consensus that the vulnerability of a species depends on its exposure, sensitivity, and adaptive capacity to climate change (Adger *et al.*, 2005; IPCC, 2007; Lindegren and Brander, 2018); Figure 6.3). Exposure depends on the magnitude and severity of climate change to which the species will be subjected, sensitivity on the probability of adverse effects of exposure on the species, and adaptive capacity on the response of the species to any adverse effects of exposure. To date, over 743 climate vulnerability assessments have been published (de los Ríos *et al.*, 2018), yet there is currently no consensus on how to quantify vulnerability in a standardized and objective manner, and assessments are often undertaken *ad hoc* (Pacifici *et al.*, 2015). Notwithstanding the lack of an accepted approach, vulnerability assessments have been an area of priority focus for intergovernmental organizations (IPCC, 2007, 2014) and are now being used by fisheries managers to incorporate climate change considerations into the management of marine resources. For example, climate vulnerability assessments have been included as a priority in the Fisheries Climate Science Strategy of the US NMFS as a tool to inform research and management activities related to understanding and adapting marine fisheries management to climate change (Busch *et al.*, 2016). In response, a vulnerability assessment methodology has been developed by the NMFS (Morrison *et al.*, 2016) and has been used to explore the vulnerability of marine species on the Northeast US Shelf (Hare *et al.*, 2016). The vulnerability estimates are used by decision-makers to identify priorities for scientific and management efforts in order to implement proactive management measures, reduce impacts, increase resilience, and advance the adaptive capacity of fisheries. Importantly, vulnerability assessments depend on knowledge from field and laboratory studies to reduce uncertainties about the tolerance, adaptive capacity, and response of species to climate change. However, once acquired, this information can together also form a pool of knowledge to be used for developing additional climate change management strategies (e.g. Duplisea *et al.*, 2020).

6.4.3 Climate forecasts and projections

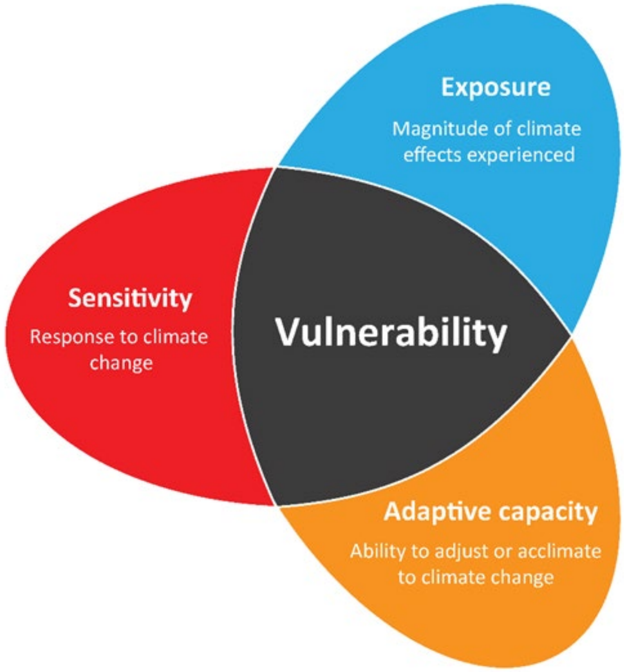

Figure 6.3 Climate change vulnerability.
The vulnerability of species to climate change is defined by its exposure (blue), sensitivity (red), and adaptive capacity (yellow). Source: Adapted from (IPCC, 2007, 2014)

The use of climate forecasting and projecting to understand how climate change will be manifest on species and ecosystems is growing. The difference between projections and forecasts is subtle: whereas projections explore possible future outcomes under different climate scenarios, forecasts represent the expected future outcomes based on realistic assumptions and expectations. In consequence, forecasts are often restricted to shorter time intervals (e.g. weeks, months) and spatial domains (e.g. local, regional) than are projections (Figure 6.4). As discussed in Chapter 6, through the use of GCMs, ESMs, and MEMs, the impacts of climate changes on the physics, biogeochemistry, and ecology can be projected into the future under different emissions and exploitation scenarios. Through organizations such as the CMIP and the Fisheries Model Intercomparison Project, such model outputs are publicly available in a standardized format, allowing them to be compared and combined. These coarse-resolution, long-term global climate projections often operate over decades to centuries and are increasingly considered in ocean management settings (Maxwell *et al.*, 2015; Barange *et al.*, 2018). Such models are used in MSEs (read below) to evaluate the robustness of different management approaches to projected future climate conditions and exploitation regimes (Chin *et al.*, 2010; Hobday *et al.*, 2011; Le Bris *et al.*, 2018). As discussed previously, the models are also frequently used to estimate the future climate exposure of species as part of species vulnerability assessments (Stortini *et al.*, 2015; Hare *et al.*, 2016; Morrison *et al.*, 2016; Greenan *et al.*, 2019). Additionally, the models are useful for long-term strategic planning, industry changes, and infrastructure considerations.

However, to be more applicable to on-the-ground fishers and managers, climate projections need to be available at high spatial resolutions and appropriate time-scales and be locally validated (Figure 6.4). While far-future projections are useful for longer-term strategic planning, and short-term forecasts influence immediate tactical decisions of when and where to fish (Dell *et al.*, 2011), seasonal projections are made over weeks to months (Spillman and Alves, 2009) and are currently used in fisheries to proactively reduce uncertainty and manage risks (Hobday and Hartog, 2014). Seasonal forecasts can be made using statistical approaches that use historical data or dynamical approaches that do not assume a constant climate baseline and often perform better under climate change

(Spillman, 2011; Hobday *et al.*, 2016). Such seasonal forecasts have been and are being used in the management of several fisheries in Australia. In all such instances, the Australian Bureau of Meteorology seasonal environmental forecast model, known as the Predictive Ocean Atmosphere Model for Australia (POAMA[5]) is used. POAMA is based on a coupled ocean–atmosphere model and an ocean–atmosphere–land observation assimilation system (Alves *et al.*, 2002; Spillman, 2011). The skill and performance of the model have been intensively vetted (Spillman and Alves, 2009; Spillman, 2011; Marshall *et al.*, 2012; Charles *et al.*, 2015; Bixby *et al.*, 2019). The output from POAMA is being used to provide real-time early-warning forecasts of environmental risks for coral bleaching prior to summer, allowing managers to focus monitoring efforts and implement strategies to minimize reef damage (Maynard *et al.*, 2009; Spillman and Alves, 2009; Spillman, 2011). Alternatively, POAMA forecasts are being used to construct habitat distribution maps for marine species, which can then be used in management (Hobday *et al.*, 2011).

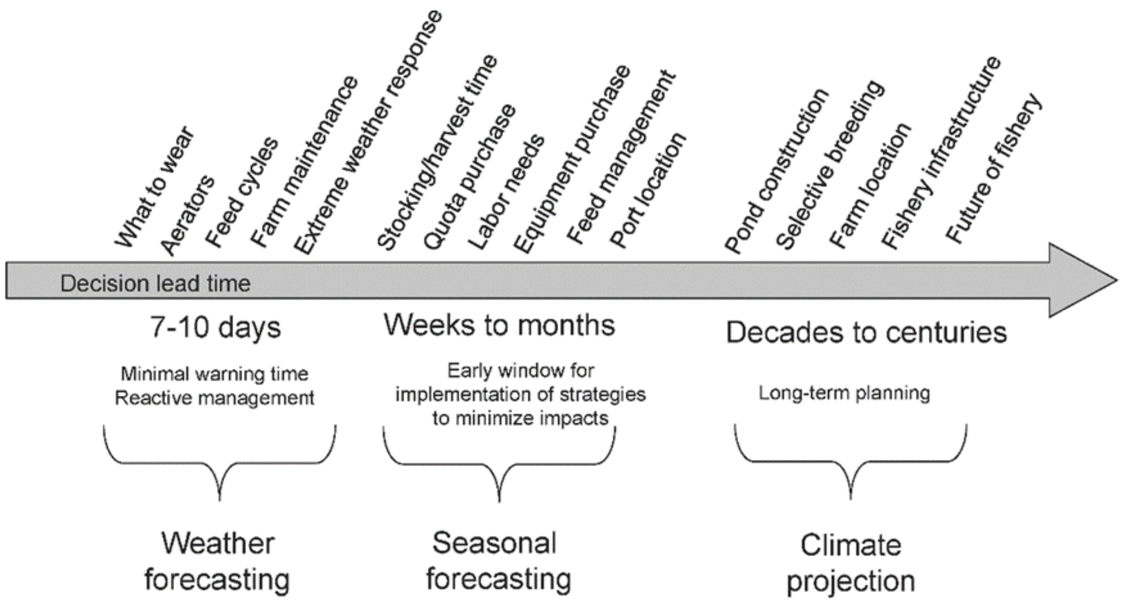

Figure 6.4 Time-scales at which information on climate projections and forecasts are relevant. Source: (Hobday et al., 2016)

Climate forecasting is critical to the management of southern bluefin tuna (SBT; *Thunnus maccoyii*) in eastern Australia. SBT makes winter migrations to the Tasman Sea off southeastern Australia, where it is vulnerable to the year-round tropical tuna longline fishery (Eastern Tuna and Billfish Fishery). Managers seek to minimize SBT bycatch in this fishery through spatial restrictions. Since 2003, a temperature-based habitat model (Hobday and Hartmann, 2006) has been used to estimate current SBT distribution (nowcast), allowing managers to make decisions about where to place management boundaries. During the fishing season, real-time reports of the predicted location of SBT habitat are made, allowing managers to dynamically set management boundaries to reduce unwanted catch (Hobday, 2010). Since 2011, POAMA temperature forecasts have also been used to generate SBT forecasts 3–4 months ahead of time (Hobday *et al.*, 2011).

[5] http://www.bom.gov.au/climate/poama2.4/about-POAMA-outlooks.shtml

These habitat maps are used by managers to proactively prepare for the upcoming season. The projections are sent via email to fishery managers and fishers. POAMA forecasts are also used to manage the SBT fishery in the Great Australian Bight. The fishery captures juvenile SBT via purse seine and tows them to Port Lincoln, where they are grown for several months before harvest. POAMA temperature forecasts have been combined with a habitat model to forecast the spatial distribution of larval SBT up to 4 months in advance. The forecasts are available to users through a private website and are used by fishers to plan where to fish. Since the fishery is managed under a quota, the forecasts do not affect the quantity of SBT landed, but may improve the efficiency of fishing operations (Hobday *et al.*, 2016). Lastly, the POAMA forecasts are being used to manage aquaculture operations such as tiger and banana prawns in Queensland and Atlantic salmon (*Salmo salar*) in Tasmania. Aquaculture farmers use the POAMA forecasts to plan when to stock and harvest their ponds, determine optimal feed mixes, implement disease management strategies, modify labour needs, and manage market expectations (Hobday *et al.*, 2016).

Notwithstanding the many challenges of climate forecasting, the potential benefits are substantial, as it offers a tangible means of incorporating climate change considerations into fisheries management proactively. Climate projections that are coupled to single-species models have shown that climate will affect the reference points used in management (Link *et al.*, 2008; Hollowed *et al.*, 2009), and the output from such models is being used to set catch levels, develop species recovery plans, and understand the impact of specific actions on fisheries (Link *et al.*, 2015). They are also useful to identify indicators that may be used as early warnings of rapid or impending changes to fisheries, habitats, and ecosystems. For example, climate change is causing many species to shift their geographic distributions more rapidly than their fisheries, in some cases enabling stocks to increase at their leading edges in response to low exploitation rates while causing decline at their trailing edges due to excessive exploitation (Pinsky and Fogarty, 2012). By considering the interactive effects of climate change and fishing in tandem, such climate and ecosystem coupled models represent a powerful tool for evaluating the multiple complex effects of climate change on fisheries. For this reason, forecasting is incorporated in the management of salmon fisheries in Canada (e.g. DFO, 2012c, 2016) and additional species elsewhere and is included as a primary objective of the NMFS Fisheries Climate Science Strategy for integrating climate change considerations into their fisheries management (Busch *et al.*, 2016). Importantly, the efficacy of projecting and forecasting in fisheries management depends heavily on the availability and skill of models. However, as Australian fisheries demonstrate, once an operational model is established, it can be applied for a range of ocean management purposes (Hobday *et al.*, 2016). Lastly, coupling social and economic models to climate models could provide a means of understanding how possible climate scenarios could impact human communities and economies. For example, NOAA has developed a set of Community Social Vulnerability Indicators of fishing community vulnerability and resilience to enable evaluation of the impacts of climate change and management responses on social factors (Colburn *et al.*, 2016).

6.4.4 Climate change research

To fully integrate climate change considerations into fisheries management, a foundational understanding of the mechanisms by which climate change effects are transmitted to marine ecosystems, habitats, species, and fish stocks, as well as humans, is required. If integrating climate change into fisheries management was viewed as a house, process-based research would be the foundation upon which it rests. Virtually all of the climate change tools discussed in this report require some level of understanding of how species and ecosystems will respond to climate change. This knowledge is important to achieving specific goals (e.g. climate-considered harvest rules) as well as understanding the factors influencing the resilience and adaptive capacity of fisheries. For example, incorporating climate change considerations into forecasting or fisheries models requires a foundational mechanistic understanding of how climate variables affect the growth and mortality of marine species. Such understanding can be achieved through process-based research, such as physiology studies conducted via experimentation in the laboratory or in the field to understand how and why species, ecosystems, and coupled human systems are affected by climate change (e.g. Frommel *et al.*, 2012). While the benefits of process-based research for applied management can sometimes be difficult to quantify, it contributes important information to the stock assessment process and ought to be prioritized to incorporate climate readiness into fisheries management. Such information should also be evaluated in the context of socio-economic factors to understand how climate-driven ecological and fisheries changes will propagate to coupled human systems.

6.5 Decision-making

The different strategies and structures of decision-making are often equated with and used to define the more integrated process of 'fisheries management.' This is understandable, as the decision-making stage is at the heart of the management process, where knowledge and advice are translated to the implementation of management tools and actions. A range of fisheries decision-making structures exists (Table 6.1). These range from community-based models to various forms of co-management that feature degrees of flexible, cooperative management between the government and various stakeholders. Each decision-making structure offers a unique set of advantages and disadvantages, making them relevant for climate change integration in different ways. However, there is little consensus on which are most appropriate for incorporating climate change and/or ecosystem considerations. For example, through a survey of practitioners and literature review, Ogier *et al.* (2016) evaluated how several decision-making structures ('management approaches') facilitated climate change adaptation in Australian fisheries. Based on both theory and survey results, the study suggested that the various decision-making structures examined were equally well equipped to enable adaptation to threats and opportunities arising due to climate-driven change. Consequently, there is little reason to recommend one decision-making structure over another in the context of climate change adaptation.

Table 6.1 Overview of common decision-making structures used in fisheries management and their relevance to climate change implementation.

The table was modified from Ogier *et al.* (2016).

Definitions	Advantages	Disadvantages	Relevance to climate change adaptation
Community management • **Fishers are given the opportunity to manage their own resources; define their needs, goals, and aspirations; and make decisions affecting their well-being (Pomeroy, 1994).** • **Since community-based management encompasses many different management situations in which natural resources, whole ecosystems or territories are 'owned' and managed by local groups, there is no general definition available (Gorris, 2016).**	• Effectiveness and equity. • More economical. • Sense of ownership, promoting long-term sustainability. • Feasible option for nations with weak state institutions. • Leverages knowledge and expertise of local communities and individuals who have a vested interest in good management. • Important alternative to centralized management systems, which have often failed to conserve fish stocks and protect vital habitat, and to support the residents of coastal communities that depend on them (Pomeroy, 1994).	• Difficult to develop and enforce rules. • Lack of rigorous data and analyses on state of fishery. • Lack of coordination between the local community and government actors (Gorris, 2016). • Lack of government resources (e.g. data collection, enforcement).	• Flexibility provides potential for rapid response to climate-driven changes in the fishery. • Empowers stakeholders through shared responsibility (Pomeroy *et al.*, 2011).
Co-management (instructive, consultative, cooperative, advisory, informative): • **"An arrangement where responsibility for resource management is shared between government and user groups" (Sen**	• Improvements in the legitimacy and efficiency of governance processes and management functions (Singleton, 2000), including improved acceptance of climate change adaptation	• Can exacerbate existing power imbalances (Berkes, 2007). • Over-representation of extractive interests can	• Provides a platform for conflict resolution and negotiation of trade-offs (Carlsson and Berkes, 2005).

and Nielsen, 1996). Support for co-management derives from the recognition of the limits of government action. It differs from community-based management in that government is involved in decision-making about fisheries management.	strategies and reduced costs for government. • Governance benefits include more appropriate, efficient, and equitable processes through decentralization of resource management decisions, encouragement of stakeholder participation, and fostering of conflict resolution (Pinkerton, 1989). • Management functions of long-term planning and inclusive decision-making may be enhanced by co-management approaches (Pinkerton, 1989). • Potential for systematic learning and innovation under conditions of uncertainty (Berkes, 2007). • Empowerment and responsibility shared with industry. • Balancing of social and economic considerations with those of ecological (according to industry). • Encourages stakeholder participation and facilitation of conflict resolution. • Learning is central to co-management's value as an adaptive strategy (Nielsen *et al.*, 2004).	overwhelm non-use values (Okey, 2003). • Resource management agencies can be captured by private interests (Singleton, 2000). • Some resource user groups may lose their customary access (Agarwal, 1997). • State power can be extended unintentionally into communities supposedly being empowered by co-management (Okey, 2003). • Local and national priorities may conflict (Jones and Burgess, 2005). • Expectations for participation and empowerment may be unfulfilled (Nielsen *et al.*, 2004). • Weakened focus on ecological system (target species issues dominate). • Without strong institutional forms, co-management arrangements can fall apart with large numbers and highly diverse commercial operators (Haward, 2000).	• Involves systematic learning and innovation (Berkes, 2007). • Builds capacity and empowers stakeholders through shared responsibility (Pomeroy *et al.*, 2011). • Collaborative engagement improves acceptance of climate change adaptation strategies (Berkes *et al.*, 2001). • Enhances long-term planning (Pinkerton, 1989). • Provides flexibility to cope with complexities imposed by increased change and variability (Nielsen *et al.*, 2004; McIlgorm *et al.*, 2010).
Adaptive management: • **Concerns the facilitation of learning from management decisions and feedback of those**	• Addresses the challenge of operating with impartial knowledge and allows progress	• Learning may become quickly outdated. • Passive adaptive management can move a	• An iterative process that reduces uncertainty in a goal-oriented and structured process (Allen *et al.*, 2011).

lessons in following rounds of decision-making (Doremus, 2002). • **Emphasizes structured learning by doing (Allen *et al.*, 2011).**	in the absence of complete information (Doremus, 2002). • Involves continual review of management outputs and outcomes and allows for adjustments in response to new information. • In cases where there is cost recovery, can allow for new research to address new questions (vs. closure, in the case of incomplete information).	system to a threshold where abrupt change occurs (McDonald and Styles, 2014). • Monitoring may be focused on compliance and not learning (Fletcher, 2006). • Areas of application may be limited (Roe, 2001). • Considerable implementation problems exist (Keith *et al.*, 2011).	• Accounts for system complexity by integrating ecological, social, and economic drivers (Gunderson *et al.*, 2008). • Better able to deal with change through managing for both short- and long-term impacts (Lester *et al.*, 2010). • Provides platform for review and adjustment of strategies. • Accounts for complexity by considering multiple sectors and policies (Berkes, 2012). • Embraces complexity, variability, and uncertainty (Arvai *et al.*, 2006).
Active adaptive management: • **A more responsive form of adaptive management (Allan and Curtis, 2005), in which the relationship between management and learning is interactive and highly coupled.** • **Management is an iterative process of experimentation, re-experimentation, and continuous hypothesis generation and testing, which guide decision-making.** • **Active adaptive management "involves a process of active learning, planning, evaluation and judgment about the socio-economic-ecological environment**	• (See strengths as listed for adaptive management) • The relationship between management and learning is interactive and highly coupled (Allan and Curtis, 2005). • Incorporates features consistent with maintaining the sustainability of fisheries in the context of uncertainty, limitations on knowledge, and high levels of system complexity: ○ Management activities are specifically designed to test hypotheses through ecosystem-scale holistic experiments.	• Application best limited to ecosystems where human influence is evident but not heavy and restoration of ecological functions and processes have the most potential (Roe, 2001). • Can be less participatory if a high-level analytical framework is used (e.g. MSE). • Continuous hypothesis generation and testing, which guide decision-making, can reduce security and stability of the operating	• Provides platform for active social learning through experimentation, re-experimentation, hypothesis generation, and testing (Allan and Curtis, 2005). • Encourages diverse inputs of knowledge and experience through mechanisms for multi-stakeholder involvement (Grafton *et al.*, 2007). • Embraces ecosystem-scale and system complexity (Grafton *et al.*, 2007).

and the effects of key decision variables" (Grafton *et al.*, 2007).	○ Complexity is embraced. ○ Mechanisms for multidisciplinary and multi-stakeholder involvement are provided. ○ There is a strong emphasis on social learning (Allan and Curtis, 2005).	environment for commercial operators. • Biophysical system remains central to management with social dimensions only included to the extent that they serve fisheries management objectives.	
Adaptive co-management: • **A matured state of co-management arrangement (Berkes, 2009), linking the iterative learning aspects of adaptive management with the shared management responsibility of co-management (Olsson *et al.*, 2004) and concerned with ecosystem dynamics (Kofinas, 2009).** • **At least five variables have been identified as most characteristic of adaptive co-management: learning, knowledge, networks, shared power, and organizational interactions (Plummer *et al.*, 2012).** • **As much concerned with the social, institutional, and ecological dimensions of resource management as with the resource itself.**	• Empowerment for industry through co-management. • A wider set of considerations than co-management (that is, it is concerned with ecosystem dynamics). • Has potential to develop adaptive capacity, social-ecological resilience, sustainable resource use, and enhanced efficiency and effectiveness of management (Plummer *et al.*, 2012). • Offers a way of studying and structuring increasingly coupled social-ecological systems (Armitage *et al.*, 2008).	• High level of engagement adaptive by industry to participate. • Long time-frame for reporting back on new evidence (e.g. need better real-time systems). • Effective adaptive co-management is dependent on how well decision-making institutions fit their social-ecological conditions, effective communication processes among key leaders, intergroup cooperation, and political management skills (Kofinas, 2009).	• Social networks set up for co-management are helpful in dealing with climate hazards (Tompkins and Adger, 2004). • Embraces complex adaptive systems thinking, e.g. cross-scale interactions and ecosystem dynamics (Armitage *et al.*, 2008). • Provides mechanisms to adjust to change (Kofinas, 2009). • Accounts for system complexity by operating across multiple levels (Pomeroy, 2007). • Encourages autonomous adjustment by fishers and their communities, values different knowledge sets (tacit, traditional, and scientific) and fosters collaborative decision-making across key stakeholders (Grafton and Quentin Grafton, 2010).

6.6 Implementation of tools & actions

6.6.1 Spatial management

Protected areas are critically important tools in marine management and conservation and will likely become increasingly so in the era of climate change. The International Union for Conservation of Nature and Natural Resources (IUCN) has promoted the use of spatial protection tools to reduce the impacts of stressors on species and ecosystems, thereby increasing stability and resilience. Fisheries closures are geographic areas in which specific types of extraction are prohibited for a specified period of time, with the primary intent of protecting fishery resources. The objectives of fisheries closures are diverse but commonly include reducing bycatch (Hobday *et al.*, 2010), protecting species during vulnerable life history stages (e.g. spawning, migration; Frank *et al.*, 2000), promoting population rebuilding, and avoiding adverse interactions with endangered species (e.g. Koubrak *et al.*, 2020). As such, fisheries closures are often context specific, with closures relating to specific species, fishing gear types, seasons, durations, and areal extents, depending on the management objectives. For example, through dynamic ocean management (read below), transient closures can be triggered when specific conditions are met (e.g. species sightings, environmental conditions), with rapid closures (e.g. in hours or days) being implemented across restricted and specific targeted areas. At the other extreme, areas can be closed to virtually all harvesting throughout the year, for several years. For instance, a closed fishing area to protect juvenile haddock (*Melanogrammus aeglefinus*) aggregations has been in effect on the offshore banks of the central Scotian Shelf (NAFO Division 4W) for over 30 years (1989-2020; Frank *et al.*, 2000). The area was established as a year-round closure to all fixed and mobile fisheries with the aim of protecting spawning haddock and subsequent juveniles from harvesting. Defining features of fisheries closures compared with other spatial management tools such as MPAs is that they are single sectoral and highly dynamic; whereas MPAs are static and permanent, fisheries closures can vary in their extent and duration over time.

Fisheries closures and MPAs are related as spatial management tools; they are also differentiated. In contrast to fisheries closures, MPAs take longer to establish but are permanent, can potentially offer greater levels of protection, and are often established as a connected network of areas. Although not typically associated with fisheries management, *per se*, MPAs are crucial tools used to protect intact ecosystems from stressors and promote biodiversity and healthy marine populations (Edgar *et al.*, 2014; Gill *et al.*, 2017). Despite the ability of MPAs to promote healthy marine ecosystems and enhance resilience to stressors such as climate change (Bates *et al.*, 2014), there is often intense opposition to their implementation by the fishing industry, possibly stemming from their permanence. For example, in Atlantic Canada, proposed MPAs are often intentionally situated in locations where fishing activity is low, to avoid conflict and delays in their implementation due to opposition from the fishing industry and communities. Such a practice, while understandable, is counterintuitive, as protection from extraction in locations where extraction is already low or non-existent may be less effective.

Notwithstanding this, it has recently been suggested that by combining management features that are static (MPAs) and dynamic (seasonal or temporal; e.g. fisheries closures), more climate-responsive seascape conservation networks could be established (Tittensor *et al.*, 2019). In theory, such a strategy could confer the benefits of permanent MPA closures or Fisheries Act habitat closures, such as protecting valuable habitats and geomorphic features, while more flexible fishery and/or "other effective area-based conservation measure" closures could be used to more dynamically respond to ongoing climate change impacts as they occur. Furthermore, the international community, including Canada, has committed to increasing the proportion of MPAs[6], creating an opportunity to integrate such climate-smart design principles into spatial management programs.

6.6.2 Dynamic management

In response to the rapid pace of climate and associated ecological changes, interest in dynamic ocean management (DOM) or real-time ocean management has intensified (Dunn *et al.*, 2011, 2014; Lewison *et al.*, 2015). In contrast to static management, DOM refers to "management that changes rapidly in space and time in response to the shifting nature of the ocean and its users based on the integration of new biological, oceanographic, social and/or economic data in near real-time" (Maxwell *et al.*, 2015). DOM is predominantly, but not exclusively, a spatial management tool. DOM has been implemented to maintain catch within quota limits, reduce bycatch of species of conservation concern, or increase the efficiency of fishing activities (Lewison *et al.*, 2015). Primary DOM approaches include grid-based hot-spot closures, real-time closures based on move-on rules, and oceanographic closures. Grid-based closures have been implemented on daily or weekly scales and operate by overlaying a grid on an area of interest and closing grid cells where bycatch has exceeded a threshold. Under move-on rules, once a predefined threshold is triggered, fishers must move a set distance away from the affected area. Move-on rules have been used extensively with closures lasting hours to weeks with distances often 2–10 km (Auster *et al.*, 2011; Dunn *et al.*, 2014; Little *et al.*, 2015). Oceanographic closures are defined by environmental conditions and have been implemented on a daily to weekly basis (Hobday and Hartmann, 2006; Hobday *et al.*, 2010). The Australian southern bluefin tuna fishery discussed previously is an example of this (Hobday *et al.*, 2016).

Where it has been evaluated, DOM has been shown using simulation to be effective in achieving diverse management objectives. For example, real-time closures based on move-on rules have been shown to reduce the bycatch of juvenile cod by 62.2% (Dunn *et al.*, 2014). Oceanographic closures and seasonal forecasting have proven to be effective approaches in Australian fisheries and aquaculture operations (Hobday *et al.*, 2016). A simulation-based study reported that DOM could significantly improve the efficiency of fisheries management in the Northeast Atlantic (Dunn *et al.*, 2016). Compared to DOM, traditional coarse-scale management measures displaced up to 5 times the fishery catch and required up to 200 times more kilometre-days of closure. Dynamic management led to USD $15–52M more in landings relative to traditional static management while achieving the same level of juvenile bycatch (Dunn *et al.*, 2016). Hazen *et al.* (2018) reported that dynamic closures in the California drift gillnet swordfish fishery could be two to ten times smaller than static ones and still provide sufficient protection to endangered non-target species. Using remotely sensed SSTs, TurtleWatch[7] provides longline fishermen in the

[6] https://www.cbd.int/sp/targets/

[7] https://oceanwatch.pifsc.noaa.gov/turtlewatch.html

North Pacific Ocean with near-real-time predictions of waters that are preferred by sea turtles so that they can reduce or eliminate their turtle bycatch (Swimmer *et al.*, 2017).

A high-profile Canadian example of DOM implementation is that of the North Atlantic right whale (*Eubalaena glacialis*; NARW), which was recently summarized in Koubrak *et al.* (2020). With only ~400 individuals remaining globally, the NARW has been assessed as endangered under the Canadian Species at Risk Act, in the US under the Endangered Species Act, and by the IUCN. The cause of the initial population collapse is historical whaling, which has been banned since 1937. Recovery has been hindered by high mortality from ship strikes and entanglement in stationary fishing gear and by low birth rates due to climate-related changes in prey availability. Recently, the NARW has been shifting its summer feeding distribution northward from the Bay of Fundy and Scotian Shelf into the Gulf of St. Lawrence, tracking climate-driven shifts in their zooplankton prey (Davies *et al.*, 2019). These spatial redistributions have been associated with increased interactions between NARWs and ship traffic and fishing operations in the Gulf of St. Lawrence. In 2017, 4% of the remaining population died, with half of the mortalities caused by entanglements and ship strikes (NOAA, 2019), raising further concern over the recovery prospects for the species. In 2017, the Canadian government participated in extensive consultations with stakeholders from the fishing and marine transportation industries, Indigenous representatives, provincial governments, NOAA representatives, and others to formulate protective measures for 2018. This led to the implementation of a combination of static and dynamic management measures in 2018 and 2019. Dynamic measures were triggered by NARW sightings and included 15-day closures to all crab and lobster fishing inside a predefined radius of the sightings and mandatory 15-day speed reductions upon NARW sightings. In 2018, the static and dynamic measures were effective, leading to zero NARW mortalities in the Gulf of St. Lawrence, but generated concerns over lost revenue from fishing opportunities and cruise ship visits. In response to this, the areas subject to fisheries closures and speed limits were reduced in 2019, and eight NARW deaths were recorded that year. Part of the increased mortality in 2019 was caused by the NARWs changing their geographic distribution relative to what was observed in 2018. The changing effectiveness of NARW management between 2018 and 2019 illustrates the challenge of managing fisheries and other ocean resources in a changing climate: Conditions will become increasingly non-stationary, and management approaches that were effective in one year may become obsolete the next as the climate conditions change. DOM can be helpful in this regard, but as the NARW example highlights, its efficacy depends on frequent, high-quality monitoring and/or forecasting (see section 6.3.1) to respond to circumstances as they evolve. In the NARW example, this requirement is, in some cases, is being addressed. For example, Whale Map[8] is a database that was developed to compile all known NARW sightings into a publicly available monitoring tool. Very-high-resolution satellite imagery (Cubaynes *et al.*, 2018) and acoustics (Davis *et al.*, 2017) are being explored as new observational platforms to detect NARWs, and forecasting is being evaluated as a predictive tool (Pendleton *et al.*, 2012). DOM also requires considerable stakeholder involvement and buy-in, and infrastructure to coordinate and communicate management regulations as they change through time.

---

[8] https://whalemap.ocean.dal.ca/

6.6.3 DOM involves managing ocean resources at finer spatial and temporal scales and thus requires higher resolution fisheries and environmental data, including, for instance, remote sensing, vessel monitoring systems, electronic logbooks, animal tracking, smartphone technology, citizen observation systems, and ocean modelling (Fairclough et al., 2014; Maxwell et al., 2015; Dunn et al., 2016; Fulton et al., 2019). To be effective, DOM requires the rapid collection of environmental and fisheries data and the transfer of information to and from fishers. In some US fisheries, such transfer systems are already in use, with mobile apps like eCatch9, Digital Deck10, and Deckhand11 used by fishers to communicate catch data in real time. In some instances, investment in data collection, analysis, and distribution may be required to effectively implement DOM. However, shifting socio-economic priorities and circumstances may make DOM vulnerable to manipulation over time. Altered priorities may reduce critical funding and support that are required for the high-resolution scientific tools, data, and other infrastructure needed for effective DOM (Holsman et al., 2019a). Integration of approaches and solutions

Thus far, the approaches described (Chapter 6) are valuable climate change adaptation strategies, yet their effectiveness can be more fully realized by integrating them. Fisheries management objectives are often segregated into strategic (e.g. long-term intentions) and tactical (e.g. shorter-term actions), with some practitioners viewing climate change as a predominantly strategic issue. However, the challenge of integrating climate change considerations into fisheries management must be taken at both strategic and tactical levels. As a long-term global phenomenon that will affect fisheries in the foreseeable future, climate change requires long-term thinking and planning to adapt effectively. However, despite its long-term nature, climate change impacts on fisheries and ecosystems are materializing now, and over increasingly shorter-term timeframes, requiring tactical actions. In short, there is a need to integrate across climate change adaptation approaches and strategies. One example where such a system is being applied is the Alaska Integrated Ecosystem assessment program[12]. The program integrates food web and multispecies assessment models, climate forecasts and projections developed by regional ocean modelling systems (ROMS), scientific surveys, and research. Through such integration, the program evaluates short-and long-term climate impacts on species, tests EBFM harvest strategies, and explores historical patterns in food-web dynamics to inform the North Pacific Fisheries Management Council.

---

[9] www.ecatch.org/

[10] https://deckhandlogbook.com/

[11] www.deckhandapp.com/

[12] https://www.integratedecosystemassessment.noaa.gov/regions/alaska/about#:~:text=Alaska's%20Integrated%20Ecosystem%20Assessment%20program,support%20effective%20Ecosystem%2DBased%20Management.

7. Climate change integration into Canadian fisheries management

7.1 Overview

Fishery stock assessments seek to evaluate the state of populations and make recommendations for harvest strategies that will maximize fisheries yield while minimizing risk to the target population. The reliability of assessments depends on many factors, including the availability, use, and quality of data, and the appropriateness and skill of the models that use the data to explain population processes such as growth, recruitment, and mortality. Traditional fisheries management approaches have sought to set harvest rates that aim to provide the MSY for fish stocks, focusing heavily on the effects of exploitation on the dynamics of single species. However, these traditional management strategies have been associated with widespread collapses of exploited marine populations (Myers and Worm, 2003; Worm *et al.*, 2009) and severely delayed or failed recoveries (Frank *et al.*, 2011; Neubauer *et al.*, 2013) in Canada and elsewhere. Along with fishing, this report has highlighted that environmental and ecological effects can drive the dynamics of exploited populations in strong, complex, and unanticipated ways with widespread consequences.

This understanding has motivated a rethinking of how to optimally conserve marine populations and of alternative management strategies. Many fisheries management bodies such as NAFO, the International Council for the Exploration of the Sea (ICES), and FAO are now developing approaches to incorporate uncertainty, ecosystem effects, and climate variability and change into management (Garcia *et al.*, 2003; Busch *et al.*, 2016; Barange *et al.*, 2018; Koen-Alonso *et al.*, 2019). These trends have also been evident in Canada where these and additional priorities have been progressively introduced by DFO as key priorities in the management of Canadian fish stocks. In 2003, a federal framework for a precautionary approach became government policy, leading in 2006 to more formal implementation of precautionary principles to fisheries management (DFO, 2006a). In 2007, the Science Management Board promoted the implementation of an ecosystem approach to fisheries management (EAFM; DFO, 2007) and wrote: "… the highest priority for DFO Science is providing scientific support for ecosystem-based management." This shift led to targeted funding for applied ecosystem research under the Strategic Program for Ecosystem-Based Research and Advice (SPERA) in 2012 and to the Sustainable Fisheries Framework, which is the foundation of the ecosystem approach to fisheries (EAF). Around the same time, DFO evaluated the risk that climate change would lead to adverse effects on marine resources and subsequently began an internal science funding program for directed climate change research under the ACCASP in 2011. According to DFO, the priorities of ACCASP include *"… to advance knowledge and understanding of the risks, impacts and opportunities created by climate change for Fisheries and Oceans Canada's mandated areas of responsibility and to begin to develop science-based adaptation tools necessary to support the consideration of climate change in departmental decision-making."* Despite the understanding that climate change poses a significant risk for Canadian marine resource use and the new availability of funding for directed climate change research under ACCASP, the extent to which climate change and these other themes are being incorporated into the practical day-to-day management of fisheries is not well resolved.

This chapter will provide an analysis of the extent to which emerging and related management priorities, including climate change, the precautionary approach, and EAF, are considered in DFO fishery assessment and decision-making. This will be accomplished through a comprehensive and detailed text mining analysis of over 1000 individual documents pertaining to the management of fisheries in Canada. The documents were analyzed to identify the frequency with which management priorities arose and how these varied between species, regions, document types, and over time. This knowledge was used to understand if these themes that have been identified as key priorities for management are reflected in the practical day-to-day management of Canada's fisheries.

7.2 The management structure of Canada's fisheries

The flow of information and decision-making steps in the management of Canada's fisheries is depicted in Figure 7.1, which broadly follows the generalized management outline described in Figure 6.1. Central to the process is the Canadian Science Advisory Secretariat (CSAS) process for producing science advice for DFO[13]. The CSAS process is a formal and predominantly transparent process for delivering science advice to decision-makers. The process is initiated by the CSAS steering committee (mainly DFO science staff, sometimes external participants), that develops terms of reference (ToR) to guide the questions to be addressed by science, including the collection and analysis of data. DFO researchers then assemble and analyze data with the intent of addressing the research questions and issues contained in the ToR; the resulting technical and scientific information is described in working paper(s). Formal CSAS meetings may be convened to critically evaluate and reach a consensus[14] on the content of the working paper(s). The CSAS meetings are often attended by various stakeholders (e.g. industry, environmental non-governmental organizations [ENGOs], academia, Indigenous representatives, provincial representatives) and external peer reviewers, by invitation only. Participants are made aware of the CSAS protocols, wherein they are participating as individuals based on their expertise and not as members of defined groups. The CSAS meetings often lead to the publication of CSAS research documents (RES-DOCs), science advisory reports (SARs), and proceedings that are publicly available and collectively form the scientific basis for advice to decision-makers. However, while all CSAS documents are peer-reviewed[15], not all are vetted by the CSAS meeting process[16]. An advisory committee meets to discuss the CSAS science advice and make formal recommendations to decision-makers. The transparency of the advisory committee meetings varies widely between regions and stocks, but formal membership seats must be acquired through application and are difficult to obtain for non-industry stakeholders. Under the guidance of the Fisheries Act, ultimate discretion for management decision-making falls to the minister of

[13] https://www.canada.ca/en/fisheries-oceans/news/2019/02/understanding-the-canadian-science-advisory-secretariat.html
[14] https://www.dfo-mpo.gc.ca/csas-sccs/process-processus/consensus-eng.html
[15] https://www.dfo-mpo.gc.ca/csas-sccs/process-processus/noncsas-nonsccs-eng.html
[16] https://www.dfo-mpo.gc.ca/csas-sccs/process-processus/srp-prs-eng.htm

Fisheries and Oceans and decisions from the minister are required for new fishing licences, deviations from existing policies, a discrepancy in science advice and TAC recommendation, multi-regional fisheries, Land Claims Management Board decisions, and objectives for key international fisheries negotiations[17]. However, in practice, many other decisions (e.g. management actions, TAC, quota transfers, opening and closures) are delegated to regional authorities (e.g. Regional Directors General)[18]. Decisions are informed by several factors, including, for instance, science advice, socio-economic considerations, formal fisheries policies (e.g. the Sustainable Fisheries Framework[19]), Indigenous and cultural considerations, and stakeholder consultations. However, not all decisions are posted publicly, nor are the factors used to reach them, factors that detract from the openness, transparency, and accountability of the process. The decision-making process leads to licence conditions, conservation harvesting plans, and the resultant harvesting conditions and quotas that describe how fishing activities will be carried out. Separate to the management process are integrated fisheries management plans (IFMPs), which are public-facing planning frameworks that describe the status of fisheries and how they are to be managed for a prespecified period of time[20]. IFMPs are initially vetted by the advisory committee and are then 'evergreen documents,' meaning they are only updated as needed. They are a product of the management process but are intended to support the management of fisheries, and most (but not all) are publicly available[21].

---

17 https://www.dfo-mpo.gc.ca/transparency-transparence/mtb-ctm/2019/binder-cahier-1/1F1-management-gestion-eng.htm

18 https://www.dfo-mpo.gc.ca/transparency-transparence/mtb-ctm/2019/binder-cahier-1/1F1-management-gestion-eng.htm

19 https://www.dfo-mpo.gc.ca/reports-rapports/regs/sff-cpd/overview-cadre-eng.htm

20 https://www.dfo-mpo.gc.ca/fisheries-peches/ifmp-gmp/guidance-guide/preparing-ifmp-pgip-elaboration-eng.html#a2

21 https://www.dfo-mpo.gc.ca/fisheries-peches/ifmp-gmp/index-eng.html

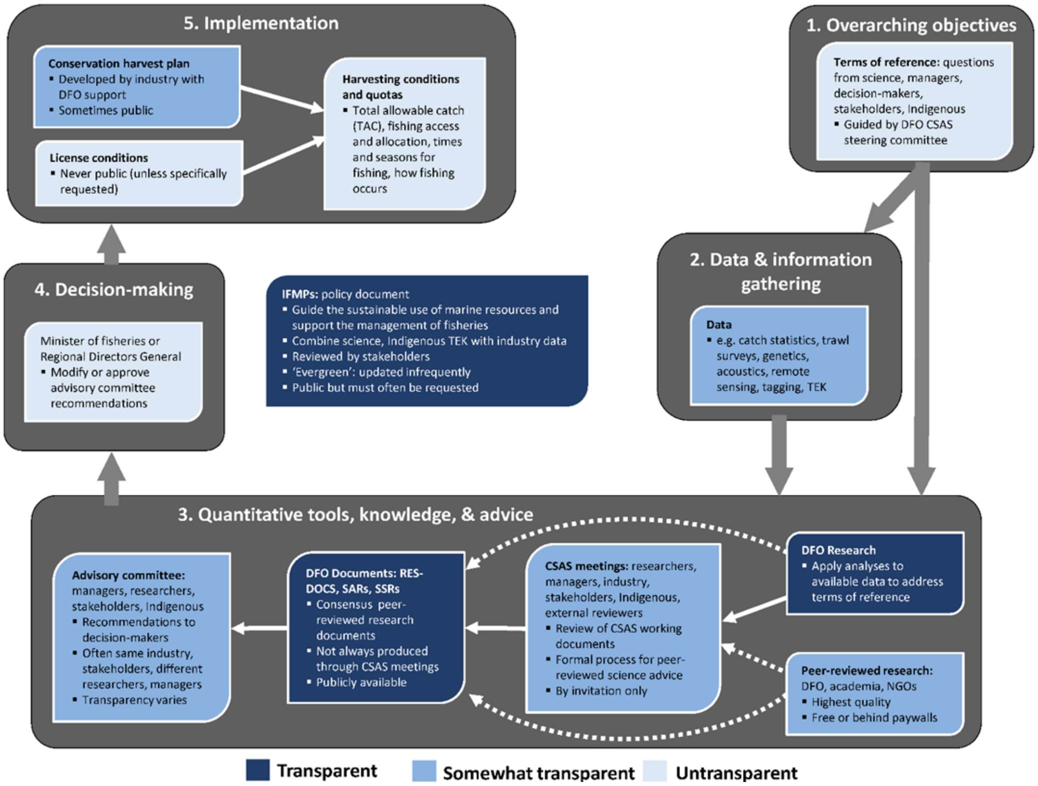

Figure 7.1 A conceptual model of the management process for fisheries in Canada.

Coloured boxes describe the steps in the fisheries management process and arrows show their sequence. Dashed arrows denote processes that occur less frequently. Box colours depict the level of transparency of the steps: light blue is low, medium blue is medium, and dark blue is high transparency. Grey shading and numbered headings depict how the various steps (coloured boxes) are grouped within the generalized fisheries management process (Figure 6.1). IFMPs are a product of the integrated management process, but can also inform it.

7.3 Methods

7.3.1 Data

A database of documents that relate to the science and management of marine species in Quebec, the Atlantic Canada, and Eastern Arctic published between 2000 and 2020 was compiled. Three DFO document types were used:

1. DFO RES-DOCs, which form the scientific basis for management (n = 729). These included research documents, stock status reports, science advisory reports (SARs), and science responses.
2. DFO IFMPs, which outline the process through which fisheries are managed for a prespecified duration (n = 68). In theory, these include the planning cycle, fishery objectives, management decisions, control measures, and Indigenous participation. IFMPs "… provide a clear and concise summary of a fishery, which includes scientific aspects, management objectives for the fishery, management measures used to achieve those objectives and criteria by which attainment of objectives will be measured.[22]" They are developed by DFO after consultation with the fishing industry, the provinces, and stakeholders such as Indigenous organizations, conservation organizations, and academia, and are informed by the RES-DOCs.

[22] https://www.dfo-mpo.gc.ca/fisheries-peches/ifmp-gmp/guidance-guide/preparing-ifmp-pgip-elaboration-eng.html#a2

3. Peer-reviewed publications (PR-DOCs) related to fisheries dynamics, which have been authored or co-authored by DFO scientists (n = 108) and published in scientific journals. Peer-reviewed studies have undergone critical evaluation by experts and represent the gold standard in scientific rigour.

The DFO RES-DOCs and IFMPs are publicly available through the DFO CSAS website. Where IFMPs were not publicly available, they were obtained through a request from DFO personnel. For each document, metadata were entered into a table that contained the title, year, species, functional group, and region of the document. Where possible, only the most recent documents for each species were retained, although older ones may also be included. The PR-DOCs were obtained by searching the Clarivate Analytics Web of Science, which provides subscription access to peer-reviewed studies published in over 21,100 journals since 1900. Table 10.3 contains the search criteria that were used to identify peer-reviewed studies of relevance. For all documents, freshwater species and those outside of the area of interest were excluded.

7.3.2 Analyses

The text within the documents was analyzed to understand how eight primary and secondary themes were represented in fisheries research and management in Canada. The three primary themes were climate change, EAF, and the precautionary approach. The five secondary themes were oceanographic factors, trophic dynamics, exploitation, climate vulnerability, and forecasting. Each theme was associated with a set of keywords or phrases (terms). For example, the fishing theme was associated with the following terms: 'exploitation,' 'fishing,' 'landings,' 'harvest,' 'hunting.' The text of the documents was searched by the software for these terms, and upon occurrence, the documents were associated with the fishing theme. The frequency with which these themes appeared in the documents was then analyzed to understand patterns in theme occurrence in relation to document types (RES-DOCs, IFMPs, PR-DOCs), species groups, and regions, and over time. The appendix contains a detailed description of the methods used to undertake this analysis, and Table 10.4 contains the words and phrases that were used to define the themes. Additional information was obtained by reading the documents that were identified as being of particular interest—for example, those that discussed climate change.

To understand the associations between these primary themes across research and management documents, 137 RES-DOCs were matched to 37 corresponding IFMPs according to the focal species, management region, and publication year. From these matches, a co-occurrence analysis was undertaken (Griffith *et al.*, 2016) to determine the frequency with which the themes were coincidentally present or absent in RES-DOCs and IFMPs. Themes that are more strongly associated across RES-DOCs and IFMPs appear closer in the multidimensional plot. Analyses were performed using the quanteda (Benoit *et al.*, 2018) and co-occur (Griffith *et al.*, 2016) packages in the R statistical computing platform (R Core Team, 2015).

The text within the documents was analyzed to understand the extent to which broader ecosystem-wide data sources (e.g. environmental, multi-trophic, genetic) were being used in fisheries research and management in Canada. The data source themes were defined by the primary observational datasets that are available to DFO researchers, including fishery landings, Argo floats, gliders, Atlantic Zone Off-Shelf Monitoring Program, conductivity-temperature-depth profiles, remote sensing, Atlantic Zone Monitoring Program, Continuous Plankton Recorder, DNA, larval surveys, acoustics, and research vessel surveys. As with management themes, each data theme was associated with a set of keywords or phrases (terms). For example, the acoustic theme was associated with the following terms: 'acoustic,' 'backscatter,' 'target strength,' and 'acoustics.' The text of the documents was searched by the software for these terms, and upon occurrence, the documents were associated with the data theme. The frequency with which these themes appeared in the documents was then analyzed to understand the frequencies with which different data types were being used and if different data types were used in combination.

Analyses were undertaken to determine if the targeted government funding for ecosystem-based (SPERA) and climate (ACCASP) research was being incorporated into the scientific basis for DFO fisheries management (RES-DOCs). To accomplish this, the text within the RES-DOCs was searched for citations to PR-DOCs (n = 108), as well as to peer-reviewed research that was funded through SPERA or ACCASP. PR-DOCS$_{SPERA}$ (n = 29) and PR-DOCS$_{ACCASP}$ (n = 64) were identified using the Clarivate Analytics Web of Science and searching for the appropriate funding sources.

7.4 Results

7.4.1 Database summary

For most regions, the availability of DFO IFMP and RES-DOCs was comparable (Figure 7.2a). However, Quebec had a notably higher proportion of IFMPs (41%) relative to RES-DOCs (23%), whereas the Maritimes has a higher proportion of RES-DOCs (31%) relative to IFMPs (21%). The RES-DOCs comprised 43% Research Documents, 40% Science Advisory Reports, 13% Science Responses, and 5% Stock Status Reports. The representation of functional groups in DFO IFMP and RES-DOCs was comparable (Figure 7.2b). Overall, DFO documents related to large groundfish (33–38%) and invertebrates (32%) were most common, followed by small pelagic fish (9–10%), small groundfish (7–12%), mammals (4–9%), and large pelagic fish (4–9%). There was an increase in the number of documents over time, with most published after 2011 and very few before 2005 (Figure 7.2d). Of all 905 documents, RES-DOCs constituted 81%, with IFMPs and PR-DOCs representing 8% and 12%, respectively. Most DFO documents originated from the Maritimes, Quebec, and Newfoundland and Labrador. Similar to trends in abundance, there was an increased frequency of documents related to invertebrates over time and a reduction in those related to large groundfish.

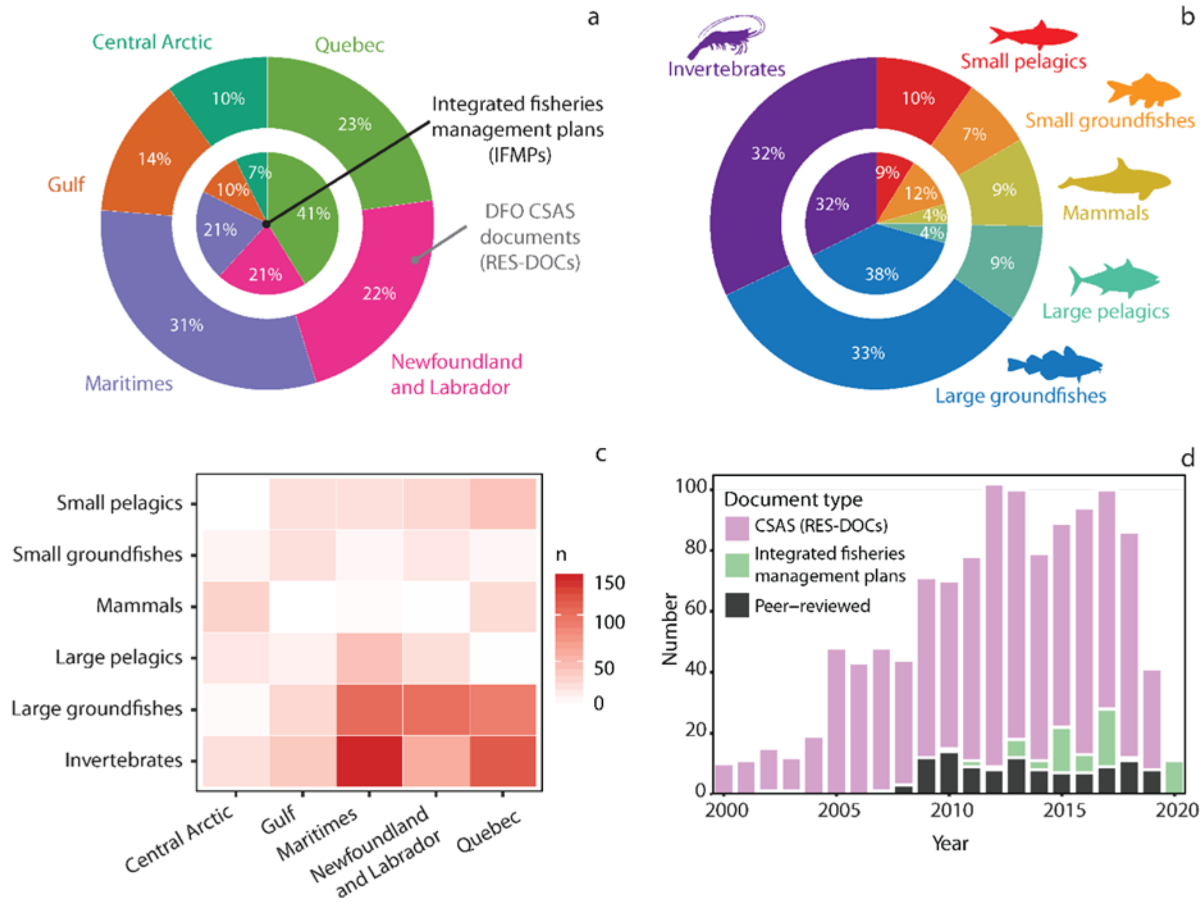

Figure 7.2 Summary of DFO documents used in this analysis.
(a–b) The proportion of available DFO documents for each document type, administrative region (a), and species functional group (b). Colours depict the different regions (a) and functional groups (b). The inner circles show IFMPs and the outer show RES-DOCs. (c) Availability of DFO documents according to their functional group (*y*-axis) and administrative region (*x*-axis). Dark red denotes a greater number of available documents. (d) The availability of document types over time are shown as colours: RES-DOCs are purple, IFMPs are green, and PR-DOCs are grey.

7.4.2 Frequencies of theme occurrence

The exploitation theme occurred almost ubiquitously across all document types, attesting to the continued strong focus on the assessments of single species (Figure 7.3a). The theme occurred more frequently in the RES-DOCs (89%) and IFMPs (85%) relative to peer-reviewed studies (67%), and was consistent over time (Figure 7.3b) and across regions or functional groups. The EAF theme arose in 29% of IFMPs, 8% of PR-DOCs, and 1% of RES-DOCs. However, the related trophic dynamics theme arose much more frequently in PR-DOCs (68%), IFMPs (47%), and RES-DOCs (39%). Trophic dynamics frequently occurred in association with invertebrates and groundfish as a mechanism to explain past ecosystem shifts. The precautionary approach theme frequently occurred in both RES-DOCs (38%) and IFMPs (56%), and less often in PR-DOCs (3%). The frequency of occurrence increased over time in both RES-DOCs and PR-DOCs but was consistently high over time in IFMPs.

The oceanographic theme, which related to any discussion of environmental factors, but not necessarily in a long-term climate change context, arose in roughly half of the RES-DOCs (51%) and IFMPs (50%) and more so in PR-DOCs (78%).

The climate change theme, which related to long-term directed changes in climate, arose more than twice as frequently in PR-DOCs (29%) and IFMPs (27%) than in RES-DOCs (11%). Among RES-DOCs, climate change arose in 81 documents (Table 10.5) and was most frequently associated with mammals, the Arctic, and large pelagic species (e.g. tunas) and least frequently with invertebrates, small pelagics (e.g. herring) and groundfish, and in the Maritimes region. Climate change search terms were mentioned at most nine times in any single RES-DOC (Atlantic salmon in the Maritimes) and arose only once in 61% of documents (Table 10.5). In contrast to peer-reviewed studies and research documents, the frequency of climate change inclusion in IFMPs increased rapidly over time, particularly after 2010 (Figure 7.3b). Secondary climate change themes, such as climate vulnerability and forecasting, arose relatively infrequently (<3 and <19%, respectively) but increasingly over time (since ~2015). Variability in theme occurrence was observed within the RES-DOCs (Figure S2), with the Science Advisory Reports generally referencing the major themes more frequently than the Research documents (see section 10.2.3 for details and Figure 10.1).

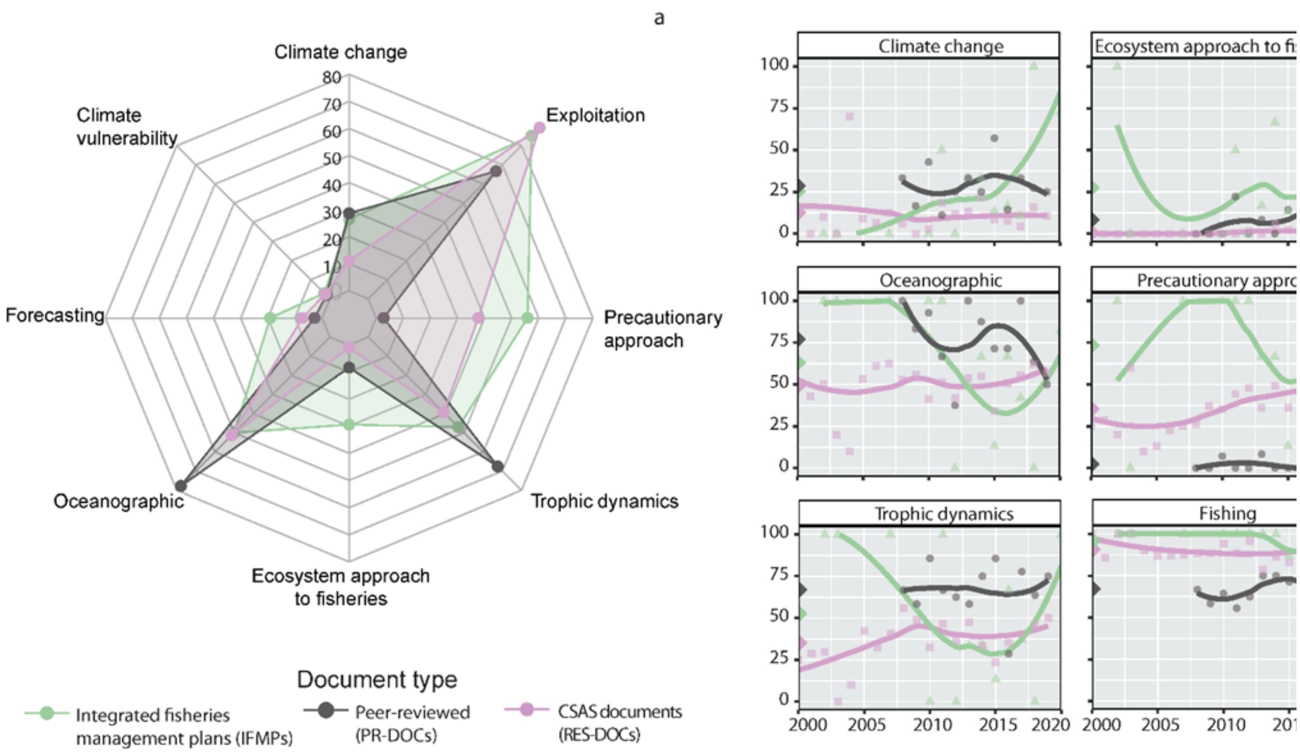

Figure 7.3 Frequencies of themes occurring across documents (a) and over time (b).

(a) The average frequency of occurrence of the themes for each document type; axes begin at the centre of the plot and extend outward. (b) Time trends in the frequency of occurrence for themes of interest. Average frequencies over the time-series are displayed as points along the y-axes. (a–b) Colours denote the document types: RES-DOCs are purple, IFMPs are green, and PR-DOCs are grey.

7.4.3 Theme associations

Among the RES-DOCs, the co-occurrence analyses suggested that themes related to fishing, trophic dynamics, oceanographic, and the precautionary approach occurred together (Figure 7.4a). Climate change and forecasting tended to co-occur, as did climate vulnerability and EAF. For IFMPs, most themes co-occurred, except for forecasting and climate vulnerability, which were not associated with any themes (Figure 7.4b). The theme associations among PR-DOCs were similar to RES-DOCs, except that climate change tended to occur with the other major drivers instead of the precautionary approach (Figure 7.4c).

For most themes, the occurrence in a RES-DOC did not increase its frequency of occurrence in the corresponding IFMP (Figure 7.3d). Fishing, oceanography, the precautionary approach, and trophic dynamics were exceptions to this pattern and were more likely to arise in IFMPs if they were also included in the corresponding RES-DOCs.

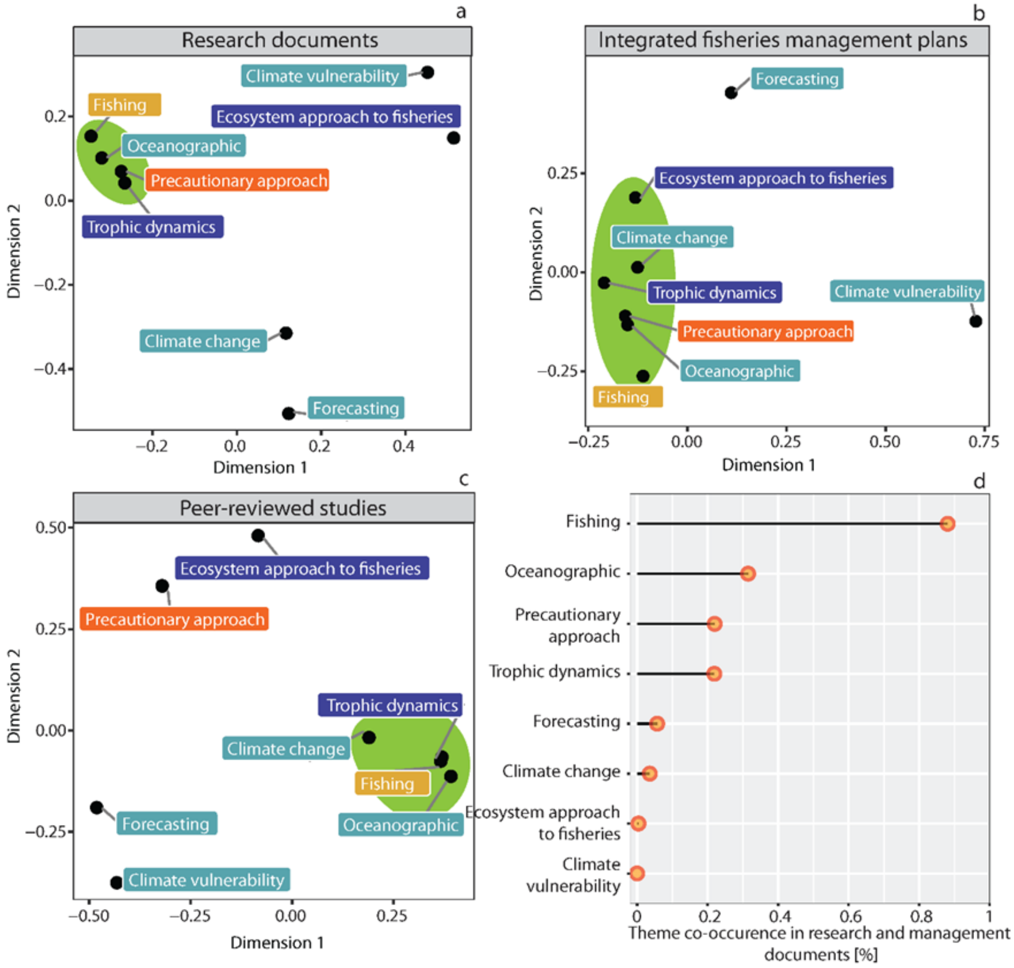

Figure 7.4 Patterns of co-occurrence across management themes.

(a) Non-metric multidimensional scaling results depicting the associations between the themes; themes that are closer are more strongly associated. The colour labels depict the type of theme: light blue is climatological, dark blue is ecological, yellow is fishing, and red is precautionary. Green ellipses denote the core cluster of themes for each document type. (b) The probability that a theme occurs, or does not occur, together in both IFMPs and their matching RES-DOCs. Statistically significant co-occurrence differences are depicted as opaque orange symbols.

7.4.4 Use of ecosystem monitoring data

Fishery catch information was the most commonly included data source across all document types, being mentioned in 86% of RES-DOCs and 99% of IFMPs. Research trawl surveys (~30–45%) and tagging studies (~15–30%) were mentioned moderately frequently across the documents (Figure 7.5). Acoustic (~10–20%), remote sensing (~9–20%), and genetics (~9–20%) were mentioned with low frequency. The remaining data sources were mentioned in ~0–10% of the documents. Considering the frequencies with which the specific data observation types were mentioned, in combination with the portion of the ecosystem that they sample, enabled us to evaluate what component of the ecosystem could conceivably be assessed. For instance, data on trophic level four and higher are assessed from genetics, research surveys, tagging studies, and landings, and the average frequency of occurrence across these data sources gives us an estimate of the frequency of mention for upper-trophic level components of the ecosystem (29–44%). Using this approach, it was clear that data sources that evaluate mid- and upper-trophic level components of the ecosystem (e.g. that directly relate to fisheries) were, on average, mentioned much more frequently (26–44%) than those related to plankton, larvae, and the physical and/or chemical environment (Figure 7.5c). Data sources that assess primary production dynamics were mentioned, on average, in 3% of RES-DOCs, 4% of IFMPs, and 6% of PR-DOCs. Those that assess zooplankton and/or larvae were mentioned in 4% of RES-DOCs, 5% of IFMPs, and 8% of PR-DOCs. Data types that can assess environmental conditions were mentioned in 7% of RES-DOCs, 8% of IFMPs, and 7% of PR-DOCs.

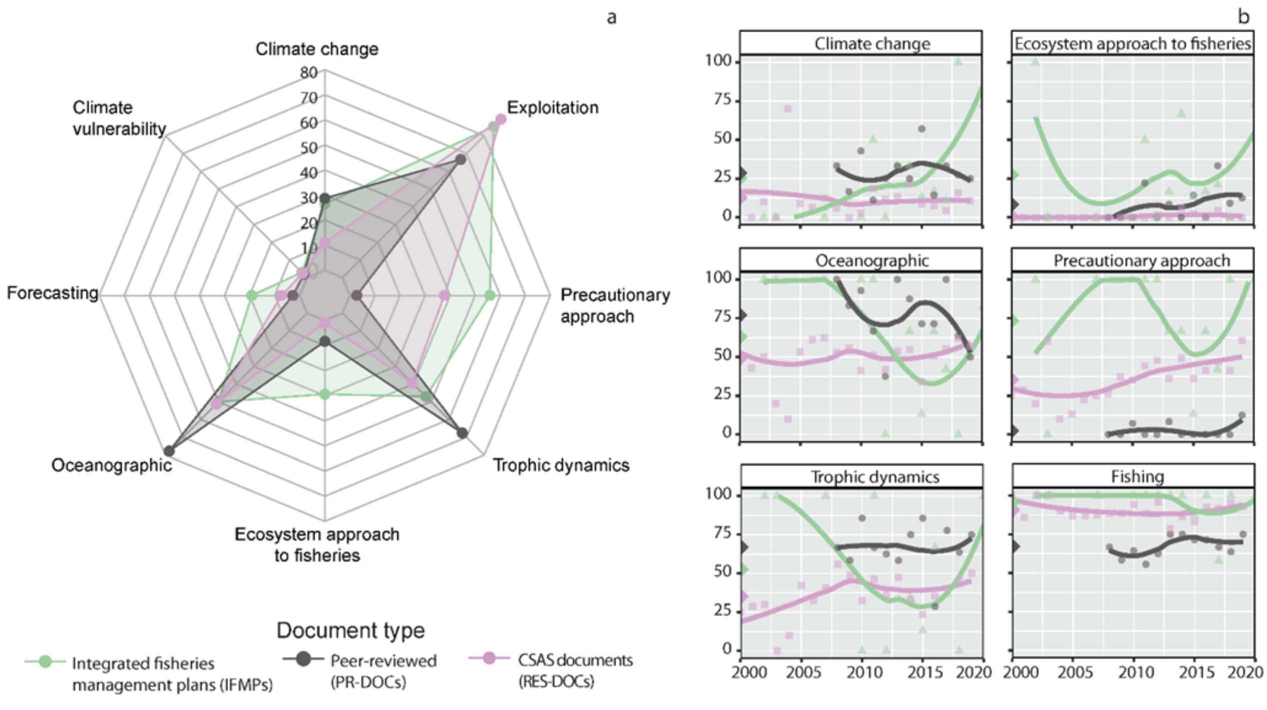

Figure 7.5 Frequencies of occurrence for major DFO data sources across documents.
(a) The average frequency of occurrence of the major DFO data types for each document type; axes begin at the centre of the plot and extend outward (%). Colours denote the document types: RES-DOCs are purple, IFMPs are green, and PR-DOCs are grey. (b) Blue shading depicts the taxonomic scope of the major DFO data types. Environmental includes observations of physical, chemical, and atmospheric characteristics. (c) The proportion of documents that reference different ecosystem data types. Colours depict the document types, as in (a).

7.4.5 Incorporation of knowledge generated through targeted funding

The results indicated that two out of 64 (3%) peer-reviewed studies funded by ACCASP that provided decision-makers with information to plan for and adapt to climate change were mentioned in RES-DOCs. None (0%) of the 29 peer-reviewed studies funded by SPERA to provide decision-makers with information about ecosystem-based considerations were mentioned in RES-DOCs. Of all 185 peer-reviewed studies authored by DFO scientists and related to fisheries management in the AOS, 22 (12%) were cited in the RES-DOCs.

7.5 Discussion

This review suggests that of the primary themes considered, climate change and EAF are currently the least frequently considered in the science and management of Canada's fisheries. Climate change was explicitly discussed with increasing frequency in almost a third (29%) of PR-DOCs, suggesting that it is a factor of importance to fisheries, and in one-quarter of IFMPs, suggesting that it is also on the radar of DFO managers. However, climate change was incorporated in only 11% of RES-DOCs, indicating that it is not routinely considered in the DFO science basis that informs the advisory process. Furthermore, on close inspection, it was found that most of the references to climate change in the RES-DOCs expressed that there was a lack of understanding of how climate change would impact the dynamics of the stock. For example, the SAR for American plaice (*Hippoglossoides platessoides*) in the Gulf of St. Lawrence for 2011 stated that "The impact of global warming is yet unknown on the biology of American Plaice" (DFO, 2011). Many other mentions acknowledged the threat of climate change either directly or in passing but did not incorporate this information into the stock assessment or advice. For example, the SAR for northern shrimp (*Pandalus borealis*) in Newfoundland in 2013 stated "Effects of climate change on shrimp resources should be considered when making management decisions. However, the meeting agreed that there is a need to conduct more research to determine whether environmental variables could be used in conjunction with recruitment signals to produce resource status predictions" (DFO, 2013) Statements of this nature are useful in identifying knowledge gaps but also emphasize that reference to climate change and other themes do not constitute knowledge or quantitative incorporation of them.

The frequency with which climate change and EAF occurred has increased over time in IFMPs but not in the RES-DOCs (Figure 7.3b). The co-occurrence analyses indicated that fishing, oceanography, and trophic dynamics were 'core' themes across all document types, but climate change and EAF were not (Figure 7.4a–c). However, climate change was a core theme in peer-reviewed studies and IFMPs. EAF was a core theme in IFMPs but not in RES-DOCs or PR-DOCs. There was a low degree of co-occurrence of the climate change theme in the RES-DOCs and their corresponding IFMPs. Cumulatively, these results suggest that climate change and EAF are current priorities and are being discussed at the fisheries management stage (IFMPs) but less so within the science process (RES-DOCs).

This low representation of climate change and EAF in RES-DOCs contrasts sharply with the precautionary approach theme, which arose in 56% of IFMPs and 38% of RES-DOCs and was discussed more frequently over time in both document types (Figure 7.3). The increasing frequency of reference to the precautionary approach in RES-DOCs coincided with the 2006 release of a framework for its incorporation into management (DFO, 2006a). This may suggest that priorities could be more effectively incorporated into science and management when there are explicit guidelines for how to do so. However, whereas the framework for the precautionary approach is relatively concise (DFO, 2006a) and integrates easily into existing fisheries management approaches, climate change and EAF are more complex challenges that lack standardized solutions (Garcia *et al.*, 2003; Busch *et al.*, 2016; Barange *et al.*, 2018; Koen-Alonso *et al.*, 2019). The optimal management approach can depend on the species, location, available data, and resources. Despite this, providing explicit guidelines for how to incorporate climate change or EAF into fisheries is tractable, and there are several tools for doing so. For example, climate vulnerability assessments (Stortini *et al.*, 2015; Greenan *et al.*, 2019) and climate and ecological forecasting (Lotze *et al.*, 2019) are approaches that can quantitatively incorporate different aspects of the sensitivity and future exposure of species to climate change at the shorter-term scales (e.g. seasonal) required by management. MSEs can find candidate management strategies that are robust to different future climate scenarios, population and ecosystem dynamics, and other uncertainties. Dynamic management can set harvest rates based on dynamics forecasts or can respond in real time to changing conditions (Dunn *et al.*, 2016). Ecosystem models can incorporate multiple species interactions and environmental effects to better understand the impact of exploitation on exploited species' dynamics. Such models are being successfully used by NOAA and include temperature-dependent weight-at-age functions and temperature-specific predation interactions (Holsman *et al.*, 2017). Ideally, such approaches would be integrated. For example, the Alaska Eastern Bering Sea Integrated Ecosystem assessment program uses food web and multispecies assessment models, climate forecasts and projections developed by regional ocean modelling systems (ROMS), and scientific surveys to inform the North Pacific Fisheries Management Council[23].

Monitoring data spanning the ecosystem's breadth are required to ensure that fisheries management strategies are robust to climate and ecosystem variation and change. For example, climate-associated changes in zooplankton distribution are currently driving the spatial distribution of right whales, an endangered species, with critical consequences for their management and recovery prospects (Plourde *et al.*, 2019). Despite this, data sources that contain such ecosystem information were mentioned in only 3-8% of RES-DOCs. DFO currently invests substantially in ecosystem monitoring, and there is a wealth of available data sources that, if treated appropriately, could enable a more direct consideration of climate change and ecosystem effects on fisheries.

Targeted funding to increase the inclusion of climate change (ACCASP) and ecosystem considerations (SPERA) into Canadian ocean management, including fisheries, has led to peer-reviewed knowledge generation. Although some articles may have been inadvertently overlooked, it was found that over the period of interest, DFO authors have published 185 studies related to fishery dynamics in the AOS. Targeted funding to ACCASP led to 64 published studies and SPERA to 29. Despite this, our text analysis suggests that the information from these

---

[23] https://www.integratedecosystemassessment.noaa.gov/regions/alaska/about#:~:text=Alaska's%20Integrated%20Ecosystem%20Assessment%20program,support%20effective%20Ecosystem%2DBased%20Management.

studies is not often connected to fisheries science and management. None of the SPERA-funded studies and only 3% of ACCASP-funded studies were mentioned across the RES-DOCs. It is possible that the knowledge from some of these studies is being communicated to fisheries researchers and decision-makers through alternative pathways, such as oral presentations. However, combined with the finding that climate and EAF themes infrequently arose in management documents, and that environmental and multi-trophic data types needed to incorporate these themes were not widely used, it is more likely that knowledge from peer-reviewed studies is not widely considered in management. A recent DFO review of ACCASP emphasized the tools, such as the Fish Stock Climate Vulnerability Assessment Tool (FSCVAT), that have been developed through ACCASP[24]. However, while the FSCVAT would indeed be a valuable tool for fisheries, it is not publicly available and has not been used in any fisheries management setting to date.

Our study complements and builds on a recent DFO CSAS report by Pepin et al. (2020) that reviewed the extent to which ecosystem considerations, broad-scale regional climate variability, and physical drivers that operate across multiple time-scales were included in a sample of 178 DFO stock assessments. Although the study did not explicitly evaluate climate change, the precautionary approach, or EAF, it did provide a substantive and detailed investigation of how environmental and ecological information was included in DFO fisheries assessments. The study reported that when ecosystem, oceanographic, or climate variability information was included quantitatively in assessments, it also tended to be included as recommendations to management. Together with our analysis, this suggests that it may be more important that this information is included quantitatively. Pepin et al. (2020) also reported that only 21% of the assessments (38 of 178) incorporated ecological, oceanographic, or climate variability in a quantitative manner and that most (42%) accomplished this by estimating a time-varying parameter (e.g. mortality, productivity) within the population model. However, these time-varying terms are often estimated as by-products of the models and may not capture a complex and unexpected range of ecological or climate-driven changes that are possible. Primarily for this reason, the approach by itself has not been recommended as a panacea for incorporating climate (Busch et al., 2016; Barange et al., 2018) or ecological (Garcia et al., 2003; Koen-Alonso et al., 2019) information into fisheries management, although it could contribute significantly towards a more integrated approach (Minto and Worm, 2012; Britten et al., 2017). If these instances are excluded from consideration, the Pepin et al. (2020) study indicates that only 13% of stock assessments include climate or ecological information quantitatively. This lack of quantitative inclusion may explain why our analysis found a low co-occurrence of climate change and EAF themes in RES-DOCs and IFMPs (Figure 7.4d). It may also explain why most (61%) of the 81 RES-DOCs that included climate change in our study contained only a single reference to any of the climate change search terms (Table 10.5). This suggests that even when climate change is mentioned, it is not rigorously evaluated or discussed. This is very much at odds with a recent report by DFO that 22% of fisheries stock assessments incorporate climate change considerations[25]. Lastly, Pepin et al. (2020) reported higher incorporation of climate variability in

[24] https://www.dfo-mpo.gc.ca/ae-ve/evaluations/19-20/ACCASP-PSACCMA-eng.html
[25] https://www.dfo-mpo.gc.ca/ae-ve/evaluations/19-20/ACCASP-PSACCMA-eng.html

salmon (Salmonidae) assessments from the Pacific, a region that were not examined in this analysis.

Why aren't these priorities incorporated more frequently in Canadas' fisheries management? Is it possible that these priorities are incorporated into management, but our textual analyses fail to detect them reliably? We ran robustness analyses to ensure that this was not the case (see SI; Figure S3). One explanation may be that the complexity of the problem combined with uncertainty in choosing from the numerous possible approaches leads to 'analysis paralysis' whereby overanalyzing or overthinking a complex challenge can impede progress through fear of making an incorrect decision. In some situations, the necessary resources, including monitoring data, technical expertise, or workers could be a contributing factor. It is also plausible that the relevant questions needed to integrate these management priorities are not being included in the Terms of Reference (ToR) that guide the science (Figure S1). Unless the ToRs request information related to climate change and ecosystem dynamics, these priorities could easily be absent from the assessments and thus the entire management process. A related possibility is that these priorities, particularly climate change, are being interpreted as strategic (*e.g.* long-term intentions), rather than tactical (*e.g.* shorter-term actions; 1-2 years) fisheries management objectives, and are thus excluded from the ToRs, which are primarily focused on tactical needs. It may be that over the shorter tactical timeframes relevant to the ToR, fishing is understood to be the dominant driver of fisheries productivity, with climate change often viewed as a slower-moving, longer-term strategic concern. However, while climate change is a long-term process, its impacts on fisheries are also commonly and increasingly manifest over shorter-term (tactical) timeframes and increasingly significant impacts relative to fishing. Attesting to this point are the many fisheries worldwide that are now including climate change within their tactical management strategies. Therefore, climate change must be taken up in both the strategic and tactical stages to be fully integrated into management. For instance, whereas primary publications, including those funded through SPERA and ACCASP are often more aligned with strategic objectives, they often contain highly relevant information to tactical management objectives and should thus be integrated with the management process.

In conclusion, although the precautionary approach is being increasingly considered in the management of Canada’s fisheries, other key priorities, such as EAF and climate change, are not. These issues are of critical importance to the productivity of fisheries in Canada’s Atlantic and Arctic regions, as this is where some of the most rapid ocean warming has occurred, a trend that may accelerate into the foreseeable future (Loder and van der Baaren, 2013; Loder *et al.*, 2015; Saba *et al.*, 2016). Such climate changes have been associated with changing species dynamics (Pinsky *et al.*, 2013) and large-scale ecosystem reconfigurations (Frank *et al.*, 2007; Shackell *et al.*, 2010) with implications for fisheries. It is suggested that a framework for the incorporation of these themes would provide a critically important starting point to increase their incorporation into fisheries management.

7.6 Key points

- The climate change theme arose in 11% of DFO RES-DOCs that provide the scientific basis for management decisions, less than half as frequently as in peer-reviewed publications (PR-DOCs; 29%) and fisheries management plans (IFMPs; 27%), relative to RES-DOCs (11%).
- Search terms related to climate change were mentioned at most nine times in any single RES-DOC (Atlantic salmon in the Maritimes) and arose only once in 61% of documents (Table 10.5).
- The exploitation theme occurred almost ubiquitously across all document types. The theme occurred more frequently in the RES-DOCs (89%) and IFMPs (85%), relative to peer-reviewed studies (67%).
- The EAF theme arose in 29% of IFMPs, 8% of PR-DOCs and 1% of RES-DOCs.
- The precautionary approach theme frequently occurred in both RES-DOCs (38%) and IFMPs (56%), and less often in PR-DOCs (3%).
- Fishery catch information was the most commonly included data source across all document types, being mentioned in 86% of RES-DOCs and 99% of IFMPs.
- Data sources that evaluate mid- and upper-trophic level components of the ecosystem were, on average, mentioned much more frequently (26–44%) than those related to plankton, larvae, and the physical and/or chemical environment. Data sources that assess primary production dynamics were mentioned, on average, in 3% of RES-DOCs, 4% of IFMPs, and 6% of PR-DOCs.
- Three per cent of the peer-reviewed studies funded by ACCASP to provide decision-makers with information to plan and adapt to climate change were mentioned in RES-DOCs.
- None of the 29 peer-reviewed studies funded by SPERA to provide decision-makers with information about ecosystem-based considerations were mentioned in RES-DOCs.
- Twelve per cent of the 185 peer-reviewed studies authored by DFO scientists and related to fisheries management were cited in the RES-DOCs.

8. Incorporating climate change and ecosystem considerations into Canadian fisheries

8.1 Overarching objectives, principles, and priorities

8.1.1 A national strategy

Although climate considerations are being incorporated into the management of some of Canada's fisheries, it is currently a piecemeal process, with little consensus on how to do so in a consistent or unified manner. A national climate change strategy for fisheries management such as that of the US NOAA (Busch *et al.*, 2016; Gregg *et al.*, 2016) would provide a blueprint for how to robustly and effectively manage Canada's ocean resources under a changing climate. Informed by best practices and building on two recent DFO CSAS publications by Pepin *et al.* (2020) and Duplisea *et al.* (2020), such a strategy would describe a range of recommended approaches, identify important information gaps, and make recommendations for what resources are needed to further incorporate climate considerations into the management of fisheries in Canada. The framework could be national but may also be tailored to the specific circumstances of each region or species. Most significantly, such a framework would provide an important roadmap for the process of climate change integration in Canadian fisheries and would help avoid 'analysis paralysis'[26] whereby overanalyzing or overthinking a complex challenge can impede progress through fear of making an incorrect decision.

In accord with a national strategy, the incorporation of climate change considerations into fisheries management requires its inclusion in the Terms of Reference (ToRs) that establish the questions addressed by DFO Science. Canadas recently updated Fisheries Act requires 'environmental conditions' to be taken to account in fisheries management decisions. Still, anecdotally climate considerations do not appear to routinely be included in the ToRs that guide the science and management of fish stocks.

Recommendations:

- A national climate change strategy that outlines priorities, approaches, and recommendations for incorporating climate change considerations into the management of Canada's fisheries and other marine living resources.
- Prioritization of climate change incorporation into fisheries management through further inclusion in the ToRs provided to DFO Science.

[26] https://en.wikipedia.org/wiki/Analysis_paralysis

8.1.2 Increased transparency and accountability

Irrespective of climate change and other considerations, for Canadian fisheries management to be effective, it is critical that the process of fisheries management, including basic data, science, advice, and decision-making processes, be open to all stakeholders (Mora *et al.*, 2009). Despite being enshrined in international law as part of the United Nations Fish Stocks Agreement (Article 12), the lack of transparency in Canadian fisheries management and data sharing has previously been highlighted as a barrier to effective management (Hutchings *et al.*, 2012; Baum and Fuller, 2016). For instance, Baum and Fuller (2016) reported that in 2015, 79% of species listed did not have management plans posted for any of their stocks. Further, DFO management decisions are posted online for Atlantic Canada, Quebec, and the Arctic, decisions for many stocks are missing, and there are no decisions posted for the Pacific region (DFO. and DFO, 2015; Edwards *et al.*, 2016). There are signs that this situation may be improving: as of 2019, increasing the openness and transparency in fisheries management is explicitly mentioned in the prime minister's mandate letter to the minister of Fisheries, Oceans, and the Canadian Coast Guard[27]. Despite this, the DFO fisheries management framework presented also emphasizes several areas where transparency and accountability could be improved (Figure 7.1). DFO management advisory committees and meetings are not open to all stakeholders, and information from the meetings is not available online. Meeting minutes are only available on member association meeting websites. For those meetings that are open to observers, the information needed to attend them (e.g. where and when they are held) is often difficult to acquire, creating barriers to their openness. This closed advisory process makes it difficult to track how and why decisions are made and why, at times, these decisions contradict scientific advice. This situation contrasts sharply with the US NOAA, which posts all management advisory councils on its website, including meeting dates (NOAA, 2015). Additionally, the Canadian management decision-making process can be circumvented through direct communication with the minister's office or regional fisheries directors due to the powers of the minister within the Fisheries Act. In the process of writing this report, it was observed that, similarly to stock assessments, the IFMPs for many species were not readily available, needed to be requested from various DFO personnel, and were only infrequently updated. To further facilitate open transparency and accountability, while also ensuring high standards of quality, all DFO stock assessments could also be peer-reviewed. Peer-review is the gold standard for academic publication, providing increased credibility and identifying possible areas of improvement.

Recommendations:

- Management decisions for all fishery stocks, including quotas, should be publicly available in a standardized and timely manner. Decisions should include what considerations were taken into account as per Section 2.1 of the Fisheries Act, and the weighting of these factors in the final decision should be made public.
- To the extent possible, management advisory committees, including dates and locations of meetings, and meeting minutes, should be publicly listed.

[27] https://pm.gc.ca/en/mandate-letters/2019/12/13/minister-fisheries-oceans-and-canadian-coast-guard-mandate-letter

- IFMPs should be publicly available and should be more frequently updated (e.g. coinciding with the update frequency of assessments) to reflect the most current science and progress in incorporating sustainable fishing practices.
- Sources of scientific uncertainty, including those related to climate change and ecosystem considerations, should be required to be listed within stock assessments and IFMPs.
- A peer-review process for stock assessments should be implemented to increase robustness, accountability, and transparency.

8.1.3 Reduce non-climate stressors

The cumulative impacts of non-climate stressors, including pollution, overfishing, bycatch, and habitat alteration, can reduce the resistance and resilience of species and ecosystems to climate change. Reducing stressors and instituting effective fisheries management can, in many instances, counter the deleterious effects of climate change on fisheries productivity (Le Bris *et al.*, 2018).

Recommendations:

- Work with other departments and jurisdictions to identify and, where possible, mitigate threats to fisheries, particularly those most vulnerable to climate change.
- In accordance with Section 6 of the Fisheries Act, which requires population rebuilding, reduce overfishing and prioritize the recovery of overfished stocks through rigorous adherence to scientific advice.

8.1.4 Embrace precaution

Understanding of climate change will introduce new sources of uncertainty to fisheries science and management in situations where climate patterns and their effects on species are not well understood. Erring on the side of caution when uncertainty regarding the stock status and climate impacts is high would provide a buffer against this lack of understanding. In addition to adhering to DFO's precautionary approach framework (DFO, 2006a, 2009b), measures could include lowering quotas or instituting moratoria until the uncertainty is reduced to sufficient levels. Considering the uncertainty in fish stock status is critical to embracing precaution. For instance, whereas the SSB for 4VWX Atlantic herring (*Clupea harengus*) was slightly above the precautionary approach framework lower reference point in 2017 (DFO, 2018b), prompting classification in the cautious zone[28], the higher uncertainty around the SSB estimate could have instead placed the stock in the critical zone, prompting a different management response. The recent state of 4VWX herring is part of a decline in overall population health since 1965 (Boyce *et al.*, 2019), with the 2018 SSB reaching its lowest level since the start of the acoustic SSB series began in 1999 (DFO, 2020c).

[28] https://www.dfo-mpo.gc.ca/reports-rapports/regs/sff-cpd/survey-sondage/index-en.html

Recommendations:

- Where uncertainty in fish stock status and the impacts of climate or ecosystem impacts on the stock is high, adopt enhanced precautionary approaches to management.
- Institute efforts to rebuild depleted fish populations that are likely to experience greater magnitudes of changes due to their status.

8.1.5 Implement flexible management plans, prepare for new opportunities and threats

Studies suggest that climate change will alter the distribution of marine species, with many new species moving north into Canadian waters (Figure 4.3), and others shifting into the Arctic where fisheries are less developed. Preparing for these new opportunities by evaluating the potential to establish new commercial and recreational fisheries should be part of climate change integration efforts. Such efforts may include establishing catch limits and permitting procedures for new fisheries. Alternatively, changes in species distributions will lead to new and potentially harmful interactions with fisheries and other marine industries that may require new approaches to mitigate them. For example, the North Atlantic right whale example discussed in section 7.5.1 highlights the range of approaches (e.g. enhanced monitoring, forecasting, DOM) that may be needed to effectively manage its populations as their geographic distribution shifts (Davies and Brillant, 2019; Koubrak *et al.*, 2020). Furthermore, while Canada is a developed nation, development status and access to resources can often be lower for some communities such as those in the Arctic. These communities may therefore require the transfer of capital, technology, and adaptive capacity to effectively manage and adapt their fisheries under climate change.

Recommendations:

- Evaluate current and future spatial shifts in marine species, through, for instance, enhanced ecosystem monitoring, citizen science programs, and forecasting.
- Assess the needs and feasibility of opening new commercial and recreational fisheries.
- Work with social scientists to couple social and economic models to climate models could provide a means of understanding how possible climate scenarios could impact human communities and economies.
- Create licence and sharing policies that are flexible to projected climate change impacts, particularly with regards to distribution and biomass.
- Prioritize Indigenous fishing rights in areas where new species ranges are projected (e.g. species expansion to the North).

8.2 Data and information gathering

8.2.1 Scoping: identifying the data and knowledge gaps

Recent DFO risk assessments cited a lack of knowledge as a primary constraint on the ability of DFO to understand and predict the impacts of climate change on populations and ecosystems (DFO, 2012a), and was also highlighted in a recent CSAS review of the DFO science advisory process in the context of climate change (Pepin *et al.*, 2020). Many of the best practices reviewed in this report also require a foundational understanding of how climate change affects species and ecosystems, and identifying knowledge gaps will be a key step along the route to filling them. Requiring climate trends and impacts on exploited species (e.g. vulnerability assessments), including ecosystem effects, and an inventory of what knowledge gaps, if any, are limiting the incorporation of climate and ecosystem considerations to be explicitly listed in DFO management documents and advice would contribute to this objective. All sources of uncertainty, including specifically those related to the climate and ecosystem effects on biological resources, should also be inventoried. Identifying such uncertainties and knowledge gaps in stock assessments may also help create accountability for filling them. A similar procedure is currently implemented in the US, where the Magnuson-Stevens Act requires the specification of scientific uncertainty associated with stock assessments (Rothschild and Yiao, 2011). Surveying fishers, researchers, managers, and stakeholders could also help to identify the resources, knowledge, and approaches that are required in different fisheries and regions (Gregg *et al.*, 2016; Whitney and Ban, 2019; McClenachan *et al.*, 2020). For example, Whitney and Ban (2019) conducted online surveys and interviews to understand how fisheries managers perceive the climate change risks, adaptation actions, and barriers to adaptation in British Columbia, Canada. Gregg *et al.* (2016) conducted an online survey that assessed the concerns about climate change impacts and evaluated the needs, opportunities, and barriers in planning for climate change in the US. To our knowledge, no such data has been collected across the AOS. However, the annual Sustainability Survey for Fisheries questionnaire is an ideal starting place for such an initiative and could be modified to identify knowledge gaps that may limit the incorporation of climate or ecosystem factors for individual fisheries. Climate vulnerability assessments could also aid in identifying knowledge gaps (read below).

Recommendations:

- Standardized reporting within DFO CSAS and IFMP documents of uncertainties related to stock status and the effects of climate and ecosystem on fisheries, including resources needed to reduce these uncertainties.
- Surveys to identify data and/or knowledge gaps that limit the incorporation of climate or ecosystem factors into the fishery; this could be pursued by amending the Sustainability Survey for Fisheries questionnaire.

8.2.2 Enhanced ecosystem monitoring and data

Critical knowledge gaps as they relate to climate and ecosystem effects on fisheries can be filled through field and laboratory studies and will require detailed ecosystem-level monitoring, computing capacity, and personnel who have the skills and abilities to carry out the research. Currently, it is unlikely that DFO has the capacity to meet all of these needs simultaneously. For example, the DFO Science Monitoring Implementation Team reported that due to limited resources and the vast, remote areas to be monitored, fish habitat, invasive species, food webs, MPAs, and human stressors are not well monitored in Canada (DFO, 2006b). The ecosystem monitoring capacity of DFO has also been reduced in recent decades, and processing of at-sea samples are, in many cases, substantially backlogged. A lack of transparency and data sharing has also been highlighted as a major barrier to research at DFO (see section 8.1.2 on transparency and accountability), including poor organization and inaccessibility of data, and a lack of scientific capacity (Baum and Fuller, 2016). These factors may, in part, explain why climate change and ecosystem dynamics are not yet commonly considered in single-species stock assessments (Figure 7.5) and advice.

Incorporating climate and ecosystem considerations will require enhanced ecosystem monitoring, including regular observations of the environment and species from plankton to fisheries (Link *et al.*, 2015; Busch *et al.*, 2016). In recognition of the practical realities of this, actions could be taken to offset the investments required to meet this recommendation. For instance, partnering with organizations such as academic or non-governmental institutions or other organizations could help increase the observational capacity while offsetting the financial burden to DFO. Working with the US NOAA could be an effective means of increasing the transfer of data, knowledge, and expertise between fisheries managers in Canada and the US, particularly as the US is more advanced in its monitoring and implementation of climate change considerations to fisheries (Busch *et al.*, 2016; Gregg *et al.*, 2016). For instance, such a collaborative framework already exists between DFO and NOAA to monitor and research ocean acidification[29] and could be expanded to additional climate change domains. New monitoring technologies that DFO is already invested in, such as ocean gliders and eDNA (CBC, 2016; Pawlowski *et al.*, 2018; Baillie *et al.*, 2019), could be further developed and evaluated as ecosystem monitoring platforms and their utility to fisheries assessment. Citizen science networks could also be further developed as crowd-sourced monitoring networks, as has been undertaken in Canada's Pacific region and elsewhere (Dunmall *et al.*, 2013; Fairclough *et al.*, 2014; Dunmall and Reist, 2018; Fulton *et al.*, 2019; SAFM, 2020). Such citizen science programs are cost-effective and could provide important opportunistic information about stock dynamics, species range shifts, and the presence of new invasive species and could supplement existing DFO monitoring (read section 8.3.1 on filling the knowledge gaps and see Figure 8.1). Working with existing citizen monitoring data specialists within Canada, such as eOceans[30], could accelerate the incorporation of citizen monitoring into fisheries management. National guidelines could be developed for ecosystem monitoring, including collecting and organizing data, standardizing laboratory protocols and methods, and interpreting results.

Developing a system of monitoring fisheries bycatch could also facilitate a greater understanding of how species and ecosystems are changing over time and space and how climate and exploitation may be driving them. Bycatch monitoring, including which species are captured, their abundance, and mortality, is a key first step towards reducing unwanted bycatch mortality, which is a major ecosystem stressor, to facilitate ecological resilience and fisheries productivity. Bycatch monitoring could also aid in detecting species redistributions that could be driven by

---

[29] https://www.dfo-mpo.gc.ca/science/publications/accasp-psaccma/noaa-collaborative/index-eng.html
[30] https://www.eoceans.co/

climate. Increasing research capacity for bycatch monitoring at DFO could be a relatively cost-effective means of furthering several climate and ecosystem considerations into management.

Furthermore, whereas DFO has produced periodic updates on different components of marine ecosystems, including the physical, geochemical, and planktonic, as well as 'state of the ocean' reports (e.g. Bernier *et al.*, 2018), these have not been regularly updated, which may be hindering their uptake into fisheries. In addition to increasing the frequency of ecosystem-level monitoring, synthesizing and broadly communicating this knowledge in the form of annual publicly available 'state of the ecosystem' reports could enhance the uptake of climate and ecosystem considerations into fisheries management, similar to the ecosystem summary sheets produced by NAFO in its Scientific Council Reports (Northwest Atlantic Fisheries Organization, 2019). Ensuring that the core observational datasets and computer code used in these reports are readily available to fisheries scientists would further increase their ability to incorporate climate and ecosystem considerations (see data availability recommendation, below) and would contribute to the mandated goal of promoting openness and transparency[31].

DFO collects a wide range of data from many different observational data platforms that are incredibly useful to those investigating climate change–related topics. These data sources carry information related to the physical and geochemical environment (e.g. temperature, oxygen, mixing, nutrients) for species ranging from the smallest picophytoplankton to apex predators, which can be used to evaluate important processes across multiple levels of biological organization (genes, species, populations, communities). Such data are vitally important to increasing our understanding of how species respond to climate change. However, as our analysis indicates, most fisheries assessments do not yet consider the full spectrum of data sources that are available, and lower trophic levels and environmental data sources are rarely included (Figure 7.5). Acquiring monitoring data for different components of the ecosystem from within DFO can be an obscure and lengthy process that can take several months, and likely deters many scientists from within DFO or from outside institutions from using them. For example, to make use of DFO monitoring data of the physical and chemical environment, phyto- and zooplankton, fish, invertebrates, and mammals would require one to make inquiries with several different DFO personnel who may store the relevant data on their computer rather than in a repository that is accessible to approved users; the process becomes much more difficult if data from different bioregions is required. Such an approach to data storage and acquisition has likely hindered the use of the valuable climate and ecosystem-relevant information both in fisheries management and climate-relevant research. Collectively, the monitoring data accessible to DFO scientists represents a massive financial investment and time commitment of hundreds of DFO personnel, and its use should, therefore, be maximized. To the extent possible, ecosystem monitoring data within DFO should be organized into regional repositories, updated as new data become available, and the procedures required for both DFO scientists and outside users to acquire the data should be streamlined and simplified. This would include both environmental observations that are in many cases already available, as well as observations of plankton, larvae, fish, invertebrates, and mammals that are, in many cases, less available.

[31] https://pm.gc.ca/en/mandate-letters/2019/12/13/minister-fisheries-oceans-and-canadian-coast-guard-mandate-letter

Furthermore, there is a wealth of valuable monitoring data collected by DFO personnel that have been used at one time but not publicly archived. Examples include tagging data (McKenzie and Tibbo, 1960; Stobo and Fowler, 2009) and a nutrient atlas for the Maritimes (Petrie *et al.*, 1999), both of which are impressive data compilations that could be useful in evaluating climate change impacts on marine resources; but if they are available, they are not readily so. Such data sources could provide important historical contexts that are required to separate climate change effects from natural variability. They could be used to increase the spatial extent and/or time-series length of existing databases and to provide critically important historical baseline conditions against which to gauge climate change effects. For example, Boyce *et al.* (2010) combined historical observations of upper ocean transparency with ship-based observations of chlorophyll concentration to document previously unrecognized global patterns of marine phytoplankton over the 20th century that were linked to climate change. This approach demonstrates the potential benefits of using observations that are available but overlooked; by doing so, the study extended the temporal scale at which global phytoplankton change could be evaluated by over 75 years, revealing previously unrecognized changes related to climate change. Cisneros-Montemayor *et al.* (2017) presented the first compilation of available information relevant to Canada's ocean ecosystems from 1094 individual assessments from various sources. Such approaches could be prioritized and expanded upon. DFO could prioritize and invest in 'data rescue' to locate, digitize, and publicly archive such data so that valuable information will not be lost. Existing knowledge from studies and other sources that is relevant to climate change and fisheries could also be compiled into a repository to facilitate its use and uptake into management.

Fisheries data are also needed. There is currently no available compiled database from which Canadian fisheries information can be obtained. Information for fish stocks must be located from various locations on the DFO website, and in many cases, stock assessments and related data are held by individual assessment authors and can only be accessed through specific requests. In many cases, the assessment information is only accessible by first contacting the central DFO advisory, who then directs one to the assessment author. When stock assessments are available, important data such as estimated biomass, fishing levels, and reference points are either presented in inaccessible formats or not reported at all. This lack of transparency in fishery data makes it difficult to determine if management advice is being followed and is effective.

Although more and better data are not a panacea to good governance, a lack thereof has been consistently identified as a limitation for managers and policy-makers (Cisneros-Montemayor *et al.*, 2017). Further, whereas DFO ship-time and research capacity have been reduced, compiling existing data represents a cost-effective means of generating 'new' data; making such data more readily available to DFO and non-DFO scientists will serve to facilitate primary research into climate change effects on fisheries. This suggestion would be cost-effective relative to increasing ship-time and would be a good return on this investment.

Recommendations

- More frequent and comprehensive (physical, geochemical, and multi-trophic) ecosystem monitoring.

- Annual reports of ecosystem status, trends, and patterns.
- Increased research capacity dedicated to monitoring fishery bycatch.
- A centralized repository of data used to produce annual ecosystem reports, available upon request to approved researchers and fishery scientists.
- Monitoring data collected or maintained by DFO should be available in regional repositories and updated as new data become available.
- The process of using monitoring data maintained by DFO should be streamlined and simplified. The process from requesting data to acquiring it should take days or a week, rather than weeks or months.
- Identifying and digitizing existing data relevant to climate change and fisheries and making these data available should be a priority.
- Compiling relevant knowledge about climate change effects on fisheries from studies and reports into publicly available databases is recommended.
- A publicly available database of Canadian fisheries data, including relevant time-series (e.g. SSB, f, recruitment), reference points, and assessment model information. A structure similar to that of the RAM assessment database (Ricard *et al.*, 2012) is suggested.

8.3 Quantitative tools, knowledge, & advice

8.3.1 Climate change research: filling the knowledge gaps

Incorporating climate considerations into fisheries management in Canada will require increased knowledge of climate change and its effects on marine resources (DFO, 2012a). Identifying information gaps, enhanced ecosystem monitoring, and data availability (read above) will facilitate the production of new knowledge. Targeted funding towards building the infrastructure (e.g. laboratory space, ecosystem monitoring, computing capacity) and capacity (e.g. personnel, skills, knowledge) required to undertake climate change research should be a central part of any climate change strategy for Canadian fisheries. Strong partnerships with non-governmental (e.g. Oceans North[32], Ecology Action Center[33], World Wildlife Fund for Nature [34], Oceana[35]), industry (e.g. eOceans[36], LEO Network[37]), and international institutions and funding agencies could and should be leveraged to more cost-effectively fill some of these needs. For example, in the Maritimes region, organizations such as Dalhousie University, the Ocean Frontier Institute, the

---

[32] https://oceansnorth.org/en/
[33] https://ecologyaction.ca/
[34] https://wwf.ca/
[35] https://oceana.org/
[36] https://www.eoceans.co/
[37] https://www.leonetwork.org/en/#lat=61.21806&lng=-149.90028&zoom=7

COVE[38], Volta[39], DeepSense[40], the Ocean Tracking Network[41], and the Nova Scotia Community College would be useful partnerships to enhance process-based research capacity. Working with the US NOAA, as DFO currently does on ocean acidification[42], would help to increase the transfer of data, knowledge, and expertise between fisheries managers in Canada and the US, particularly as the US has been more rapid and advanced in its monitoring and implementation of climate change considerations to fisheries (Link *et al.*, 2015; Busch *et al.*, 2016). A joint DFO-NOAA climate change collaboration agreement is rumoured to be in development; at the time of this report, it was not yet implemented.

Identifying and filling such knowledge gaps would also be greatly facilitated through the development of a national framework for assessing the vulnerability of aquatic species. A framework that is open access, comprehensive, data driven, and easy to implement, understand, and communicate could be transformational for the management of marine resources in Canada. Climate vulnerability assessments would enable fisheries to be triaged so that those that are most vulnerable and socio-economically important could be identified as priorities for the implementation of climate-responsive management. The vulnerability of species to climate change could be included as a standard component of fisheries assessments, allowing scientists to quickly determine how sensitive and exposed the stock is to current and future climate change and if the existing assessment approach should be modified. Vulnerability may also be useful in understanding when to use specific climate adaptation tools, and for which species they may be most effective. Assessing the vulnerability of fisheries to climate change should also be iterative, with an update frequency tied to the IPCC assessment reports (~5 years). This aspect should provide further motivation for the development of a vulnerability assessment approach that is open source, widely available, and easily implemented for a range of species. Building on previous DFO-led vulnerability studies by Stortini *et al.* (2015) and Greenan *et al.* (2019) conducted in the AOS, a framework that is open source, standardized, and with input data sources readily available would enable vulnerability assessments to be repeated with the ease and at the frequencies required by management, thus increasing their application to fisheries.

As this report has emphasized, climate and ecosystem modelling are becoming increasingly commonplace in fisheries management settings. Long-term projections are used in climate vulnerability assessments and within some MSE models, while nowcasts and seasonal forecasts are used to adjust quota allocations, reduce bycatch, and increase the efficiency of fishing activity (Hobday *et al.*, 2016; Ogier *et al.*, 2016). Within the AOS, physical climate models (e.g. Wang *et al.*, 2018) and regional ecosystem models exist (e.g. Bundy *et al.*, 2000; Wang *et al.*, 2018), but projections from the models are not yet available at the space–time scales required for fisheries management. While longer-term projections are useful for developing strategies and identifying priorities, they do not address the shorter space–time scales required for fisheries management. Facilitating climate and ecosystem model development that can make reliable nowcasts and projections at the higher spatial and temporal scales required by fisheries should be a priority for

---

[38] https://coveocean.com/
[39] https://voltaeffect.com/
[40] https://deepsense.ca/
[41] https://oceantrackingnetwork.org/
[42] https://www.dfo-mpo.gc.ca/science/publications/accasp-psaccma/noaa-collaborative/index-eng.html

DFO. While these projections could be used in multiple climate-relevant settings, such as in MSE and vulnerability frameworks, they could also be included as a standard component of fishery assessments to explore climate trends and impacts on fishery resources. The development of climate and ecosystem models would require a high initial investment of funding and personnel, but once they are developed, the models could be applied in a range of marine management settings and to a range of commercial fishery species, as POAMA has demonstrated[43]. The feasibility of coupling such climate projections to bioeconomic models that consider human behaviour and economic constraints (e.g. Willis and Bailey, 2020) to evaluate the impacts of different actions on socio-economic considerations should also be explored.

The need for increased data and knowledge will be particularly acute in the Canadian Arctic, where climate change is rapid and ecosystem monitoring is limited by weather, infrastructure, and accessibility. In such situations, community- and citizen-based monitoring and integrating TEK into management should be considered as approaches to filling knowledge deficiencies. Citizen monitoring and TEK would enable ecological changes to be monitored more rapidly and cost-effectively than scientific surveys across vast and remote geographic areas (Gofman, 2010) while facilitating co-management between Indigenous communities and DFO. Whereas citizen science programs are less common in the Arctic (Dunmall and Reist, 2018), they may be a beneficial approach of increasing the pace and scope of ecological monitoring of climate change effects while also incorporating Indigenous knowledge into marine management. While incorporating citizen monitoring and TEK into fisheries management can be daunting, such programs are already being implemented across Canada for several taxa including, for instance, salmon (Dunmall and Reist, 2018), sea turtles[44], and whales[45], and there is expertise within DFO to expand these efforts to incorporate additional species. Using the successful "Arctic Salmon" citizen science project as a template (Dunmall *et al.*, 2013), Dunmall & Reist (2018) proposed a generalized framework for co-management that seeks to bridge Indigenous and scientific knowledge systems (Figure 8.1). The framework seeks to standardize the flow of information between Indigenous and scientific systems through communication, ongoing evaluation, and adaptation. Such a framework could provide a springboard for further incorporating citizen monitoring and TEK in Canadian fisheries management, particularly in locations where knowledge is currently low and monitoring difficult, such as the Arctic.

---

[43] http://poama.bom.gov.au/
[44] https://seaturtle.ca/
[45] https://whalemap.ocean.dal.ca

Recommendations:

- Develop a national framework for assessing the climate change vulnerability of marine species. The ideal framework would be data driven, comprehensive, standardized, reproducible, and open source, thus enabling the frequent and transparent evaluation of vulnerability.
- The restoration of DFO research capacity through increased funding to and prioritization of process-based climate research.
- Enhance knowledge through targeted competitive funding opportunities (e.g. ACCASP, SPERA) that require dedicated communication of research results to managers and assessment committees.
- Encourage relevant climate change and ecosystem studies that are funded through DFO to be communicated to relevant fisheries scientists, managers, and stakeholders (e.g. CSAS meetings).
- Strengthen partnerships and coordination with non-DFO academic institutions and with NOAA, such as the existing collaborative framework to monitor and research ocean acidification46.
- National workshops to communicate and share developments and approaches to climate change integration into fisheries.
- Regional or national training workshops to train personnel in emerging approaches to incorporating climate change considerations into fisheries management (e.g. MSE, estimation of time-varying biological parameters).
- Climate vulnerability assessments to be a standard component of fishery stock assessments and to be included in CSAS documents and IFMPs.
- Prioritize the continued development ecosystem and climate models that can make accurate projections and forecasts at the spatial and temporal resolutions required by ocean management. Enhance and further modelling skills and approaches within DFO through dedicated training and workshops.
- Further develop the computing infrastructure that is required to develop and implement the ecosystem and climate models, and to make projections available to users.
- Facilitate citizen monitoring and traditional and community ecological knowledge systems and fisheries co-management, particularly in knowledge-deficient or inaccessible regions, such as the Arctic. The framework proposed by Dunmall & Reist (2018) could serve as a starting point.

[46] https://www.dfo-mpo.gc.ca/science/publications/accasp-psaccma/noaa-collaborative/index-eng.html

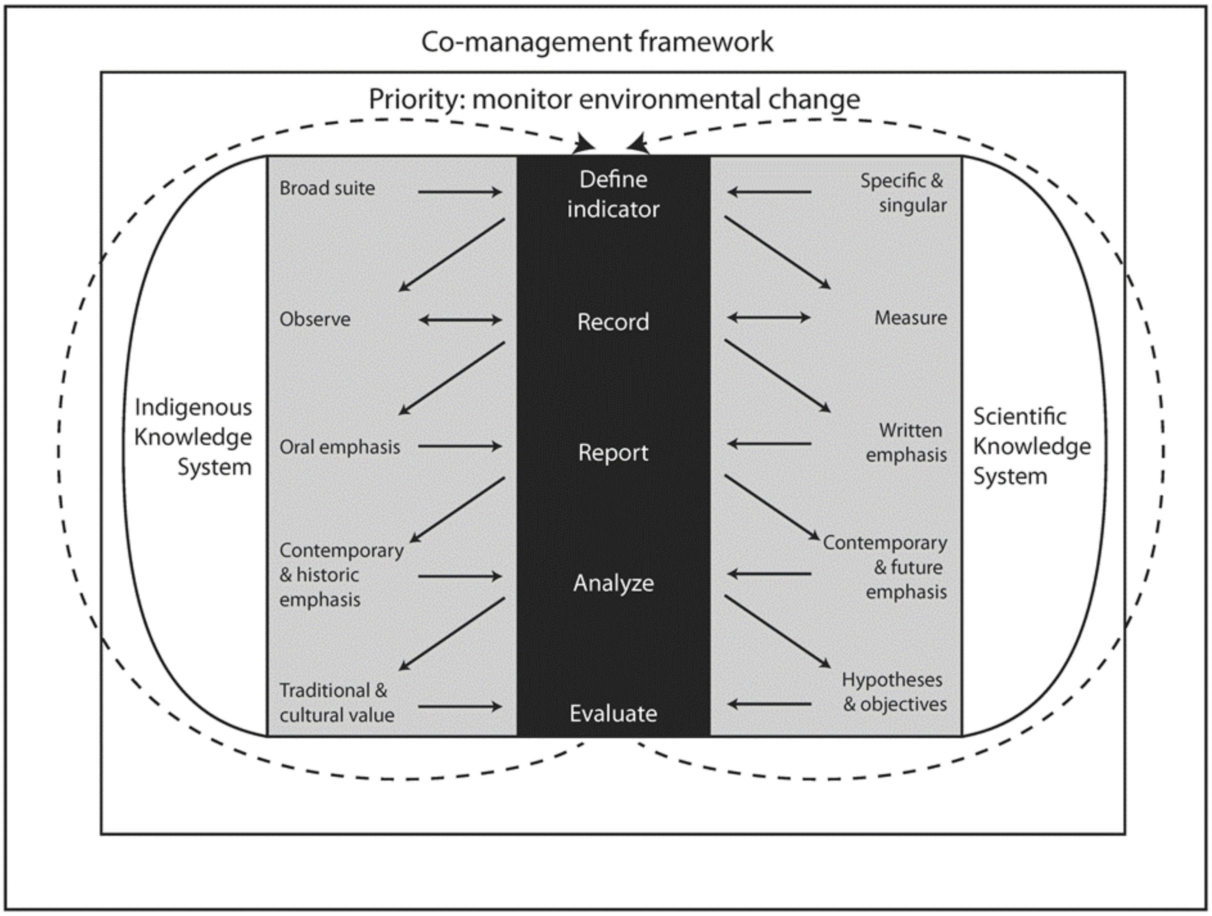

Figure 8.1 A conceptual model for citizen science.
Under an overarching objective of monitoring environmental change, citizen science (grey square) can bridge Indigenous and scientific knowledge systems (white semi-circles) to increase the pace and scale at which environmental change is monitored. The arrows depict the flow of information from the generalized citizen science framework (black box) out to each knowledge system and back at each step in the process, which standardizes the value of information derived from both systems and contributes to knowledge co-production. Source: Dunmall *et al.* (2018)

8.4 Decision-making

8.4.1 Climate and ecosystem-considered assessments, advice, and harvest rules

Ensuring sustainable fisheries management that is robust to climate change can be facilitated by incorporating the data and knowledge discussed previously into fisheries assessment models that inform decision-makers. Optimally, such modelling approaches would include the effects of climate and ecosystem effects across different life stages, evaluate these effects dynamically, and quantify risk and uncertainty. There is no single ‘best’ approach to achieving this. MSEs are an appealing approach, as they can flexibly incorporate a wide spectrum of data, knowledge, and modelling approaches within a framework that explicitly evaluates risk. MSE has been applied using simple operating models in fisheries that are data and knowledge limited and using more complex multispecies climate models that are spatially explicit and account for dynamically changing productivity and/or mortality. Implementing multi-model inference is conceptually similar to MSE but less computationally and labour intensive and would help to evaluate uncertainty and risk in fishery assessments. Alternative modelling approaches that can better address causation incorporate complex ecological interactions should also be incorporated where feasible.

For many fisheries, significant time and resources may be required to implement ecosystem monitoring, generate climate and ecosystem-relevant knowledge, and implement this knowledge into stock assessment models such as MSE. Alternatively, dynamic models could be broadly used to evaluate non-stationary fisheries dynamics, potentially capturing the effects of climate and other factors as they are manifest. Dynamic assessment models are not a panacea but represent a straightforward and cost-effective approach that could be applied rapidly across most of Canada's fisheries. Then, monitoring data and knowledge could be incorporated as they become available. Accordingly, the use of dynamic stock assessment models that can account for non-stationary ecological characteristics should be a priority for Canadian fisheries.

Regardless of the statistical approach, any integration of climate and ecosystem considerations into science, advice, and harvest rules will need sufficient data and knowledge and will require personnel with the technical skills to incorporate them into fishery assessments. Targeted hiring and ongoing training can help to ensure that such skills are present within DFO. For instance, recent efforts to implement MSE for the Division 4VWX herring fishery required DFO to employ an external consulting agency with the required skills to appropriately implement MSE.

Recommendations:

- Increase capacity within DFO to implement population assessments and harvest recommendations that can incorporate climate and ecosystem impacts across multiple life stages, while evaluating uncertainty and risk.
- Models that evaluate time-varying biological parameters (e.g. production, mortality) should become standard practice for all assessments.
- Regardless of approach, fisheries assessments and advice should be risk and uncertainty based.
- MSE is appealing as a general framework; the capacity to implement it should be a priority for DFO.

9. Conclusions and next steps

This report describes widespread climate-driven changes that are already occurring across the AOS (e.g. Figure 4.1) and will continue over the next century (Figure 5.2), with impacts on fisheries and the well-being of many Canadians. The report also demonstrates that climate change and ecosystem considerations are currently not yet extensively incorporated into the science and management of Canada's fisheries across the AOS. Together, these results suggest unless rectified, Canada's fisheries management approach may not be robust to the climate changes that are projected over the coming decades.

As this report also emphasizes, incorporating climate and ecosystem considerations into fisheries management is a complex problem with several possible solutions, many of which are interrelated and work in concert. Where to begin? The challenge of incorporating these numerous recommendations into the management of the over 200 fish stocks maintained by DFO is daunting, to say the least. The challenge can be overwhelming, leading to a 'paralysis of inaction' that can delay progress. By developing a national framework that outlines the recommended approaches to incorporating climate and ecosystem information, including when and how to implement them, the process can begin. Given the many recommendations listed here, the vastness of the Canadian EEZ, and the finite DFO resources, a framework that triages the implementation of targeted recommendations for fisheries that are most vulnerable to climate impacts could also be a way forward. While many recommendations (e.g. increasing transparency and accountability, reducing non-climate risks, estimating time-varying biological parameters) could and should be applied simultaneously to all >200 fisheries, many others may not need to be, for example, in situations where they are already implemented. Furthermore, due to their differential vulnerability to climate impacts, some fisheries will more urgently require climate adaptation than others. Accordingly, a generalized framework is presented that could be used to identify fisheries that are in most urgent need of resources and which recommendations could advance the incorporation of climate and ecosystem factors into their management. This framework does not imply that the recommendations need only apply to certain species, but rather that it may not be realistic, given the practical constraints under which DFO operates, to apply all recommendations to all species simultaneously. The framework also acknowledges that some of these recommendations are already being incorporated into the management of some species (e.g. ecosystem monitoring, knowledge generation), but that the extent of the incorporation differs between stocks and regions. Thus, the framework fills two important needs: prioritizing stocks and regions that are most in need of climate adaptation resources, and identifying what resources and tools would most effectively move them towards greater climate and/or ecosystem integration based on how they are currently managed.

The framework operates on the basis that fully incorporating climate and ecosystem considerations into fisheries science and management is, to a large extent, a stepwise progression that requires as a starting point adequate data and information gathering. Foundational data and information (step 1) are critical to developing the quantitative tools, knowledge, and advice (step 2) that ultimately support and enable climate-considered fisheries management decisions that incorporate risk and uncertainty (step 3). Therefore, understanding where stocks fall on this stepwise continuum could help identify which specific resources are needed to move them towards management decisions that are climate considered. In parallel with this stepwise progression, a range of recommendations that are independent of the availability of data and information or quantitative tools and knowledge (e.g. flexible and adaptive regulatory frameworks, transparency and accountability, reducing non-climate stressors) could be broadly implemented.

The framework presented (Figure 9.1) distinguishes recommendations that can be broadly applied to all fisheries ('broad-scale' recommendations; red in Figure 9.1) from those that may instead apply to specific stocks and/or regions ('stock-specific' recommendations; black in Figure 9.1). The framework identifies stock-specific recommendations by identifying where individual stocks fall on this continuum, thus identifying which resources could be most effective in furthering climate adaptation into management. The main steps in the generalized framework are depicted in Figure 9.1 as follows:

1. As part of an initial scoping process, the availability of data and knowledge that are needed to understand climate and/or ecosystem effects can be identified for each stock, species, and/or region. Scoping could be undertaken through targeted surveys of stakeholders for individual stocks, as has been undertaken elsewhere (Gregg *et al.*, 2016; Whitney and Ban, 2019; McClenachan *et al.*, 2020), by modifying the existing DFO Sustainability Survey for Fisheries, or via ad hoc approaches. The scoping process could categorize the climate and ecosystem data availability: the highest availability would occur where multi-trophic and environmental time-series were available with high synoptic spatial coverage, with high spatio-temporal resolution, and from a range of monitoring sources. Likewise, the highest knowledge of climate and ecosystem impacts would occur for stocks that possess peer-reviewed studies, including cause and effect experiments, rigorous population assessments, climate or ecosystem projections, and TEK.
2. By evaluating stocks, species, or regions by their vulnerability to climate change and conservation status, they can be triaged such that those that are vulnerable and have low conservation status are ranked at higher priority for the allocation of resources. Population status is already reported as part of the DFO Sustainability Survey for Fisheries, which assigns each stock into one of four categories (critical, cautious, healthy, or uncertain) by placing the estimated stock biomass level within the precautionary approach framework (DFO, 2009b). Climate vulnerability could be assessed through the development of a standardized vulnerability assessment framework, as recommended (Quantitative tools, knowledge, & advice).
3. Through the scoping process (step 1), individual stocks, species, or regions can be placed on the continuum discussed previously, and specific recommendations to further climate adaptation into their management can be identified. This process identifies broad resource needs, while more specific actions to achieve them are listed in Chapter 9 and could be tailored to stock or region-specific constraints.
4. By combining steps 1, 2, and 3, individual stocks can be triaged (ranked) as priorities for resource allocations. Then, both stock-specific (black text in Figure 9.1) and broad-scale (red text in Figure 9.1) recommendations can be identified along with global recommendations that could facilitate climate and ecosystem-considered management decisions.

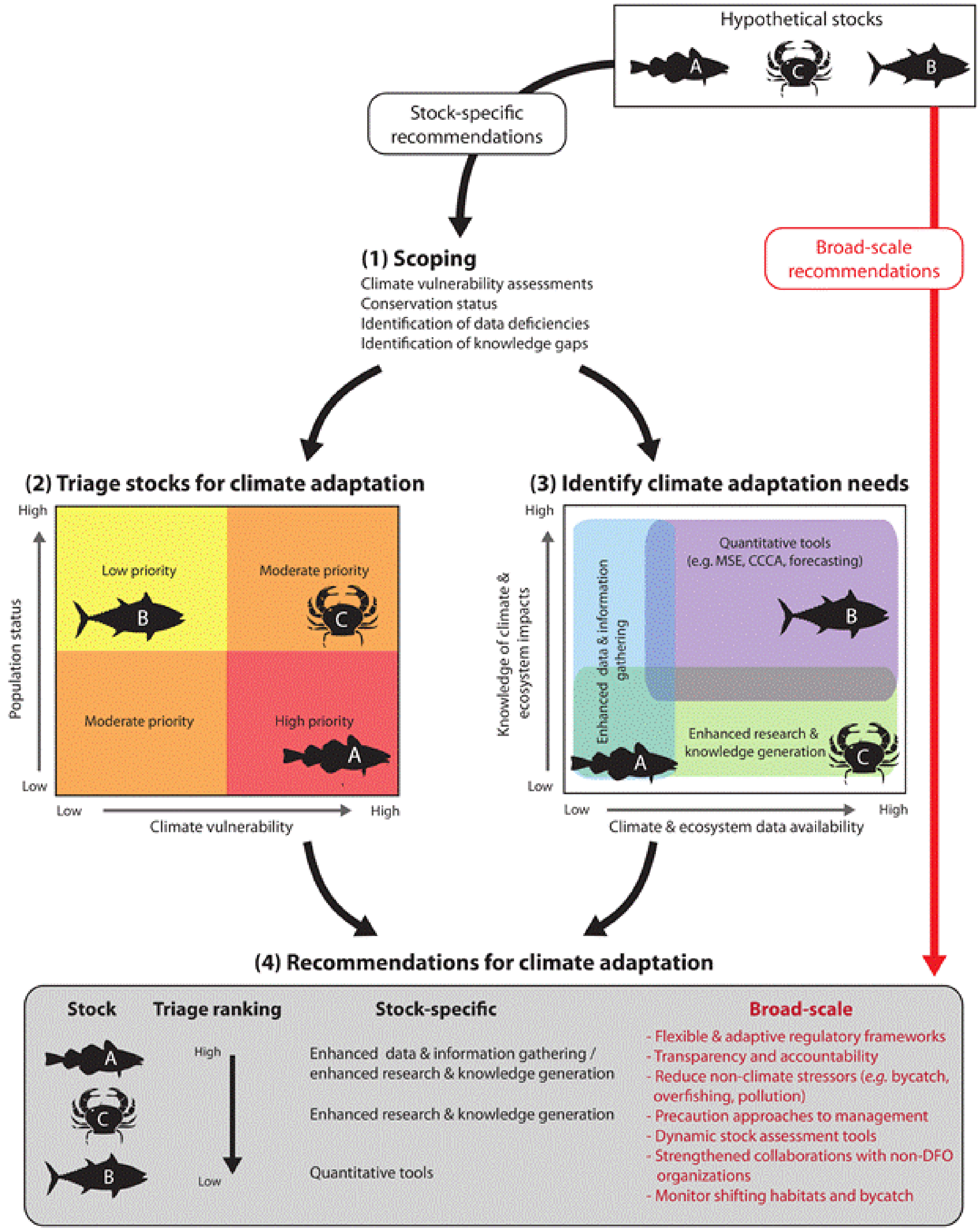

Figure 9.1 A conceptual model for implementing recommendations for individual stocks. Scoping assesses the data and knowledge available for stocks, and vulnerability assessments estimate their risk of adverse effects of climate change (step 1). Stocks are ranked by their climate vulnerability and conservation status (step 2). Based on the availability of climate and ecosystem data and knowledge, resources to facilitate climate adaptation for the stock can be identified (step 3). When this information is combined, a set of recommendations for actions to move individual stocks towards climate change integration can be made: stocks are ranked according to the urgency of climate adaptation resources and the broad-scale (red) and stock-specific (black) resources are identified. A, B, and C represent hypothetical fishery stocks.

The hypothetical examples in Figure 9.1 (stocks A, B, C) demonstrate how this framework could be applied. The high vulnerability to climate change and low conservation status of stock A make it an urgent priority for the implementation of recommendations. The low availability of data and knowledge related to climate and ecosystem factors for stock A leads to a specific recommendation to enhance data and information gathering and knowledge generation (black text in Figure 9.1) in addition to the global recommendations (red text in Figure 9.1). Alternatively, the low climate vulnerability and high conservation status of species B make it a lower priority for the implementation of recommendations. Species B also has a high availability of climate and ecosystem data and knowledge, meaning that resource allocation should instead focus on developing quantitative tools that can incorporate climate and ecosystem data and knowledge (black text in Figure 9.1), in addition to the adoption of global recommendations (red text in Figure 9.1).

While conceptually simple, this framework, or one like it, could be used to efficiently move from a long and daunting set of needs and recommendations to a more targeted and feasible implementation of them, in a timely and cost-effective manner. Perhaps more important, the framework incorporates risk—those stocks, species, or regions that are less at risk of climate change (less vulnerable) are ranked lower for the adoption of context-specific recommendations.

Importantly, in concert with this system of triaging individual stocks (Figure 9.1), the many global recommendations that do not rely on data or knowledge could be immediately taken. Such actions include, for instance, immediately employing dynamic stock assessment models to estimate biological parameters (e.g. productivity, mortality); increasing transparency and accountability; enhancing the availability of data within DFO; reducing stressors such as bycatch, pollution, and habitat destruction; adopting precautionary approaches; strengthening collaborations with NOAA and other non-DFO institutions; and exploring new management structures and observational platforms (e.g. citizen science). Many of these are general actions that would make the system of management more amenable to integrating climate and ecosystem considerations.

10. Appendices

10.1 Appendix A: Data sources

Table 10.1 Data sources used in this report.

Variable	Variable	Years	Resolution	Agency	Website
Fisheries	Commercial landings	1970–2020	NAFO divisions	NAFO	www.nafo.int/Data/Catch-Statistics
	Fisheries sustainability survey	2018	-	DFO	www.dfo-mpo.gc.ca/reports-rapports/regs/sff-cpd/survey-sondage/index-en.html
	RAM stock assessment database	1950–2018	-	-	www.ramlegacy.org/
	Marine animal biomass	2006–2100	1°	Fish-MIP	www.isimip.org/about/marine-ecosystems-fisheries/
Plankton	Zooplankton carbon biomass	2006–2100	1°	CMIP5	www.esgf-node.llnl.gov/search/cmip5/
	Primary production	2003–2012	4 km^2	MODIS	www.sites.science.oregonstate.edu/ocean.productivity/
	Primary production	2006–2100	1°	CMIP5	www.esgf-node.llnl.gov/search/cmip5/
	Chlorophyll	1998–2008	4 km^2	SeaWiFS	www.oceancolor.gsfc.nasa.gov/
Environmental	SST	2000–2010	4 km^2	Pathfinder	www.nodc.noaa.gov/SatelliteData/pathfinder4km/
	SST	1900–2019	1°	Met Office	www.metoffice.gov.uk/hadobs/hadisst/index.html
	SST	2006–2100	1°	CMIP5	www.esgf-node.llnl.gov/search/cmip5/
	Nitrate	-	1°	WOA	www.nodc.noaa.gov/OC5/woa18/
	Bathymetry	-	1 minute	NOAA	www.ngdc.noaa.gov/mgg/global/
	Cumulative impacts	1985–2009	1°	-	www.science.sciencemag.org/content/319/5865/948
Documents	RES-DOCs	2000–2020	-	DFO	www.isdm-gdsi.gc.ca/csas-sccs/applications/Publications/search-recherche-eng.asp

IFMPs	2000–2020	-	DFO	www.dfo-mpo.gc.ca/
PR-DOCs	2000–2020	-	DFO	www.clarivate.com/webofsciencegroup/solutions/web-of-science/

Table 10.2 Global climate and marine ecosystem models used in this report.

Variable	ESM	MEM	Years	Resolution	Agency
Animal biomass	IPSL-CM5A-LR	APECOSM	2006–2100	1°	Fish-MIP
	IPSL-CM5A-LR	BOATS	2006–2100	1°	Fish-MIP
	IPSL-CM5A-LR	DBEM	2006–2100	1°	Fish-MIP
	IPSL-CM5A-LR	DBPM	2006–2100	1°	Fish-MIP
	IPSL-CM5A-LR	ECOOCEAN	2006–2100	1°	Fish-MIP
	IPSL-CM5A-LR	MACROECOLOGICAL	2006–2100	1°	Fish-MIP
	GFDL-ESM2M	BOATS	2006–2100	1°	Fish-MIP
	GFDL-ESM2M	DBEM	2006–2100	1°	Fish-MIP
	GFDL-ESM2M	ECOOCEAN	2006–2100	1°	Fish-MIP
	GFDL-ESM2M	MACROECOLOGICAL	2006–2100	1°	Fish-MIP
Primary production	IPSL-CM5A-LR	-	2006–2100	1°	CMIP5
	IPSL-CM5A-MR	-	2006–2100	1°	CMIP5
	CNRM-CM5	-	2006–2100	1°	CMIP5
	GFDL-ESM2G	-	2006–2100	1°	CMIP5
	IPSL-CM5B-LR	-	2006–2100	1°	CMIP5
Zooplankton biomass	HADGEM2-ES	-	2006–2100	1°	CMIP5
	MPI-ESM-LR	-	2006–2100	1°	CMIP5
	MPI-ESM-MR	-	2006–2100	1°	CMIP5
	IPSL-CM5A-LR	-	2006–2100	1°	CMIP5
	IPSL-CM5A-MR	-	2006–2100	1°	CMIP5

	GFDL-ESM2G	-	2006–2100	1°	CMIP5
	GISS-E2-H-CC	-	2006–2100	1°	CMIP5
	GISS-E2-R-CC	-	2006–2100	1°	CMIP5
	HADGEM2-CC	-	2006–2100	1°	CMIP5
	IPSL-CM5B-LR	-	2006–2100	1°	CMIP5
	MRI-ESM1	-	2006–2100	1°	CMIP5
Surface temperature	HADGEM2-ES	-	2006–2100	1°	CMIP5
	CNRM-CM5	-	2006–2100	1°	CMIP5
	IPSL-CM5A-LR	-	2006–2100	1°	CMIP5
	IPSL-CM5A-MR	-	2006–2100	1°	CMIP5
	CANESM2	-	2006–2100	1°	CMIP5
	FGOALS-S2	-	2006–2100	1°	CMIP5
	GISS-E2-H	-	2006–2100	1°	CMIP5
	GISS-E2-R	-	2006–2100	1°	CMIP5
	GFDL-CM3	-	2006–2100	1°	CMIP5
	GFDL-ESM2G	-	2006–2100	1°	CMIP5
	CMCC-CESM	-	2006–2100	1°	CMIP5
	CMCC-CM	-	2006–2100	1°	CMIP5
	CMCC-CMS	-	2006–2100	1°	CMIP5
	GISS-E2-H-CC	-	2006–2100	1°	CMIP5
	GISS-E2-R-CC	-	2006–2100	1°	CMIP5
	HADGEM2-CC	-	2006–2100	1°	CMIP5
	IPSL-CM5B-LR	-	2006–2100	1°	CMIP5

10.2 Appendix B: Management themes

10.2.1 Document acquisition

CSAS documents within the area of interest were searched from the DFO CSAS website[47]. Query results were formatted as a spreadsheet containing the document series and publication numbers, year of publication, authors, titles, regions, species and functional group of the species in question, and weblinks to access the documents. Documents were downloaded as PDFs and converted to accessible text files.

The Web of Science was searched to systematically find peer-reviewed publications that were conducted within the AOS on commercial species of interest and authored by DFO researchers between 2000 and 2019. The search strings used to retrieve relevant documents are included in Table 10.3. From the results, 108 studies that related to the status of commercially exploited species were downloaded.

10.2.2 Analysis of text

Using the quanteda package (Benoit *et al.*, 2018) in the R statistical computing platform, the text of documents was imported into R. All English and French stop-words were removed, as were abbreviations, numbers, symbols, weblinks, punctuation, and all text within the references section of the documents. All text was converted to lower case and tokenized. From the resulting text tokens, n-grams of lengths ranging from one to four were created; n-grams are word combinations such as 'climate change.' Next, several themes were defined using key words and word combinations (Table 10.4). The primary themes examined included climate change, climate variability, oceanography, trophic dynamics, Indigenous knowledge, precautionary approach, and ecosystem approach to fisheries, while secondary themes included climate vulnerability, forecasting, and dynamic processes. Themes around the use of key data sources within the documents, including remote sensing, the Atlantic Zone Monitoring Program, the Atlantic Off-Shelf Monitoring Program, research vessel surveys, the Continuous Plankton Recorder, conductivity-temperature-depth profiles, the BioChem database, glider data, and Argo floats, were also explored.

10.2.3 Frequencies of theme occurrence within RES-DOCs

The RES-DOCs in this study were comprised of Research Documents, Science Advisory Reports, Science Responses, and Stock Status Reports, which all relate to the status of fishery resources but have slightly different objectives and are in some cases available in different years[48]. The majority (311 or 43%) of the RES-DOCs were comprised of Research Documents (RDs) that represent the scientific basis for evaluating fisheries resources. RDs contain detailed descriptions of stock status and the data and methods used to evaluate it and thus tend to be lengthy (average word count=14,067). Science Advisory Reports (SARs) comprised 40% (n=288) of the

---

[47] http://www.isdm-gdsi.gc.ca/csas-sccs/applications/Publications/search-recherche-eng.asp
[48] http://www.isdm-gdsi.gc.ca/csas-sccs/applications/Publications/index-eng.asp

RES-DOCs; they were created in 2005 and encompass "management strategies, frameworks and guidelines on the assessment or evaluation on specific issues, impacts of human activities on ecosystem components as well as recovery assessments on a species or population." With an average word count of 10,795, SARs are less lengthy than the RDs. Science Responses (SRs) accounted for 13% (n=97) of the RES-DOCs; they were created in 2006 and document the responses provided by DFO Science for issues handled by the Science Response (SRs). SRs are much briefer than the other types of RES-DOCs (average word count=5,702). Stock Status Reports (SSRs) made up 5% (n=33) of the RES-DOCs; they were available 1993-2004 and document the status of fish, invertebrates and marine mammal stocks as well as some ecosystem and environmental issues. SSRs are of moderate length (average word count=10,089).

There was some degree of variability in theme occurrence frequency among the RES-DOC types (Figure S2). In general, the Research Documents cited most of the major themes (precautionary approach, climate change, and the ecosystem approach to fisheries) with less frequency than the other RES-DOC types, which is somewhat surprising given their greater length and more technical makeup. Research documents and Stock Status Reports cited most themes in similar frequency, despite the latter being available for only the first four years of the period of interest (2000-2004). In general, the Science Advisory Reports cited the themes most frequently, with a few exceptions.

10.2.4 Robustness of our textual analysis methods

It was essential to ensure that our textual analyses were valid: that they were reliably and accurately detecting variability in management theme occurrences across documents, species, and regions, and over time. As a primary check on this, we read a subset of the documents to verify that our textual analysis methods were valid and were reliably detecting the search terms. As an additional robustness check, we evaluated a compilation of 89 stock assessments conducted over the same timeframe by the US National Marine Fishery Service (NOAA). These assessments represented those that were publicly available to us. Because NOAA is widely believed to be a global leader at incorporating climate change and ecosystem considerations into their fisheries management, we would expect, *a priori*, that our analysis would detect differences in the frequency of these themes in NOAA relative to DFO documents. Climate change and ecosystem factors should be mentioned with some frequency in NOAA documents, and likely more so than in the DFO documents. Alternatively, while the precautionary approach has been widely promoted within DFO, there has been less focus on it in NOAA. Hence we may expect an increased reference to the precautionary approach within DFO relative to NOAA documents. Our results confirmed this view (Figure S3): climate change was discussed twice as frequently (24%), and EAF 20x more frequently (21%) in NOAA relative to DFO documents. Alternatively, the precautionary approach theme occurred in only 6% of NOAA, compared with 38% of DFO documents. In general, themes related to climate variability and change, including oceanographic, forecasting, climate change, climate variability, and climate vulnerability, were referenced much more frequently in NOAA relative to DFO documents. Trophic themes, including EAF and trophic dynamics, were also mentioned more often in NOAA documents. This analysis is not exhaustive, as we did not include all NOAA fishery documents. Yet, it suggests that our textual analyses detect real differences in the incorporation of management themes into fishery management documents and provide increased confidence in our approach.

Table 10.3 Search terms used to identify peer-reviewed articles authored by DFO scientists.

Search category	Search criteria
Year range	2000 to 2019
Funding agency	'DFO' or 'Canadian Department of Fisheries and Oceans' or 'Fisheries and Oceans Canada' or 'Department of Fisheries and Oceans Canada' or 'Fisheries & Oceans'
Topic	('fisheries' or 'fish' or 'invertebrate' or 'cod' or 'herring' or 'lobster' or 'shrimp' or 'groundfish' or 'halibut' or 'crab' or 'mackerel' or 'plaice' or 'redfish' or 'redfishes' or 'pollock' or 'haddock' or 'hake' or 'capelin' or 'flounder' or 'scallop') and ('Marine' or 'Ocean') and ('Atlantic' or 'New Brunswick' or 'Nova Scotia' or 'Quebec' or 'Newfoundland' or 'Labrador' or 'Arctic' or 'Bay of Fundy' or 'Scotian Shelf' or 'Grand Banks' or 'Gulf of St. Lawrence' or 'Prince Edward Island')

Table 10.4 Words and n-grams used to identify themes in the fishery management documents.

Theme	Words or n-grams
Climate change	climate_change, climate_changing, changing_climate, global_warming, ocean_warming, long_term_warming, trend_climate, climate_trend, long_term_cooling, long_term_acidification, long_term_trend_acidification, increasing_acidification, declining_acidification, acidification_trend, changing_acidification, long_term_hypoxia, long_term_trend_hypoxia, increasing_hypoxia, declining_hypoxia, hypoxia_trend, changing_hypoxia, changing_acidity, increasing_acidity, declining_acidity, trend_acidity, increasing_anoxia, declining_anoxia, long_term_deoxygenation, deoxygenation_trend, long_term_oxygen, oxygen_trend, changing_oxygen, increasing_oxygen, declining_oxygen, deoxygenation_trend, long_term_sea_ice, trend_sea_ice, sea_ice_trend, declining_sea_ice, increasing_sea_ice, changing_sea_ice
Oceanographic	currents, temperature, salinity, sst, sea_ice_extent, sea_ice_thickness, sea_ice, oxygen, vertical_mixing, stratification, sea_surface_temperature, bottom_temperature, hypoxia, anoxic, anoxia, ph, wind, advection, ekman
Climate variability	nao, enso, pdo, amo, ao, north_atlantic_oscillation, arctic_oscillation, atlantic_multidecadal_oscillation, southern_oscillation, climate_variability
Trophic dynamics	predator, prey, trophic, plankton, phytoplankton, zooplankton, copepod, predation, diatom, plankton
Precautionary approach	precautionary_approach, precautionary_principle
Ecosystem approach to fisheries	ecosystem_based_management, ebm, ecosystem_based_fisheries_management, ecosystembased_management, ecosystem-based_management, ecosystem-based_fisheries_management, ecosystembased_fisheries_management, EAF, ecosystem approach to fisheries, eaf
Exploitation	exploitation, fishing, landings, harvest, hunting
Indigenous knowledge	indigenous, traditional_knowledge, first_nations, inuit
Forecasting	projected_warming, projected_cooling, projected_biomass, projected_spawning, projected_ssb, forecasted, climate_forecast, biomass_projection, climate_model, climate_projection, roms_model, bnam_model, cmip, cmip5, rcp, forecasted_warming, forecasted_cooling, forecasted_biomass, forecasted_spawning, forecasted_ssb
Climate vulnerability	climate_change_vulnerability, climate_vulnerability, climate_exposure, climate_sensitivity, climate_adaptive_capacity, time_of_emergence, thermal_habitat, thermal_safety, thermal_limit, vulnerable_climate
Ocean warming	ocean_warming, warming_trend, increasing_temperature, long_term_warming, climate_change, cooling, cooling_trend, declining_temperature, longterm_cooling, increasing_sst, sst_increase, declining_sst, sst_decline, increasing_bottom_temperature, declining_bottom_temperature
Acidification	acidification, acidifying, acidity, ph
Deoxygenation	deoxygenation, de_oxygenation, hypoxia, oxygenation, oxygen, hypoxic
Sea ice	sea_ice_extent, sea_ice_thickness, melting_sea_ice, melting_ice, sea_ice
Distribution	range_shift, shifting_range, range_expansion, shifting_north, shifting_northward, expanding_range, shifting_distribution, expanding_distribution, changing_distribution, spatial_distribution, spatial_range, migration
Metabolism	metabolic, growth_rate
Physiology	condition_factor, body_size, average_mass, average_length, average_size, fish_condition, mean_size, mean_mass, mean_length, median_size, median_mass, median_size
Size or age	age, ages, cohort, year_class
Biomass	biomass, ssb, spawning_stock_biomass, abundance
Larval	larvae, larval, eggs, spawning
Recruitment	pups, recruits, recruitment

Table 10.5 DFO research documents that included the climate change search terms used in this analysis.

N and % are the number and frequency at which climate change search terms arose in each document. Species are listed in order of decreasing frequency of occurrence (%).

Species	Functional group	Region	Year	N	%	CSAS type
Atlantic cod	Large groundfishes	Newfoundland/Labrador	2014	8	0.0631	SCR
Beluga	Mammals	Central Arctic	2005	4	0.0399	SAR
Porbeagle shark	Large pelagics	Maritimes	2005	4	0.0399	SAR
Arctic char	Large pelagics	Central Arctic	2014	4	0.0389	SAR
Bowhead whale	Mammals	Central Arctic	2007	3	0.0327	SAR
Atlantic salmon	Large pelagics	Quebec	2013	6	0.0303	SAR
Atlantic mackerel	Small pelagics	Quebec	2014	6	0.0243	RES
Bowhead whale	Mammals	Central Arctic	2007	2	0.0229	SAR
Snow crab	Invertebrates	Maritimes	2007	2	0.0229	SAR
Skate	Small groundfishes	Newfoundland/Labrador	2013	2	0.0228	SAR
Bluefin tuna	Large pelagics	Maritimes	2011	3	0.0224	SAR
American plaice	Large groundfishes	Gulf	2011	5	0.0221	SAR
Bowhead whale	Mammals	Central Arctic	2006	1	0.0217	RES
Sculpin	Small groundfishes	Central Arctic	2013	7	0.0197	RES
Beluga	Mammals	Quebec	2012	2	0.0186	SAR
Harp seal	Mammals	Newfoundland/Labrador	2014	2	0.0181	SAR
Redfish	Large groundfishes	Quebec	2000	2	0.0181	SSR
Harp seal	Mammals	Quebec	2011	2	0.0167	RES
Beluga	Mammals	Quebec	2014	1	0.0154	SAR
Arctic char	Large pelagics	Central Arctic	2014	4	0.0153	RES
Atlantic salmon	Large pelagics	Maritimes	2006	3	0.0148	RES
Atlantic cod	Large groundfishes	Newfoundland/Labrador	2018	2	0.0141	SAR
Beluga	Mammals	Quebec	2016	1	0.0131	SAR
Atlantic salmon	Large pelagics	Newfoundland/Labrador	2012	3	0.0127	SAR
Monkfish	Large groundfishes	Newfoundland/Labrador	2018	1	0.0126	SAR
Atlantic sturgeon	Large groundfishes	Quebec	2013	2	0.0124	SAR
Narwhal	Mammals	Central Arctic	2012	1	0.0121	SAR
White hake	Large groundfishes	Newfoundland/Labrador	2018	1	0.0119	SAR
White hake	Large groundfishes	Newfoundland/Labrador	2018	1	0.0118	RES

Greenland halibut	Large groundfishes	Quebec	2017	1	0.0116	SAR
Beluga	Mammals	Central Arctic	2012	1	0.0113	RES
Atlantic salmon	Large pelagics	Quebec	2012	2	0.0102	RES
Harp seal	Mammals	Quebec	2008	1	0.0102	SAR
Capelin	Small pelagics	Newfoundland/Labrador	2013	1	0.0097	SAR
Northern shrimp	Invertebrates	Newfoundland/Labrador	2013	1	0.0097	SAR
Narwhal	Mammals	Central Arctic	2011	1	0.0095	RES
Atlantic salmon	Large pelagics	Maritimes	2004	1	0.0095	SSR
Atlantic whitefish	Large groundfishes	Maritimes	2004	1	0.0095	SSR
Cusk	Large groundfishes	Maritimes	2004	1	0.0095	SSR
Atlantic cod	Large groundfishes	Newfoundland/Labrador	2011	2	0.0095	SAR
Atlantic cod	Large groundfishes	Newfoundland/Labrador	2004	1	0.0095	SSR
Atlantic cod	Large groundfishes	Newfoundland/Labrador	2004	1	0.0095	SSR
Northern wolffish	Large groundfishes	Newfoundland/Labrador	2004	1	0.0095	SSR
Greenland halibut	Large groundfishes	Quebec	2018	1	0.009	SAR
Harp seal	Mammals	Newfoundland/Labrador	2011	1	0.0087	SAR
Capelin	Small pelagics	Newfoundland/Labrador	2015	1	0.0083	SAR
Snow crab	Invertebrates	Gulf	2016	1	0.0082	SAR
Snow crab	Invertebrates	Gulf	2015	1	0.0081	SAR
Greenland halibut	Large groundfishes	Quebec	2019	1	0.0081	SAR
Snow crab	Invertebrates	Newfoundland/Labrador	2015	2	0.008	SAR
Capelin	Small pelagics	Newfoundland/Labrador	2018	1	0.0079	SAR
Atlantic cod	Large groundfishes	Gulf	2019	1	0.0076	SAR
Redfish	Large groundfishes	Quebec	2011	1	0.0075	SAR
Northern shrimp	Invertebrates	Newfoundland/Labrador	2015	1	0.0073	SAR
Harp seal	Mammals	Quebec	2014	1	0.0072	RES
Atlantic salmon	Large pelagics	Maritimes	2014	7	0.0071	RES
Snow crab	Invertebrates	Gulf	2019	1	0.007	SAR
Snow crab	Invertebrates	Quebec	2018	1	0.007	SAR
Atlantic salmon	Large pelagics	Maritimes	2014	9	0.0069	RES
Atlantic salmon	Large pelagics	Maritimes	2008	2	0.0066	SAR
Arctic char	Large pelagics	Central Arctic	2004	2	0.0058	RES

Snow crab	Invertebrates	Maritimes	2018	1	0.0058	SAR
Harp seal	Mammals	Newfoundland/Labrador	2016	1	0.0051	RES
Snow crab	Invertebrates	Gulf	2018	1	0.005	RES
Grey seal	Mammals	Maritimes	2017	1	0.0049	RES
Haddock	Large groundfishes	Maritimes	2005	1	0.0049	SAR
Beluga	Mammals	Quebec	2012	1	0.0047	RES
Arctic char	Large groundfishes	Quebec	2005	1	0.0047	RES
Atlantic salmon	Large pelagics	Maritimes	2014	2	0.0045	SAR
Atlantic cod	Large groundfishes	Gulf	2011	1	0.0041	SAR
Atlantic cod	Large groundfishes	Quebec	2007	1	0.0041	RES
Herring	Small pelagics	Quebec	2002	1	0.0041	SSR
Eel	Small groundfishes	Central Arctic	2013	2	0.004	SAR
Herring	Small pelagics	Gulf	2016	1	0.0039	RES
Skate	Small groundfishes	Gulf	2016	3	0.0038	RES
Atlantic salmon	Large pelagics	Gulf	2012	1	0.0036	SAR
Arctic surfclam	Invertebrates	Maritimes	2012	1	0.0034	RES
Atlantic salmon	Large pelagics	Gulf	2010	1	0.0033	RES
American lobster	Invertebrates	Gulf	2014	1	0.0017	RES
Herring	Small pelagics	Gulf	2018	1	0.0017	RES
Eel	Small groundfishes	Central Arctic	2013	1	0.0012	RES

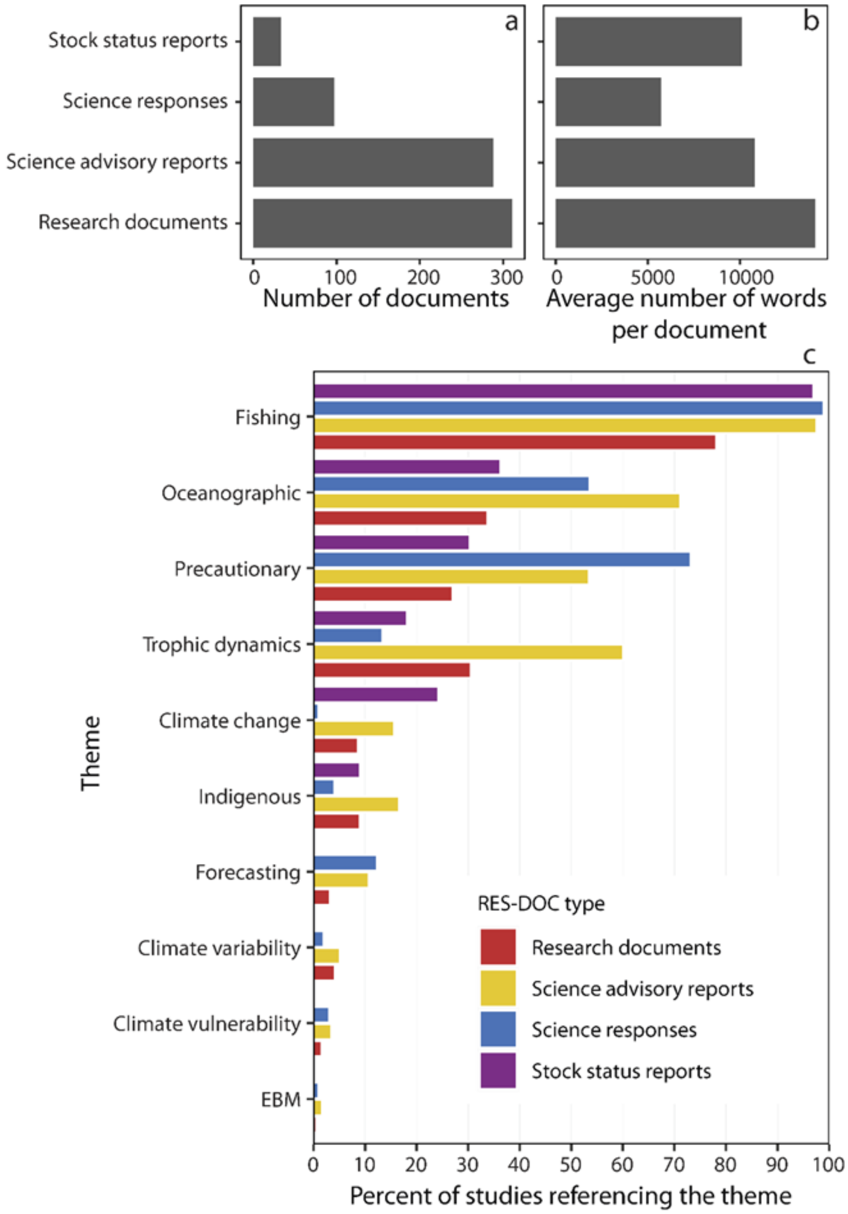

Figure 10.1 Summary of the different RES-DOCs used in this study.
(a) The number of RES-DOC types used in this study. (b) The average length (number of words) of each RES-DOC type. (c) Differences in the frequency of theme occurrence across the different RES-DOC types. Colours depict the RES-DOC type: Red=Research Documents, yellow=Science Advisory Reports, blue=Science Responses, purple=Stock Status Reports.

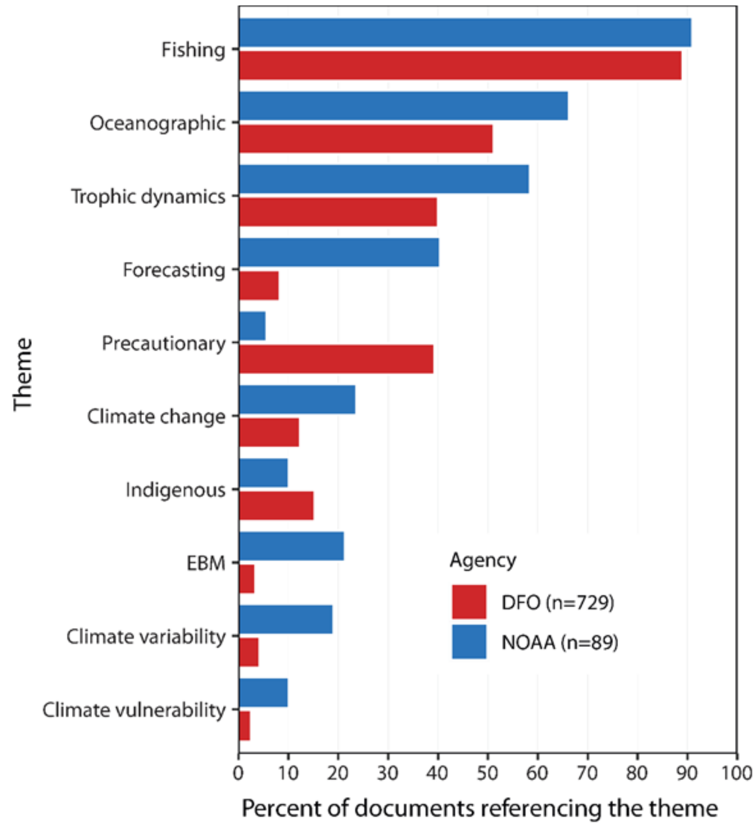

Figure 10.2 Differences in theme occurrence between DFO and NOAA stock assessments.

The bars are the percent of fishery management documents referencing the listed themes. Colours depict the fishery agency: red are DFO documents (n=729) and blue are NOAA documents (n=89)

10.3 Appendix C: Cumulative climate change across the AOS

The cumulative past and future climate change impacts across the AOS (Figure 4.5) were estimated using the historical SST trends (Figure 4.1 and Figure 4.2), and the future projected trends in NPP, SST, zooplankton biomass, and animal biomass under RCP8.5 (Figure 5.2 & Figure 5.3), the ToE of SST and oxygen (Figure 5.4), and the cumulative human impacts (Figure 4.5). ToE values were converted such that rapid emergences were represented by larger values. For each individual variable and within each NAFO division, the median of all 1° estimates was calculated. These values were then standardized to units of variance from the mean (z-scores) and expressed as absolute values to represent unidirectional magnitude. Through this procedure, the sum of individual climate changes in each division provides a measure of the cumulative past and future change and of human stressors.

10.4 Appendix D: Case study demonstrating how climate adaptation recommendations could be applied to the Division 4VWX herring fishery

Identified recommendations for climate adaptation in the fishery are in bold text.

10.4.1 Overview of the fishery

The 4VWX herring fishery is the largest fishery in Canada and has been a major contributor to the local economy for over a century (Lotze and Milewski, 2004). Between 1990 and 2018, landings of the fishery have accounted for 19% of Canada's total seafood landings, the largest of any individual species. However, the TAC of the herring stock has progressively declined, from ~150,000 t in 1994 to 35,000 in 2019[49]. The decline in the productivity and overall health of herring was quantified by Boyce *et al.* (2019) using 33 indices of herring status that relate to size, age and condition, population production, spatial dynamics, behaviour, and energy allocation. The study reported that the health of the herring stock has declined since at least 1965, reaching historically low biomass levels after 2005 (Boyce *et al.*, 2019). Despite the implementation of the Integrated Herring Management Plan in 2003 to protect the declining stock (Fisheries and Oceans Canada, 2003), the herring population has thus far failed to respond; biomass levels are projected to remain low in the near future (Boyce *et al.*, 2019). The fishing industry has recently self-suspended its Marine Stewardship Council certification. Biomass levels in 2019 were in the critical zone, below which the DFO precautionary approach suggests that the fishing be kept to the lowest possible levels (DFO, 2006a). The cause of the long-term decline in herring state and failure of the stock to respond to reduced exploitation are unknown, critically impairing management and conservation efforts.

---

[49] https://www.dfo-mpo.gc.ca/fisheries-peches/decisions/fm-2019-gp/atl-34-eng.html

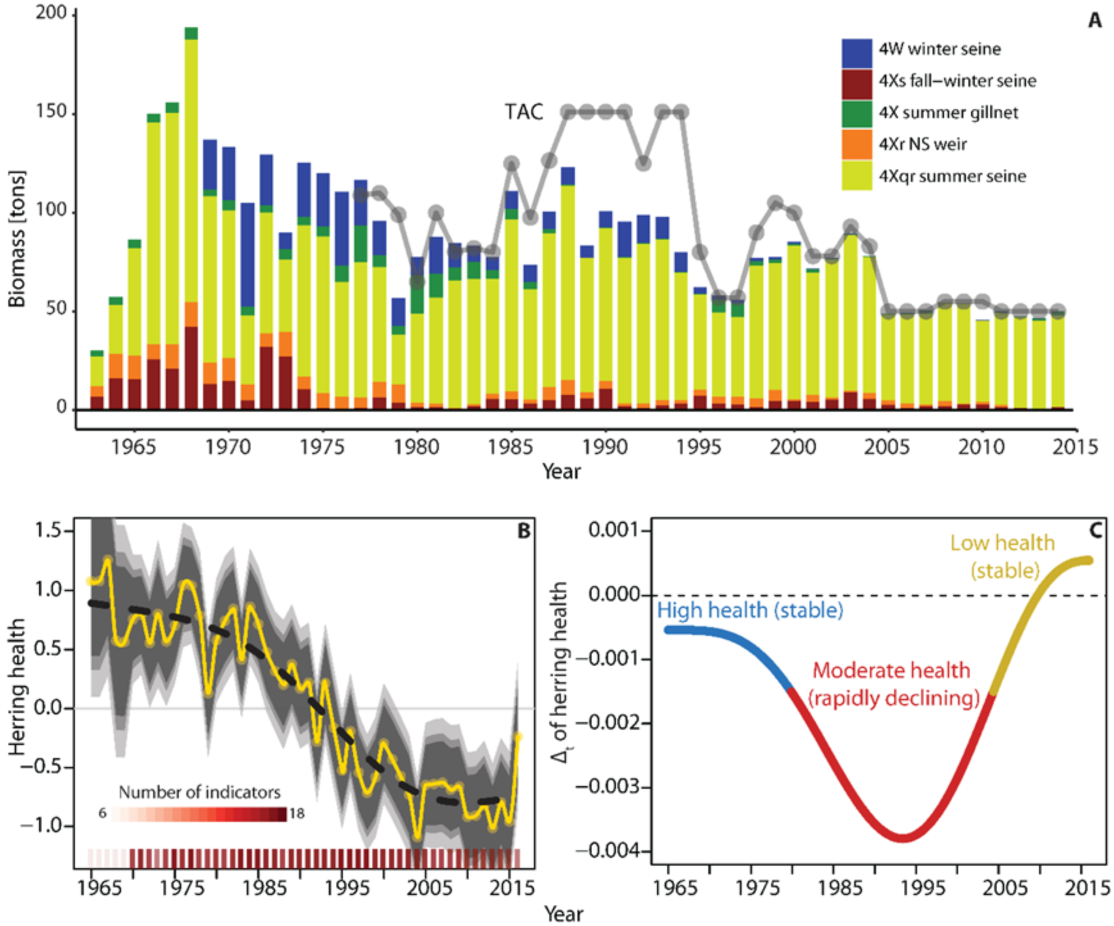

Figure 10.3 Long-term changes in Division 4VWX herring status.
(A) Landings of herring in NAFO Division 4WX separated by major fisheries. Colours denote the fishery from which the landings originate. Points and lines are the total allowable catch. (B–C) Multivariate index of herring state. (A) Points depict the predicted annual herring state from 16 indicators of herring population status, with dark, medium, and light grey shading depicting the 90%, 95%, and 99% confidence intervals about the means. The black line depicts the best-fitting linear model (spline) fitted to the data. Shaded ticks on the *x*-axis depict the number of indices that were used to produce the index in each year. (B) First differences (D_t) of the estimated time trend in herring state (broken line in panel B). Shaded lines depict the identified transitions from high but stable health (blue), to moderate and rapidly decline (red), to low and stable health (yellow). The horizontal dashed line denotes the point at which the first differences are 0 (flat trend). Source: Boyce *et al.* 2019

The status and management of the 4VWX herring fishery are highly uncertain due to several factors.

1. Herring have complex life histories, exhibiting fine-scale population spatial structure associated with hydrodynamically energetic environments, high and variable natural mortality, and large unexplained fluctuations in abundance (McClatchie *et al.*, 2017), factors that have challenged conventional management approaches. The 4VWX herring population structure and life history cycle are poorly understood. The 4WX herring

fisheries are managed as four components: (1) Southwest Nova Scotia and Bay of Fundy (SWNS-BoF), (2) South Shore, Eastern Shore, Cape Breton coast, (3) the offshore Scotian Shelf banks, and (4) the southwest New Brunswick migrant juveniles. Spawning herring undergo a seasonal cycle that involves separate geographic domains and differential mixing with other herring populations dependent on life stage. For example, mark and recapture studies (Stobo and Fowler, 2009) suggest that adult herring (>2–3 years old) from the SWNS spawning complex undergo a cyclic seasonal migration pattern of August–November spawning near German Bank/Lurcher Shoals, January–March overwintering approximately 700 km to the northeast in Chedabucto Bay, and April–July feeding on the Scotian Shelf and Bay of Fundy. Upon hatching, the larval herring are hypothesized to be retained within an area well-defined by ocean mixing regimes off SWNS (Iles and Sinclair, 1982; Stephenson *et al.*, 2015). Juvenile herring join a migrant juvenile community containing herring from other Canadian and US spawning complexes near Passamaquoddy Bay. Historically, fishing has occurred at all life stages excepting larval.

2. Changes in the assessment methods. Before 2006, assessments were based on virtual population analysis (Garvis, 1988) calibrated with larval abundance estimates (1980–1998) and then on an acoustic biomass index (1999–present). These assessments revealed that herring SSB, recruitment, and weight-at-age had declined since 1965 (Power *et al.*, 2006). However, since 2006, the acoustic survey estimates suggest that herring SSB is four to eight times higher than previously reported (DFO, 2015). This led to an abrupt and radical shift in the perception of herring stock status. Further complicating matters, analyses of standardized research vessel bottom trawl observations (1970–present) suggest irruptive increases of herring in the mid- to late 1980s in response to predator declines (Frank *et al.*, 2005, 2011).
3. Stock assessments for herring do not evaluate the long-term (pre-1999) herring population trends. Focusing on short-term acoustic series means that the assessments consider herring status during a recent period of historically low health and status. Rebuilding targets for herring ought to be focused on the conditions during the 1960s and 1970s, when the stock was healthier, yet the short acoustic time-series preclude this.
4. Stock assessments for herring do not evaluate climate or ecosystem impacts on herring status and productivity. Herring assessments focus heavily on exploitation as a driver of stock productivity, with limited integration of studies that have evaluated the response of herring to environmental and ecosystem impacts and the many dataseries available to quantitatively evaluate them.

10.4.2 Triaging the fishery for climate adaptation

Previous studies have assessed herring as having a low to medium climate vulnerability (Stortini *et al.*, 2015; Hare *et al.*, 2016). **However, the economic, ecological, and cultural importance of herring, coupled with its long-term declining status, provides a strong incentive to prioritize their management, including ensuring that climate change and ecosystem impacts are considered.** As herring SSB has recently dipped below the lower LRP, further fishing restrictions will be necessary to rebuild the stock.

10.4.3 Identifying climate adaptation needs

The herring fishery has numerous stakeholders that actively participate in assessment meetings, including academia, industry, NGOs, Indigenous groups, and government scientists. The industry is particularly active and engaged in the management of herring. In 2001, the purse seiner herring fleet in SWNS-BoF created the Herring Science Council[50] (HSC) to undertake research to increase knowledge about herring, which is then incorporated into assessments. The acoustic index of SSB, which forms the basis for the assessment and management of herring, is funded, planned, and supervised by the HSC. The acoustic data are analyzed by the HSC before being provided to DFO. The HSC also engages in plankton sampling and herring tagging to increase understanding of herring dynamics. This example demonstrates how collaborating with stakeholders, in this case industry, can increase research capacity while offsetting costs. In addition to the high industry involvement, there is often an active ENGO presence at herring assessment meetings, including the Ecology Action Centre, Oceans North, and the World Wildlife Fund for Nature, among others. This high stakeholder engagement could be leveraged. **Surveying the many stakeholders to identify what data sources, skills, tools, and other resources would assist in improving the management of herring, including the incorporation of climate and ecosystem factors into management, is recommended.** Identifying perceived gaps in management is a key step towards filling them.

10.4.4 Stock-specific recommendations

Enhanced ecosystem monitoring and data

Despite the strong focus of herring assessments on SSB estimated from acoustic surveys and on catch statistics, there are many additional data sources within the spatial domain of the fishery that could be used to broaden the scope at which herring are evaluated. For example, Boyce *et al.* (Boyce *et al.*, 2019) evaluated 33 proxy indicators of the ecological dynamics across the larval, juvenile, and adult stages of 4VWX herring. In a follow-up study, Boyce *et al.* (in preparation) assembled a database of over 100 time-series of oceanographic, atmospheric, biological, and anthropogenic factors that could influence 4VWX herring productivity. These time-series include, for instance, those related to the environment (temperature, nutrients, ocean mixing), predation and competition across different herring life stages, the nature and intensity of exploitation, and the abundance and composition of primary production and herring prey. In many cases, these time-series extend back to the 1970s or earlier (decades longer than the acoustic SSB index); they could provide a valuable longer-term perspective on herring drivers and dynamics and help in identifying recovery targets. Many of the time-series in the database originate from DFO data sources. Importantly, the databases are formatted and publicly available, should the herring assessment team wish to incorporate them. Herring have been intensively studied over the years, yielding many additional data sources such as tagging databases (McKenzie and Skud, 1958; Stobo and Fowler, 2009) or of predator consumption that could possibly be incorporated into assessments. Herring assessments could be supplemented with these additional data

---

[50] http://herringscience.ca/

sources to evaluate a broader suite of ecological or environmental factors and to extend the temporal scale over which herring dynamics are considered. Making the input data to the assessments publicly available would increase transparency and openness and could increase knowledge of herring dynamics should other researchers make use of them.

As discussed previously, there is substantial uncertainty related to herring life history and population structure, including their geographic distribution and migration patterns, and the extent of mixing between different herring spawning complexes, including those in US waters, particularly during the migrant juvenile stage. Much of the information about 4VWX herring population structure and life history patterns was developed through detailed field studies (e.g. ichthyoplankton surveys, tagging studies) that were undertaken decades ago and may be outdated. For instance, whereas SWNS-spawning herring (the largest spawning complex) were believed to overwinter far to the north in Chedabucto Bay, there are reports that this is no longer the case, yet research capacity is insufficient to evaluate this hypothesis or to explore where they now overwinter. **Enhanced research and monitoring capabilities are needed to better understand these factors, particularly as they may be shifting under climate change. Tagging and genetic studies, technologies such as eDNA and gliders with acoustic sensors, and enhanced bycatch monitoring could be useful approaches.** The level of mixing between Canadian and US herring populations is unknown but believed to be high, particularly at the juvenile stage. This provides a strong motivation to **further develop and strengthen collaborations between herring researchers at DFO and NOAA to better understand the extent of mixing between stocks.**

Quantitative tools

As this report was being prepared, an MSE approach to assessment was being developed for the management of 4VWX herring. MSE may be particularly suited to this fishery, as there are multiple sources of uncertainty that could potentially be incorporated into the management process within the MSE framework. Ideally, by incorporating regional climate projections (Wang *et al.*, 2018; Greenan *et al.*, 2019; Lavoie *et al.*, 2019), such a framework would also evaluate the uncertainty in herring status associated with future climate change scenarios (*e.g.* A'Mar *et al.*, 2009). Another recommendation that could be applied broadly, as well as to the herring fishery, is the evaluation of population status using a time-varying approach (Britten *et al.*, 2016, 2017) that would not assume stationary population dynamics (e.g. mortality, growth).

Building on the MSE and time-varying estimation approaches, the additional ecosystem data sources discussed above would facilitate a greater consideration of climate and ecosystem factors in herring assessments and management advice. This could include **basic examinations of time trends in important indicators (e.g. temperature, predation, prey) or relationships between environmental variables and indicators of herring population status, or more detailed evaluations of climate and ecosystem factors using some of the statistical approaches discussed previously** (e.g. MSEs). Including climate and ecosystem data in the assessments would also **allow the increased uncertainty in herring status that is associated with these factors to be better evaluated and could enable the development of forecasting models to evaluate future changes in herring**. **Understanding the response of**

herring to ecosystem variation could also lead to the adjustment of TAC when conditions become more or less favourable, as has been done for Pacific sardines (*Sardinops sagax*) in California (Pinsky and Mantua, 2014).

10.4.5 Global recommendations

There are several recommendations to increase climate change adaptation that could be applied broadly to most of Canada's fisheries, including that of Division 4VWX herring. For example, **the openness and transparency of the herring management process could be improved.** While the assessment meetings for herring are technically open, attendance requires advance knowledge of when and where the assessment meetings will occur—knowledge that is not publicly available—and also acquiring a formal invitation to the meeting from the organizers. Given the importance of Division 4VWX herring and its long-term declining status, **increasing the precaution with which the fishery is managed, in line with the precautionary approach** (DFO, 2006a)**, is critical.** Biomass levels in 2019 were estimated to be below lower LRP with high uncertainty, again providing a strong incentive to adopt a high degree of precaution and to reduce stressors such as overfishing and pollution. Taking steps to reduce the uncertainty about herring stock structure, life history, and migration patterns, and to track geographic shifts due to climate change are recommended, including **enhanced monitoring (including bycatch), increased collaborations with NOAA and other institutions, and enhanced process-based research.** Since herring are critical as forage for many commercially important predators, as well as important as bait for valuable invertebrate fisheries (e.g. lobster), **accounting for all sources of mortality and adopting an ecosystem approach to management is also critical.** According to the Fisheries Resource Conservation Council there are close to 1200 bait licence holders in the Maritimes Region and the amount of herring landed for bait in the growing invertebrate fisheries is currently not known[51]. **Tracking and recording this should be a high priority.** Listing all sources of scientific uncertainty and identifying management actions based on the precautionary approach, including those related to climate change and ecosystem considerations within stock assessments and IFMPs could also help to create transparency and accountability regarding the extent to which these factors are considered and find a pathway to action. Lastly, prioritizing and incorporating climate change considerations into fisheries assessments and decision-making could be increased, through greater inclusion in the Terms of Reference (ToR) that set out the questions to be addressed by DFO Science.

[51] https://www.dfo-mpo.gc.ca/fisheries-peches/ifmp-gmp/herring-hareng/herring-hareng-2013-eng.html

11. References

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

Adger, W. N., Brown, K., and Tompkins, E. L. 2005. The political economy of cross-scale networks in resource co-management. ECOLOGY AND SOCIETY, 10.

Agarwal, B. 1997. Environmental action, gender equity and women’s participation. Development and Change, 28: 1–44.

Allan, C., and Curtis, A. 2005. Nipped in the bud: Why regional scale adaptive management is not blooming. Environmental Management, 36: 414–425.

Allen, A. P., Brown, J. H., and Gillooly, J. F. 2002. Global biodiversity, biochemical kinetics, and the energetic-equivalence rule. Science, 297: 1545–1548. http://www.ncbi.nlm.nih.gov/pubmed/12202828.

Allen, C. R., Fontaine, J. J., Pope, K. L., and Garmestani, A. S. 2011. Adaptive management for a turbulent future. Journal of Environmental Management, 92: 1339–1345.

Altizer, S., Ostfeld, R. S., Johnson, P. T. J., Kutz, S., and Harvell, C. D. 2013. Climate Change and Infectious Diseases: From Evidence to a Predictive Framework. SCIENCE, 341: 514–519.

Alves, O., Wang, G., Zhong, A., Smith, N., Warren, G., Marshall, A., Tzeitkin, F., *et al.* 2002. POAMA: Bureau of Meteorology operational coupled model seasonal forecast system. Proceedings of the ECMWF Workshop on the Role of the Upper Ocean in Medium and Extended Range Forecasting.

Amaro, T., Bianchelli, S., Billett, D. S. M., Cunha, M. R., Pusceddu, A., and Danovaro, R. 2010. The trophic biology of the holothurian Molpadia musculus: implications for organic matter cycling and ecosystem functioning in a deep submarine canyon. BIOGEOSCIENCES, 7: 2419–2432.

Anderson, S. C., Ward, E. J., Shelton, A. O., Adkison, M. D., Beaudreau, A. H., Brenner, R. E., Haynie, A. C., *et al.* 2017a. Benefits and risks of diversification for individual fishers. Proceedings of the National Academy of Sciences, 114: 10797–10802. http://www.pnas.org/lookup/doi/10.1073/pnas.1702506114

Anderson, S. C., Branch, T. A., Cooper, A. B., and Dulvy, N. K. 2017b. Black-swan events in animal populations. PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA, 114: 3252–3257.

Andonegi, E., Antonio Fernandes, J., Quincoces, I., Irigoien, X., Uriarte, A., Perez, A., Howel, D., *et al.* 2011. The potential use of a Gadget model to predict stock responses to climate change in combination with Bayesian networks: the case of Bay of Biscay anchovy. ICES JOURNAL OF MARINE SCIENCE, 68: 1257–1269.

Armitage, D., Marschke, M., and Plummer, R. 2008. Adaptive co-management and the paradox of learning. Global Environmental Change - Human and Policy Demensions, 18: 86–98.

Aronson, R. B., Bruno, J. F., Precht, W. F., Glynn, P. W., Harvell, C. D., Kaufman, L., Rogers, C. S., *et al.* 2003. Causes of coral reef degradation. SCIENCE, 302: 1502.

Arvai, J., Bridge, G., Dolsak, N., Franzese, R., Koontz, T., Luginbuhl, A., Robbins, P., *et al.* 2006. Adaptive management of the global climate problem: Bridging the gap between climate research and climate policy. Climatic Change, 78: 217–225.

Asch, R. G. 2015. Climate change and decadal shifts in the phenology of larval fishes in the California Current ecosystem. Proceedings of the National Academy of Sciences: 201421946. http://www.pnas.org/lookup/doi/10.1073/pnas.1421946112.

Atwood, T. B., Connolly, R. M., Ritchie, E. G., Lovelock, C. E., Heithaus, M. R., Hays, G. C., Fourqurean, J. W., *et al.* 2015. Predators help protect carbon stocks in blue carbon ecosystems. Nature Climate Change, 5: 1038–1045. Nature Publishing Group.

Auster, P. J., Gjerde, K., Heupel, E., Watling, L., Grehan, A., and Rogers, A. D. 2011. Definition and detection of vulnerable marine ecosystems on the high seas: problems with the ``move-on{''} rule. ICES JOURNAL OF MARINE SCIENCE, 68: 254–264.

Azam, F., and Malfatti, F. 2007. Microbial structuring of marine ecosystems. NATURE REVIEWS MICROBIOLOGY, 5: 782–791. http://www.ncbi.nlm.nih.gov/pubmed/17853906 (Accessed 8 November 2013).

Bailey, M., Favaro, B., Otto, S. P., Charles, A., Devillers, R., Metaxas, A., Tyedmers, P., *et al.* 2016. Canada at a crossroad: The imperative for realigning ocean policy with ocean science. Marine Policy, 63: 53–60.

Baillie, S. M., McGowan, C., May-McNally, S., Leggatt, R., Sutherland, B. J. G., and Robinson, S. 2019. Environmental DNA and its applications to Fisheries and Oceans Canada: National needs and priorities. Can. Tech. Rep. Fish. Aquat. Sci., 3329: 84.

Bamber, J., van den Broeke, M., Ettema, J., Lenaerts, J., and Rignot, E. 2012. Recent large increases in freshwater fluxes from Greenland into the North Atlantic. GEOPHYSICAL RESEARCH LETTERS, 39.

Barange, M., and Perry, R. I. 2009. Physical and Ecological Impacts of Climate Change Relevant to Marine and Inland Capture Fisheries and Aquaculture. *In* Climate Change Implications for Fisheries and Aquaculture: Overview of Current Scientific Knowledge, pp. 7–106. Ed. by K. Cochrane, C. De Young, D. Soto, and T. Bahri. FAO Fisheries and Aquaculture Technical Paper 530, Rome, Italy, Italy.

Barange, M., Cheung, W. W. L., Merino, G., and Perry, R. I. 2010. Modelling the potential impacts of climate change and human activities on the sustainability of marine resources. CURRENT OPINION IN ENVIRONMENTAL SUSTAINABILITY, 2: 326–333.

Barange, M., Bahiri, T., Beveridge, M. C. M., Cochrane, K. L., Funge-Smith, S., and Poulain, F. (Eds). 2018. Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. *In* FAO Fisheries and Aquaculture Technical Paper, p. 628. Rome.

Barneche, D. R., White, C. R., and Marshall, D. J. 2018. Fish reproductive-energy ouput increases disproportionately with body size. Science, 645: 642–645.

Bartolino, V., Colloca, F., Taylor, L., and Stefansson, G. 2011. First implementation of a Gadget model for the analysis of hake in the Mediterranean. FISHERIES RESEARCH, 107: 75–83.

Barton, A., Hales, B., Waldbusser, G. G., Langdon, C., and Feely, R. A. 2012. The Pacific oyster, Crassostrea gigas, shows negative correlation to naturally elevated carbon dioxide levels: Implications for near-term ocean acidification effects. LIMNOLOGY AND OCEANOGRAPHY, 57: 698–710.

Barton, A. D., Irwin, A. J., Finkel, Z. V., and Stock, C. A. 2016. Anthropogenic climate change drives shift and shuffle in North Atlantic phytoplankton communities. PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA, 113: 2964–2969. http://www.pnas.org/lookup/doi/10.1073/pnas.1519080113.

Bates, A. E., Barrett, N. S., Stuart-Smith, R. D., Holbrook, N. J., Thompson, P. A., and Edgar, G. J. 2014. Resilience and signatures of tropicalization in protected reef fish communities. Nature Climate Change, 4: 62–67. Nature Publishing Group. http://dx.doi.org/10.1038/nclimate2062.

Baum, J. K., Myers, R. A., Kehler, D. G., Worm, B., Harley, S. J., and Doherty, P. a. 2003. Collapse and conservation of shark populations in the Northwest Atlantic. Science, 299: 389–92. http://www.ncbi.nlm.nih.gov/pubmed/12532016 (Accessed 29 January 2013).

Baum, J. K., and Myers, R. A. 2004. Shifting baselines and the decline of pelagic sharks in the Gulf of Mexico. Ecology Letters, 7: 135â€“145.

Baum, J. K., and Worm, B. 2009. Cascading top-down effects of changing oceanic predator abundances. Journal of Animal Ecology, 78: 699–714.

Baum, J. K., and Fuller, S. D. 2016. Canada’s marine fisheries: status, recovery potential and pathways to success. Toronto, Canada. 154 pp.

Bax, N. J. 1998. The significance and prediction of predation in marine fisheries. ICES J Mar Sci, 55: 997–1030.

Beaulieu, C., Henson, S. A., Sarmiento, J. L., Dunne, J. P., Doney, S. C., Rykaczewski, R. R., and Bopp, L. 2013. Factors challenging our ability to detect long-term trends in ocean chlorophyll. Biogeosciences, 10: 2711–2724. http://www.biogeosciences.net/10/2711/2013/ (Accessed 2 July 2013).

Behrenfeld, M. J., O’Malley, R. T., Siegel, D. a, McClain, C. R., Sarmiento, J. L., Feldman, G. C., Milligan, A. J., *et al.* 2006. Climate-driven trends in contemporary ocean productivity. NATURE, 444: 752–755. http://www.ncbi.nlm.nih.gov/pubmed/17151666 (Accessed 5 November 2013).

Bellwood, D. R., Hughes, T. P., Folke, C., and Nystrom, M. 2004. Confronting the coral reef crisis. Nature, 429: 827–833. http://dx.doi.org/10.1038/nature02691.

Benoit, K., Watanabe, K., Wang, H., Nulty, P., Obeng, A., Müller, S., and Matsuo, A. 2018. quanteda: An R package for the quantitative analysis of textual data. Journal of Open Source Software, 3: 774.

Berkes, F., Mathias, J., Kislalioglu, M., and Fast, H. 2001. The Canadian Arctic and the Oceans Act: the development of participatory environmental research and management. Ocean & Coastal Management, 44: 451–469.

Berkes, F. 2007. Adaptive co-management and complexity: exploring the many faces of co-management. *In* Adaptive Co-management: Collaboration, Learning, and Multi-level Governance, pp. 19–37. Ed. by D. R. Armitage, F. Berkes, and N. Doubleday. UBC Press, Vancouver, B.C., Canada.

Berkes, F. 2009. Evolution of co-management: Role of knowledge generation, bridging organizations and social learning. Journal of Environmental Management, 90: 1692–1702.

Berkes, F. 2012. Implementing ecosystem-based management: evolution or revolution? Fish and Fisheries, 13: 465–476.

Bernier, R. Y., Jamieson, R. E., and Moore, A. M. 2018. State of the Atlantic Ocean Synthesis Report. Canadian Techical Reports of Fisheries and Aquatic Sciences, 3167: 149.

Billett, D. S. M., Bett, B. J., Rice, A. L., Thurston, M. H., Galeron, J., Sibuet, M., and Wolff, G. A. 2001. Long-term change in the megabenthos of the Porcupine Abyssal Plain (NE Atlantic). PROGRESS IN OCEANOGRAPHY, 50: 325–348.

Bixby, H., Bentham, J., Zhou, B., Di Cesare, M., Paciorek, C. J., Bennett, J. E., Taddei, C., *et al.* 2019. Rising rural body-mass index is the main driver of the global obesity epidemic in adults. Nature, 569: 260–264.

Blanchard, J. L., Jennings, S., Holmes, R., Harle, J., Merino, G., Allen, J. I., Holt, J., *et al.* 2012. Potential consequences of climate change for primary production and fish production in large marine ecosystems. Philosophical transactions of the Royal Society of London. Series B, Biological sciences, 367: 2979–89.

Bond, N. A., Cronin, M. F., Freeland, H., and Mantua, N. 2015. Causes and impacts of the 2014 warm anomaly in the NE Pacific. GEOPHYSICAL RESEARCH LETTERS, 42: 3414–3420.

Bopp, L., Resplandy, L., Orr, J. C., Doney, S. C., Dunne, J. P., Gehlen, M., Halloran, P., *et al.* 2013. Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. BIOGEOSCIENCES, 10: 6225–6245.

Bourne, D. G., Morrow, K. M., and Webster, N. S. 2016. Insights into the Coral Microbiome: Underpinning the Health and Resilience of Reef Ecosystems. *In* ANNUAL REVIEW OF MICROBIOLOGY, VOL 70, p. 317+. Ed. by Gottesman, S.

Boyce, D. D. G. D., Lewis, M. R. M. M. R., and Worm, B. 2010. Global phytoplankton decline over the past century. Nature, 466: 591–596. Nature Publishing Group. http://dx.doi.org/10.1038/nature09268.

Boyce, D. G., Dowd, M., Lewis, M. R., and Worm, B. 2014. Estimating global chlorophyll changes over the past century. Progress in Oceanography, 122: 163–173. Elsevier Ltd. http://dx.doi.org/10.1016/j.pocean.2014.01.004 (Accessed 25 February 2014).

Boyce, D. G., Frank, K. T., and Leggett, W. C. 2015a. From mice to elephants: overturning the ‘one size fits all’ paradigm in marine plankton food chains. Ecology Letters, 18: 504–515. http://doi.wiley.com/10.1111/ele.12434.

Boyce, D. G., and Worm, B. 2015. Patterns and ecological implications of historical marine phytoplankton change. Marine Ecology Progress Series, 534: 251–272.

Boyce, D. G., Frank, K. T., Worm, B., and Leggett, W. C. 2015b. Spatial patterns and predictors of trophic control across marine ecosystems. Ecology Letters, 18: 1001–1011.

Boyce, D. G., Petrie, B., and Frank, K. T. 2019. Multivariate determination of Atlantic herring population health in a large 1 marine ecosystem. ICES Journal of Marine Science.

Boyce, D. G., Lotze, H. K., Tittensor, D. P., Carozza, D. A., and Worm, B. 2020. Future ocean biomass losses may widen socioeconomic equity gaps. Nature Communications.

Brander, K. 2010. Impacts of climate change on fisheries. Journal of Marine Systems, 79: 389–402.

Brander, K. M. 2007. Global fish production and climate change. Proceedings of the National Academy of Sciences, 104: 19709–19714. http://www.pnas.org/cgi/doi/10.1073/pnas.0702059104.

Brickman, D., Wang, Z., and DeTracey, B. 2016. High resolution future climate ocean model simulations for the Northwest Atlantic Shelf region. Can. Tech. Rep. Hydrogr. Ocean Sci., 315: 143.

Britten, G. L., Dowd, M., Minto, C. C., Ferretti, F., Boero, F., and Lotze, H. K. 2014. Predator decline leads to decreased stability in a coastal fish community. ECOLOGY LETTERS, 17: 1518–1525. http://doi.wiley.com/10.1111/ele.12354 (Accessed 17 September 2014).

Britten, G. L., Dowd, M., and Worm, B. 2016. Changing recruitment capacity in global fish stocks. PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA, 113: 134–139. http://www.pnas.org/content/113/1/134.abstract.

Britten, G. L., Dowd, M., Kanary, L., and Worm, B. 2017. Extended fisheries recovery timelines in a changing environment. Nature Communications, 8: 15325. Nature Publishing Group. http://www.nature.com/doifinder/10.1038/ncomms15325.

Bruno, J. F., Selig, E. R., Casey, K. S., Page, C. A., Willis, B. L., Harvell, C. D., Sweatman, H., *et al.* 2007. Thermal stress and coral cover as drivers of coral disease outbreaks. PLOS BIOLOGY, 5: 1220–1227.

Bryndum-Buchholz, A., Tittensor, D. P., Blanchard, J. L., Cheung, W. W. L., Coll, M., Galbraith, E. D., Jennings, S., *et al.* 2018. 21 St Century Climate Change Impacts on Marine Animal Biomass and Ecosystem Structure Across Ocean Basins. Global Change Biology, 25: 459–472. http://doi.wiley.com/10.1111/gcb.14512.

Bryndum-Buchholz, A. 2020. Marine ecosystem impacts and management responses under 21st century climate change. Dalhousie University. 229 pp. https://dalspace.library.dal.ca/handle/10222/79658?show=full.

Bryndum-Buchholz, A., Prentice, F., Tittensor, D. P., Blanchard, J. L., Cheung, W. W. L., Christensen, V., Galbraith, E. D., *et al.* 2020. Differing marine animal biomass shifts under 21st century climate change between Canada's three oceans. Facets, 5: 105–122. http://www.facetsjournal.com/doi/10.1139/facets-2019-0035.

Bunce, M., Rodwell, L. D., Gibb, R., and Mee, L. 2008. Shifting baselines in fishers' perceptions of island reef fishery degradation. OCEAN & COASTAL MANAGEMENT, 51: 285–302.

Bundy, A., Lilly, G. R., and Shelton, P. A. 2000. A mass balance model of the Newfoundland-Labrador Shelf. Canadian Technical Report of Fisheries and Aquatic Sciences, 2310: 157.

Burge, C. A., Eakin, C. M., Friedman, C. S., Froelich, B., Hershberger, P. K., Hofmann, E. E., Petes, L. E., *et al.* 2014. Climate Change Influences on Marine Infectious Diseases: Implications for Management and Society. *In* ANNUAL REVIEW OF MARINE SCIENCE, VOL 6, pp. 249–277. Ed. by Carlson, CA and Giovannoni, SJ.

Busch, D. S., Griffis, R., Link, J., Abrams, K., Baker, J., Brainard, R. E., Ford, M., *et al.* 2016. Climate science strategy of the US National Marine Fisheries Service. Marine Policy, 74: 58–67.

Butterworth, D. S., and Rademeyer, R. A. 2010. Greenland halibut MSE results for updated SCAA reference case and robustness test operating models. 18 pp. http://www.mth.uct.ac.za/maram/pub/2010/wgmsewp%0A10-13_MSE_update.pdf.

Byrne, M. 2011. IMPACT OF OCEAN WARMING AND OCEAN ACIDIFICATION ON MARINE INVERTEBRATE LIFE HISTORY STAGES: VULNERABILITIES AND POTENTIAL FOR PERSISTENCE IN A CHANGING OCEAN. *In* OCEANOGRAPHY AND MARINE BIOLOGY: AN ANNUAL REVIEW, VOL 49, pp. 1–42. Ed. by Gibson, RN and Atkinson, RJA and Gordon, JDM.

Canada, H. 2007. Income-related household food security in Canada. Canadian Community Health Survey Cycle 2.2, Nutrition 2004, Ottawa, ON.

Caputi, N., Kangas, M., Denham, A., Feng, M., Pearce, A., Hetzel, Y., and Chandrapavan, A. 2016. Management adaptation of invertebrate fisheries to an extreme marine heat wave event at a global warming hot spot. ECOLOGY AND EVOLUTION, 6: 3583–3593.

Carlsson, L., and Berkes, F. 2005. Co-management: concepts and methodological implications. Journal of Environmental Management, 75: 65–76.

Carozza, D. A., Bianchi, D., and Galbraith, E. D. 2016. The ecological module of BOATS-1.0: A bioenergetically constrained model of marine upper trophic levels suitable for studies of fisheries and ocean biogeochemistry. Geoscientific Model Development, 9: 1545–1565.

Carozza, D. A., Bianchi, D., and Galbraith, E. D. 2019. Metabolic impacts of climate change on marine ecosystems: Implications for fish communities and fisheries. Global Ecology and Biogeography, 28: 158–169.

Cavicchioli, R., Ripple, W. J., Timmis, K. N., Azam, F., Bakken, L. R., Baylis, M., Behrenfeld, M. J., *et al.* 2019. Scientists' warning to humanity: microorganisms and climate change. Nature Reviews Microbiology. http://www.nature.com/articles/s41579-019-0222-5.

Cavole, L.-C. M., Demko, A. M., Diner, R. E., Giddings, A., Koester, I., Pagniello, C. M. L. S., Paulsen, M.-L., *et al.* 2016. Biological Impacts of the 2013-2015 Warm-Water Anomaly in the Northeast Pacific. OCEANOGRAPHY, 29: 273–285.

CBC. 2016. Unmanned gliders to help DFO measure and monitor oceans. https://www.cbc.ca/news/canada/nova-scotia/unmanned-gliders-ocean-dfo-fisheries-research-1.3778654 (Accessed 7 August 2020).

Cermeno, P., Dutkiewicz, S., Harris, R. P., Follows, M., Schofield, O., and Falkowski, P. 2008. The role of nutricline depth in regulating the ocean carbon cycle. Proceedings of the National Academy of Sciences of the United States of America, 105: 20344–20349.

Cerrano, C., Bavestrello, G., Bianchi, C. N., Cattaneo-vietti, R., Bava, S., Morganti, C., Morri, C., *et al.* 2000. A catastrophic mass-mortality episode of gorgonians and other organisms in the Ligurian Sea (Northwestern Mediterranean), summer 1999. ECOLOGY LETTERS, 3: 284–293.

Charles, A. N., Duell, R. E., Wang, X., and Watkins, A. B. 2015. Seasonal Forecasting for Australia using a Dynamical Model: Improvements in Forecast Skill over the Operational Statistical Model. Australian Meteorological and Oceanographic Journal, 65: 356–375.

Charpy-Roubaud, C., and Sournia, A. 1990. The comparative estimation of phytoplanktonic, microphytobenthic and macrophytobenthic primary production in the oceans. Marine Microbial Food Webs, 4: 31–57.

Chassot, E., Melin, F., Le Pape, O., and Gascuel, D. 2007. Bottom-up control regulates fisheries production at the scale of eco-regions in European seas. Marine Ecology-Progress Series, 343: 45–55.

Chassot, E., Bonhommeau, S., Dulvy, N. K., Mélin, F., Watson, R., Gascuel, D., and Le Pape, O. 2010. Global marine primary production constrains fisheries catches. Ecology Letters, 13: 495–505. http://www.ncbi.nlm.nih.gov/pubmed/20141525 (Accessed 29 January 2013).

Chavez, F. F. P., Ryan, J., Lluch-Cota, S. E. S., Niquen C., M., and Niquen, C. 2003. From anchovies to sardines and back: Multidecadal change in the Pacific Ocean. Science, 299: 217–221. http://www.ncbi.nlm.nih.gov/pubmed/12522241 (Accessed 29 January 2013).

Chen, K., Gawarkiewicz, G. G., Lentz, S. J., and Bane, J. M. 2014. Diagnosing the warming of the Northeastern US Coastal Ocean in 2012: A linkage between the atmospheric jet stream variability and ocean response. JOURNAL OF GEOPHYSICAL RESEARCH-OCEANS, 119: 218–227.

Cheung, W., Lam, V., and Pauly, D. 2016a. Modelling present and climate-shifted distribution of marine fishes and invertebrates. Fisheries Centre Research Reports.

Cheung, W. W. L., Lam, V. W. Y., Sarmiento, J. L., Kearney, K., Watson, R., Zeller, D., and Pauly, D. 2010. Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. Global Change Biology, 16: 24–35. http://doi.wiley.com/10.1111/j.1365-2486.2009.01995.x.

Cheung, W. W. L., Dunne, J., Sarmiento, J. L., and Pauly, D. 2011. Integrating ecophysiology and plankton dynamics into projected maximum fisheries catch potential under climate change in the Northeast Atlantic. ICES JOURNAL OF MARINE SCIENCE, 68: 1008–1018.

Cheung, W. W. L., Sarmiento, J. L., Dunne, J., Frölicher, T. L., Lam, V. W. Y., Deng Palomares, M. L., Watson, R., *et al.* 2013a. Shrinking of fishes exacerbates impacts of global ocean changes on marine ecosystems. NATURE CLIMATE CHANGE, 3: 254–258. Nature Publishing Group. http://dx.doi.org/10.1038/nclimate1691.

Cheung, W. W. L., Watson, R., and Pauly, D. 2013b. Signature of ocean warming in global fisheries catch. Nature, 497: 365–368. Nature Publishing Group. http://www.nature.com/doifinder/10.1038/nature12156 (Accessed 21 May 2013).

Cheung, W. W. L., Jones, M. C., Reygondeau, G., Stock, C. A., Lam, V. W. Y., and Frölicher, T. L. 2016b. Structural uncertainty in projecting global fisheries catches under climate change. Ecological Modelling, 325: 57–66. Elsevier B.V. http://dx.doi.org/10.1016/j.ecolmodel.2015.12.018.

Cheung, W. W. L. L., Pinnegar, J., Merino, G., Jones, M. C., and Barange, M. 2012. Review of climate change impacts on marine fisheries in the UK and Ireland. Aquatic Conservation-Marine and Freshwater Ecosystems, 22: 368–388.

Chin, A., Kyne, P. M., Walker, T. I., and Mcauley, R. B. 2010. An integrated risk assessment for climate change: analysing the vulnerability of sharks and rays on Australia's Great Barrier Reef. GLOBAL CHANGE BIOLOGY, 16: 1936–1953.

Christensen, V., and Walters, C. J. 2004. Ecopath with Ecosim: methods, capabilities and limitations. Ecological Modelling, 172: 109–139. https://linkinghub.elsevier.com/retrieve/pii/S030438000300365X.

Christensen, V., Coll, M., Buszowski, J., Cheung, W. W. L. L., Frölicher, T., Steenbeek, J., Stock, C. A., *et al.* 2015. The global ocean is an ecosystem: Simulating marine life and fisheries. Global Ecology and Biogeography, 24: 507–517.

Chu, C. 2009. Thirty years later: the global growth of ITQs and their influence on stock status in marine fisheries. FISH AND FISHERIES, 10: 217–230.

Ciannelli, L., Fisher, J., Skern-Mauritzen, M., Hunsicker, M., Hidalgo, M., Frank, K., and Bailey, K. 2013. Theory, consequences and evidence of eroding population spatial structure in harvested marine fishes: a review. Marine Ecology Progress Series, 480: 227–243. http://www.int-res.com/abstracts/meps/v480/p227-243/.

Cisneros-Montemayor, A. M., Cheung, W. W. L., Bodtker, K., Teh, L., Steiner, N., Bailey, M., Hoover, C., *et al.* 2017. Towards an integrated database on canadian ocean resources: Benefits, current states, and research gaps. Canadian Journal of Fisheries and Aquatic Sciences, 74: 65–74.

Clarke, A., and Johnston, N. M. 1999. Scaling of metabolic rate with body mass and temperature in teleost fish. JOURNAL OF ANIMAL ECOLOGY, 68: 893–905.

Colburn, L. L., Jepson, M., Weng, C., Seara, T., Weiss, J., and Hare, J. A. 2016. Indicators of climate change and social vulnerability in fishing dependent communities along the Eastern and Gulf Coasts of the United States. Marine Policy, 74: 323–333. https://linkinghub.elsevier.com/retrieve/pii/S0308597X16302123.

Comeaux, R. S., Allison, M. A., and Bianchi, T. S. 2012. Mangrove expansion in the Gulf of Mexico with climate change: Implications for wetland health and resistance to rising sea levels. ESTUARINE COASTAL AND SHELF SCIENCE, 96: 81–95.

Corliss, B. H., Brown, C. W., Sun, X., and Showers, W. J. 2009. Deep-sea benthic diversity linked to seasonality of pelagic productivity. DEEP-SEA RESEARCH PART I-OCEANOGRAPHIC RESEARCH PAPERS, 56: 835–841.

Cossarini, D. M., MacDonald, B. H., and Wells, P. G. 2014. Communicating marine environmental information to decision makers: Enablers and barriers to use of publications (grey literature) of the Gulf of Maine Council on the Marine Environment. Ocean & Coastal Management, 96: 163–172. https://linkinghub.elsevier.com/retrieve/pii/S096456911400163X.

Costello, C., Gaines, S. D., and Lynham, J. 2008. Can catch shares prevent fisheries collapse? SCIENCE, 321: 1678–1681.

Costello, C., Lynham, J., Lester, S. E., and Gaines, S. D. 2010. Economic Incentives and Global Fisheries Sustainability. *In* ANNUAL REVIEW OF RESOURCE ECONOMICS, VOL 2, 2010, pp. 299–318. Ed. by Rausser, GC and Smith, VK and Zilberman, D.

Côté, I. M., Canada, R. S. of, and (Firm), C. E. L. 2012. Sustaining Canada’s marine biodiversity responding to the challenges posed by climate change, fisheries, and aquaculture. Ottawa, Ont. : Royal Society of Canada, Ottawa, Ont. 21 pp.

Cox, S. P., and Kronlund, A. R. 2008. Practical stakeholder-driven harvest policies for groundfish fisheries in British Columbia, Canada. FISHERIES RESEARCH, 94: 224–237.

Crain, C. M., Kroeker, K., and Halpern, B. S. 2008. Interactive and cumulative effects of multiple human stressors in marine systems. Ecology Letters, 11: 1304–1315.

Cronin, T. M., and Raymo, M. E. 1997. Orbital forcing of deep-sea benthic species diversity. NATURE, 385: 624–627.

Cubaynes, H. C., Fretwell, P. T., C., B., Gerrish, L., and Jackson, J. A. 2018. Whales from space: Four mysticete species described using new VHR satellite imagery. Marine Mammal Science, 35: 466–491.

Cunningham, C. J., Anderson, C. M., Wang, J. Y. L., Link, M., and Hilborn, R. 2019. A management strategy evaluation of the commercial sockeye salmon fishery in bristol bay, alaska. Canadian Journal of Fisheries and Aquatic Sciences, 76: 1669–1683.

Currie, D. J., Mittelbach, G. G., Cornell, H. V, Field, R., Guegan, J. F., Hawkins, B. A., Kaufman, D. M., *et al.* 2004. Predictions and tests of climate-based hypotheses of broad-scale variation in taxonomic richness. ECOLOGY LETTERS, 7: 1121–1134.

Curti, K. L., Collie, J. S., Legault, C. M., and Link, J. S. 2013. Evaluating the performance of a multispecies statistical catch-at-age model. Canadian Journal of Fisheries and Aquatic Sciences, 70: 470–484. http://www.nrcresearchpress.com/doi/10.1139/cjfas-2012-0229.

Cushing, D. H. 1969. The regularity of the spawning season of some fishes. J. Cons. Int. Explor. Mer., 33: 81–92.

Cushing, D. H. 1990. Plankton production and year-class strength in fish populations - an update of the match mismatch hypothesis. Advances in Marine Biology, 26: 249–293.

Darling, E. S., and Cote, I. M. 2008. Quantifying the evidence for ecological synergies. ECOLOGY LETTERS, 11: 1278–1286.

Daufresne, M., Lengfellner, K., and Sommer, U. 2009. Global warming benefits the small in aquatic ecosystems. PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA, 106: 12788–12793.

Davies, K. T. A., Brosn, M. W., Hamilton, P. K., Knowlton, A. R., Taggart, C. T., and Vanderlaan, A. S. M. 2019. Variation in North Atlantic right whale Eubalaena glacialis occurrence in the Bay of Fundy, Canada, over three decades. Endangered Species Research, 39: 159–171.

Davies, K. T. A., and Brillant, S. W. 2019. Mass human-caused mortality spurs federal action to protect endangered North Atlantic right whales in Canada. Marine Policy, 104: 157–162.

Davis, G. E., Baumgartner, M. F., Bonnell, J. M., Bell, J., Berchok, C., Bort Thornton, J., Brault, S., *et al.* 2017. Long-term passive acoustic recordings track the changing distribution of North Atlantic right whales (*Eubalaena glacialis*) from 2004 to 2014. Scientific Reports, 7: 13460. http://www.nature.com/articles/s41598-017-13359-3.

De Leo, F. C., Drazen, J. C., Vetter, E. W., Rowden, A. A., and Smith, C. R. 2012. The effects of submarine canyons and the oxygen minimum zone on deep-sea fish assemblages off Hawai'i. DEEP-SEA RESEARCH PART I-OCEANOGRAPHIC RESEARCH PAPERS, 64: 54–70.

de los Ríos, C., Watson, J. E. M., and Butt, N. 2018. Persistence of methodological, taxonomical, and geographical bias in assessments of species' vulnerability to climate change: A review. Global Ecology and Conservation, 15.

Defra. 2013. Economics of climate resilience: natural environment theme: sea fish. London, UK, UK. 99 pp. http://randd.defra.gov.uk/Document.aspx?Document=10658_CA0401-%0Arep-fishfinalfinal.pdf-AdobeAcrobatProfessional.pdf.

Delaney, A. E., and Hastie, J. E. 2007. Lost in translation: Differences in role identities between fisheries scientists and managers. Ocean & Coastal Management, 50: 661–682. https://linkinghub.elsevier.com/retrieve/pii/S0964569107000439.

Dell, J., Wilcox, C., and Hobday, A. J. 2011. Estimation of yellowfin tuna (Thunnus albacares) habitat in waters adjacent to Australia's East Coast: making the most of commercial catch data. FISHERIES OCEANOGRAPHY, 20: 383–396.

Delworth, T. L., Zeng, F., Vecchi, G. A., Yang, X., Zhang, L., and Zhang, R. 2016. The North Atlantic Oscillation as a driver of rapid climate change in the Northern Hemisphere. NATURE GEOSCIENCE, 9: 509+.

DFO., and DFO. 2015. Fisheries Management Decisions. http://www.dfo-mpo.gc.ca/fisheries-peches/decisions/index-eng.html (Accessed 7 August 2020).

DFO. 2006a. A harvest strategy compliant with the precautionary approach. Canadian Science Advisory Secretariat science advisory report, 2006/023: 1–7.

DFO. 2006b. Aquatic Monitoring in Canada. DFO Can. Sci. Advis. Sec. Proceed. Ser., 2006/003: 54.

DFO. 2007. A new ecosystem science framework in support of integrated management. Ottawa, Canada. 18 pp.

DFO. 2009a. Development of a framework and principles for the biogeographic classification of Canadian marine areas. Can. Sci. Advis. Secret. Sci. Advis. Rep., 2009/056.

DFO. 2009b. A fishery decision-making framework incorporating the precautionary approach. https://www.dfo-mpo.gc.ca/reports-rapports/regs/sff-cpd/precaution-eng.htm (Accessed 11 August 2020).

DFO. 2011. Recovery potential assessment of the Maritime designatable unit of American plaice (Hippoglossoides platessoides). Canadian Science Advosory Secretariat Science Advosory Report, 2011/043: 1–30.

DFO. 2012a. Risk-based assessment of climate change impacts and risks on the biological systems and infrastructure within Fisheries and Oceans Canada's mandate - Atlantic Large Aquatic Basin. Canadian Science Advisory Secretariat Science Response, 2012/044: 43.

DFO. 2012b. Risk-based assessment of climate change impacts and risks on the biological systems and infastructure within fisheries and oceans Canada's mandate - Pacific large aquatic basin. Canadian Science Advisory Secretariat Science Response, 2013/011: 43.

DFO. 2012c. Pre-season run size forecasts for Fraser River Sockeye (*Oncorhynchus nerka*) and Pink (*O. gorbuscha*) salmon in 2013. DFO Canadian Science Advisory Secretariat Research Document, 2012/145: 42.

DFO. 2013. Assessment of divisions 2G-3K (Shrimp fishing areas 4-6) northern shrimp. Canadian Science Advisory Secretariat Science Advisory Report.

DFO. 2015. 2015 ASSESSMENT OF 4VWX HERRING Context : SUMMARY SW Nova Scotia / Bay of Fundy. Sci. Advis. Sec. Sci. Advis. Rep.: 1–23.

DFO. 2016. Supplement to the pre-season run size forecasts for Fraser River Sockeye Salmon (*Oncorhynchus nerka*) in 2016. DFO Canada Science Advisory Secretariat Science Science Response, 2016/047.

DFO. 2018a. Canada's Fish and Seafood Trade: Overview. Economic Policy and Research Economic Analysis and Statistics Directorate Strategic Policy Sector.

DFO. 2018b. 2018 Assessment of 4VWX Herring. Canadian Science Advisory Secretariat Science Advisory Report, 2018/052: 26.

DFO. 2020a. Employment. https://www.dfo-mpo.gc.ca/stats/cfs-spc/tab/cfs-spc-tab2-eng.htm (Accessed 9 April 2020).

DFO. 2020b. Seafisheries Landings. https://www.dfo-mpo.gc.ca/stats/commercial/sea-maritimes-eng.htm (Accessed 9 April 2020).

DFO. 2020c. Stock status update of 4VWX Herring for the 2018/2019 fishing season. Canadian Science Advisory Secretariat Science Response, 2020/001: 12.

Diaz, R. J. R. J., and Rosenberg, R. 2008. Spreading dead zones and consequences for marine ecosystems. Science, 321: 926–9. http://www.ncbi.nlm.nih.gov/pubmed/18703733 (Accessed 29 January 2013).

Dichmont, C. M., Deng, A., Punt, A. E., Ellis, N., Venables, W. N., Kompas, T., Ye, Y., *et al.* 2008. Beyond biological performance measures in management strategy evaluation: Bringing in economics and the effects of trawling on the benthos. FISHERIES RESEARCH, 94: 238–250.

Donato, D. C., Kauffman, J. B., Murdiyarso, D., Kurnianto, S., Stidham, M., and Kanninen, M. 2011. Mangroves among the most carbon-rich forests in the tropics. NATURE GEOSCIENCE, 4: 293–297.

Doney, S. C., Fabry, V. J., Feely, R. A., and Kleypas, J. A. 2009. Ocean Acidification: The Other CO2 Problem. ANNUAL REVIEW OF MARINE SCIENCE, 1: 169–192.

Doney, S. C., Ruckelshaus, M., Duffy, J. E., Barry, J. P., Chan, F., English, C. a., Galindo, H. M., *et al.* 2012. Climate Change Impacts on Marine Ecosystems. Annual Review of Marine Science, 4: 11–37. http://www.annualreviews.org/doi/abs/10.1146/annurev-marine-041911-111611 (Accessed 29 January 2013).

Doremus, H. 2002. Adaptive management, the Endangered Species Act, and the institutional challenges of "New Age". Wahsburn Law Journal, 41: 50–81.

Drinkwater, K., and Kristiansen, T. 2018. A synthesis of the ecosystem responses to the late 20th century cold period in the northern North Atlantic. ICES Journal of Marine Science, 75: 2325–2341.

Drinkwater, K. F. 2002. A review of the role of climate variability in the decline of northern cod. *In* FISHERIES IN A CHANGING CLIMATE, pp. 113–129. Ed. by McGinn, NA.

Drinkwater, K. F. 2005. The response of Atlantic cod (Gadus morhua) to future climate change. ICES JOURNAL OF MARINE SCIENCE, 62: 1327–1337.

Dufresne, J.-L., Foujols, M.-A., Denvil, S., Caubel, A., Marti, O., Aumont, O., Balkanski, Y., *et al.* 2013. Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5. Climate Dynamics, 40: 2123–2165.

Dulvy, N. K., Rogers, S. I., Jennings, S., Stelzenmuller, V., Dye, S. R., and Skjoldal, H. R. 2008. Climate change and deepening of the North Sea fish assemblage: A biotic indicator of warming seas. Journal of Applied Ecology, 45: 1029–1039.

Dunmall, K., and Reist, J. 2018. Developing a Citizen Science Framework for the Arctic Using the 'Arctic Salmon' Initiative. Impacts of a Changing Environment on the Dynamics of High-latitude Fish and Fisheries: 31–47.

Dunmall, K. M., Reist, J. D., Carmack, E. C., Babaluk, J. A., Heike-Jorgensen, M. P., and Docker, M. F. 2013. Pacific salmon in the Arctic: Harbingers of change. *In* Responses of arctic marine ecosystems to climate change, pp. 141–163. Ed. by F. J. Mueter, D. M. S. Dickson, H. P. Huntington, J. R. Irvine, E. A. Logerwell, S. A. MacLean, L. T. Quakenbush, et al. Alaska Sea Grant, University of Alaska Fairbanks, Fairbanks, AK, USA.

Dunn, D. C., Boustany, A. M., and Halpin, P. N. 2011. Spatio-temporal management of fisheries to reduce by-catch and increase fishing selectivity. FISH AND FISHERIES, 12: 110–119.

Dunn, D. C., Boustany, A. M., Roberts, J. J., Brazer, E., Sanderson, M., Gardner, B., and Halpin, P. N. 2014. Empirical move-on rules to inform fishing strategies: a New England case study. FISH AND FISHERIES, 15: 359–375.

Dunn, D. C., Maxwell, S. M., Boustany, A. M., and Halpin, P. N. 2016. Dynamic ocean management increases the efficiency and efficacy of fisheries management. Proceedings of the National Academy of Sciences, 113: 668–673. http://www.pnas.org/lookup/doi/10.1073/pnas.1513626113.

Dunne, J. P., John, J. G., Adcroft, A. J., Griffies, S. M., Hallberg, R. W., Shevliakova, E., Stouffer, R. J., *et al.* 2012. GFDL's ESM2 Global Coupled Climate-Carbon Earth System Models. Part I: Physical Formulation and Baseline Simulation Characteristics. Journal of, 25: 6646–6665.

Dunne, J. P., John, J. G., Shevliakova, E., Stouffer, R. J., Krasting, J. P., Malyshev, S. L., Milly, P. C. D., *et al.* 2013. GFDL's ESM2 Global Coupled Climate-Carbon Earth System Models. Part II: Carbon System Formulation and Baseline Simulation Characteristics. Journal of Climate, 26: 2247–2267.

Duplisea, D. E., Roux, M.-J., Hunter, K. L., and Rice, J. 2020. Resource management under climate change: a risk-based strategy to develop climate-informed science advice. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/044: 45.

Dupont, S., Havenhand, J., and Thorndyke, M. 2008. CO2-driven acidification radically affects larval survival and development in marine organisms. COMPARATIVE BIOCHEMISTRY AND PHYSIOLOGY A-MOLECULAR & INTEGRATIVE PHYSIOLOGY, 150: S170.

Durack, P. J., and Wijffels, S. E. 2010. Fifty-Year Trends in Global Ocean Salinities and Their Relationship to Broad-Scale Warming. JOURNAL OF CLIMATE, 23: 4342–4362.

Durack, P. J., Wijffels, S. E., and Matear, R. J. 2012. Ocean Salinities Reveal Strong Global Water Cycle Intensification During 1950 to 2000. SCIENCE, 336: 455–458.

Easterling, D. R. R., Meehl, G. A., Parmesan, C., Changnon, S. A., Karl, T. R., and Mearns, L. O. 2000. Climate extremes: Observations, modeling, and impacts. SCIENCE, 289: 2068–2074.

Edgar, G. J., Stuart-Smith, R. D., Willis, T. J., Kininmonth, S., Baker, S. C., Banks, S., Barrett, N. S., *et al.* 2014. Global conservation outcomes depend on marine protected areas with five key features. Nature, 506: 216–220.

Edwards, A. M., Robinson, J. P. W., Plank, M. J., Baum, J. K., and Blanchard, J. L. 2016. Testing and recommending methods for fitting size spectra to data. Methods in Ecology and Evolution: in press.

Edwards, M., Richardson, A. J., and Martin Edwards & Anthony J. Richardson. 2004. Impact of climate change on marine pelagic phenology and trophic mismatch. NATURE, 430: 881–884. http://dx.doi.org/10.1038/nature02808 L3 - http://www.nature.com/nature/journal/v430/n7002/suppinfo/nature02808.html.

Ekau, W., Auel, H., Poertner, H.-O., and Gilbert, D. 2010. Impacts of hypoxia on the structure and processes in pelagic communities (zooplankton, macro-invertebrates and fish). BIOGEOSCIENCES, 7: 1669–1699.

Elvarsson, B. P., Woods, P. J., Bjornsson, H., Lentin, J., and Thordarson, G. 2018. Pushing the limits of a data challenged stock: A size- and age-structured assessment of ling (Molva molva) in Icelandic waters using Gadget. FISHERIES RESEARCH, 207: 95–109.

Essington, T. E., Melnychuk, M. C., Branch, T. A., Heppell, S. S., Jensen, O. P., Link, J. S., Martell, S. J. D., *et al.* 2012. Catch shares, fisheries, and ecological stewardship: a comparative analysis of resource responses to a rights-based policy instrument. CONSERVATION LETTERS, 5: 186–195.

Estes, J. a., Tinker, M. T., Williams, T. M., and Doak, D. F. 1998. Killer Whale Predation on Sea Otters Linking Oceanic and Nearshore Ecosystems. Science, 282: 473–476. http://www.sciencemag.org/cgi/doi/10.1126/science.282.5388.473 (Accessed 29 January 2013).

Estes, J. A., Terborgh, J., Brashares, J. S., Power, M. E., Berger, J., Bond, W. J., Carpenter, S. R., *et al.* 2011. Trophic Downgrading of Planet Earth. Science, 333: 301–306. http://www.ncbi.nlm.nih.gov/pubmed/21764740 (Accessed 29 January 2013).

Eyring, V., Cox, P. M., Flato, G. M., Gleckler, P. J., Abramowitz, G., Caldwell, P., Collins, W. D., *et al.* 2019. Taking climate model evaluation to the next level. Nature Climate Change, 9: 102–110. Springer US. http://dx.doi.org/10.1038/s41558-018-0355-y.

Fabry, V. J., Seibel, B. A., Feely, R. A., and Orr, J. C. 2008. Impacts of ocean acidification on marine fauna and ecosystem processes. ICES Journal of Marine Science, 65: 414–432. https://academic.oup.com/icesjms/article/65/3/414/789605.

Fairclough, D. V., Brown, J. I., Carlish, B. J., Crisafulli, B. M., and Keay, I. S. 2014. Breathing life into fisheries stock assessments with citizen science. Scientific Reports, 4.

FAO. 1997. FAO Technical guidelines for responsible fisheries - Fisheries management - 4. Rome, Italy.

FAO. 2020. The State of World Fisheries and Aquaculture 2020. Sustainability in action. Rome. https://doi.org/10.4060/ca9229en.

Feng, Y., Hare, C. E., Leblanc, K., Rose, J. M., Zhang, Y., DiTullio, G. R., Lee, P. A., *et al.* 2009. Effects of increased pCO(2) and temperature on the North Atlantic spring bloom. I. The phytoplankton community and biogeochemical response. MARINE ECOLOGY PROGRESS SERIES, 388: 13–25.

Ferretti, F., Worm, B., Britten, G. L., Heithaus, M. R., and Lotze, H. K. 2010. Patterns and ecosystem consequences of shark declines in the ocean. Ecology letters, 13: 1055–71. http://www.ncbi.nlm.nih.gov/pubmed/20528897 (Accessed 28 January 2013).

Field, C. B., Behrenfeld, M. J., Randerson, J. T., and Falkowski, P. 1998. Primary Production of the Biosphere: Integrating Terrestrial and Oceanic Components. Science, 281: 237–240. http://www.sciencemag.org/cgi/doi/10.1126/science.281.5374.237.

Fisher, J. a D., Frank, K. T., Petrie, B., Leggett, W. C., and Shackell, N. L. 2008. Temporal dynamics within a contemporary latitudinal diversity gradient. ECOLOGY LETTERS, 11: 883–897. WILEY-BLACKWELL, COMMERCE PLACE, 350 MAIN ST, MALDEN 02148, MA USA. http://www.ncbi.nlm.nih.gov/pubmed/18616548 (Accessed 8 October 2014).

Fisheries and Oceans Canada. 2003. 2003-2006 Scotia-Fundy Fisheries Integrated Herring Management Plan, NAFO Subdivisions 4WX, 4Vn and 5Z. Fisheries and Oceans Canada.

Fletcher, W. J. 2006. Frameworks for managing marine resources in Australia through ecosystem approaches: Do they fit together and are they useful? BULLETIN OF MARINE SCIENCE, 78: 691–704.

Foden, W. B., Young, B. E., Akçakaya, H. R., Garcia, R. A., Hoffmann, A. A., Stein, B. A., Thomas, C. D., *et al.* 2019. Climate change vulnerability assessment of species. Wiley Interdisciplinary Reviews: Climate Change, 10: 1–36.

Fourqurean, J. W., Duarte, C. M., Kennedy, H., Marba, N., Holmer, M., Angel Mateo, M., Apostolaki, E. T., *et al.* 2012. Seagrass ecosystems as a globally significant carbon stock. NATURE GEOSCIENCE, 5: 505–509.

Frank, K. T., Shackell, N. L., and Simon, J. E. 2000. An evaluation of the Emerald/Western Bank juvenile haddock closed area. ICES Journal of Marine Science, 57: 1023–1034.

Frank, K. T., Petrie, B., Choi, J. S., and Leggett, W. C. 2005. Trophic Cascades in a Formerly Cod - Dominated Ecosystem. Science, 308: 1621–3.

Frank, K. T., Petrie, B., Shackell, N. L., and Choi, J. S. 2006. Reconciling differences in trophic control in mid-latitude marine ecosystems. Ecology Letters, 9: 1096–1105.

Frank, K. T., Petrie, B., and Shackell, N. L. 2007. The ups and downs of trophic control in continental shelf ecosystems. Trends in Ecology & Evolution, 22: 236–242.

Frank, K. T., Petrie, B., Fisher, J. A. D., and Leggett, W. C. 2011. Transient dynamics of an altered large marine ecosystem. Nature, 477: 86–89. Nature Publishing Group, London, UK. http://www.nature.com/articles/nature10285.

Frank, K. T., Petrie, B., Leggett, W. C., and Boyce, D. G. 2019. Fishingmatters: Age-specific deepening is driven by exploitation. Proceedings of the National Academy of Sciences.

Free, C. M., Thorson, J. T., Pinsky, M. L., Oken, K. L., Wiedenmann, J., and Jensen, O. P. 2019. Impacts of historical warming on marine fisheries production. Science, 363: 979–983.

Frommel, A. Y., Maneja, R., Lowe, D., Malzahn, A. M., Geffen, A. J., Folkvord, A., Piatkowski, U., *et al.* 2012. Severe tissue damage in Atlantic cod larvae under increasing ocean acidification. NATURE CLIMATE CHANGE, 2: 42–46.

Fulton, E., Punt, A., Dichmont, C., Gorton, R., Sporcic, M., Dowling, N., Litle, L., *et al.* 2016. Developing risk equivalent data-rich and data-limited harvest strategies. Fisheries Research, 183: 574–587.

Fulton, E. A., Smith, A. D. ., and Johnson, C. R. 2004. Effects of spatial resolution on the performance and interpretation of marine ecosystem models. Ecological Modelling, 176: 27–42. https://linkinghub.elsevier.com/retrieve/pii/S0304380003005416.

Fulton, E. A., Smith, A. D. M., Smith, D. C., and Johnson, P. 2014. An Integrated Approach Is Needed for Ecosystem Based Fisheries Management: Insights from Ecosystem-Level Management Strategy Evaluation. PLOS ONE, 9.

Fulton, S., López-Sagástegui, C., Weaver, A. H., Fitzmaurice-Cahluni, F., Galindo, C., Melo, F. F. R., Yee, S., *et al.* 2019. Untapped potential of citizen science in Mexican small-scale fisheries. Frontiers in Marine Science, 6.

Gaichas, S., Gamble, R., Fogarty, M., Benoit, H., Essington, T., Fu, C., Koen-Alonso, M., *et al.* 2012. Assembly rules for aggregate-species production models: simulations in support of management strategy evaluation. MARINE ECOLOGY PROGRESS SERIES, 459: 275+.

Garcia, S. M., and Grainger, R. 1997. Fisheries management and sustainability: A new perspective of an old problem? *In* Developing and sustaining world fisheries resources. The state of science and management, pp. 175–236. Ed. by D. A. Hancok, D. C. Smith, A. Grant, and J. . Beumer. CSIRO Publishing, Melbourne.

Garcia, S. M., Zerbi, A., Aliaume, C., Do Chi, T., Lasserre, G., T., D. C., Lasserre, G., *et al.* 2003. The ecosystem approach to fisheries. Issues, terminology, principles, institutional foundations, implementation and outlook. Rome. 71 pp.

Garvis, S. 1988. An adaptive framework for the estimation of population size. 12 pp.

Gattuso, J.-P. J.-P. P., Magnan, A., Billé, R., Cheung, W. W. L. L., Howes, E. L., Joos, F., Allemand, D., *et al.* 2015. Contrasting futures for ocean and society from different anthropogenic CO2 emissions scenarios. SCIENCE, 349: aac4722-1-aac4722-10. http://www.sciencemag.org/cgi/doi/10.1126/science.aac4722.

Gendron, L., Lefaivre, D., and Sainte-Marie, B. 2019. Local egg production and larval losses to advection contribute to interannual and long-term variability of American lobster (Homarus americanus) settlement intensity. CANADIAN JOURNAL OF FISHERIES AND AQUATIC SCIENCES, 76: 350–363. CANADIAN SCIENCE PUBLISHING, NRC RESEARCH PRESS, 65 AURIGA DR, SUITE 203, OTTAWA, ON K2E 7W6, CANADA.

Genner, M. J., Sims, D. W., Wearmouth, V. J., Southall, E. J., Southward, A. J., Henderson, P. A., and Hawkins, S. J. 2004. Regional climatic warming drives long-term community changes of British marine fish. PROCEEDINGS OF THE ROYAL SOCIETY B-BIOLOGICAL SCIENCES, 271: 655–661.

Gilbert, D., Sundby, B., Gobeil, C., Mucci, A., and Tremblay, G. H. 2005. A seventy-two-year record of diminishing deep-water oxygen in the St. Lawrence estuary: The northwest Atlantic connection. LIMNOLOGY AND OCEANOGRAPHY, 50: 1654–1666.

Gill, D. A., Mascia, M. B., Ahmadia, G. N., Glew, L., Lester, S. E., Barnes, M., Craigie, I., *et al.* 2017. Capacity shortfalls hinder the performance of marine protected areas globally. Nature, 543: 665–669. Nature Publishing Group. http://www.nature.com/doifinder/10.1038/nature21708.

Gilly, W. F., Beman, J. M., Litvin, S. Y., and Robison, B. H. 2013. Oceanographic and Biological Effects of Shoaling of the Oxygen Minimum Zone. *In* ANNUAL REVIEW OF MARINE SCIENCE, VOL 5, pp. 393–420. Ed. by Carlson, CA and Giovannoni, SJ. http://www.annualreviews.org/doi/abs/10.1146/annurev-marine-120710-100849%5Cnhttp://www.annualreviews.org/doi/pdf/10.1146/annurev-marine-120710-100849.

Ginger, K. W. K., Vera, C. B. S., Dineshram, R., Dennis, C. K. S., Adela, L. J., Yu, Z., and Thiyagarajan, V. 2013. Larval and Post-Larval Stages of Pacific Oyster (Crassostrea gigas) Are Resistant to Elevated CO2. PLOS ONE, 8.

Glantz, M. H. (Ed). 1992. Climate Variability, Climate Change and Fisheries. Cambridge University Press. 450 pp. https://www.cambridge.org/core/product/identifier/9780511565625/type/book.

Goethel, D. R., Lucey, S. M., Berger, A. M., Gaichas, S. K., Karp, M. A., Lynch, P. D., and Walter, J. F. 2019. Recent advances in management strategy evaluation: Introduction to the special issue "Under pressure: Addressing fisheries challenges with management strategy evaluation". Canadian Journal of Fisheries and Aquatic Sciences, 76: 1689–1696.

Gofman, V. 2010. Community based monitoring handbook: Lessons from the Arctic. CAFF CBMP Report CAFF CBMP Report No.21, August 2010. Akureyri, Iceland. 52 pp.

Gooday, A. J., Bett, B. J., Shires, R., and Lambshead, P. J. D. 1998. Deep-sea benthic foraminiferal species diversity in the NE Atlantic and NW Arabian sea: a synthesis. DEEP-SEA RESEARCH PART II-TOPICAL STUDIES IN OCEANOGRAPHY, 45: 165–201.

Gooday, A. J., Bernhard, J. M., Levin, L. A., and Suhr, S. B. 2000. Foraminifera in the Arabian Sea oxygen minimum zone and other oxygen-deficient settings: taxonomic composition, diversity, and relation to metazoan faunas. DEEP-SEA RESEARCH PART II-TOPICAL STUDIES IN OCEANOGRAPHY, 47: 25–54.

Gooday, A. J. 2003. Benthic foraminifera (protista) as tools in deep-water palaeoceanography: Environmental influences on faunal characteristics. *In* ADVANCES IN MARINE BIOLOGY, VOL 46, pp. 1–90. Ed. by Southwards, AJ and Tyler, PA and Young, CM and Fuiman, LA.

Gooday, A. J., Levin, L. A., da Silva, A. A., Bett, B. J., Cowie, G. L., Dissard, D., Gage, J. D., *et al.* 2009. Faunal responses to oxygen gradients on the Pakistan margin: A comparison of foraminiferans, macrofauna and megafauna. DEEP-SEA RESEARCH PART II-TOPICAL STUDIES IN OCEANOGRAPHY, 56: 488–502.

Gorris, P. 2016. Deconstructing the reality of community-based management of marine resources in a small island context in Indonesia. Frontiers in Marine Science, 3.

Grady, J. M., Maitner, B. S., Winter, A. S., Kaschner, K., Tittensor, D. P., Record, S., Smith, F. A., *et al.* 2019. Metabolic asymmetry and the global diversity of marine predators. SCIENCE, 363: 366+. AMER ASSOC ADVANCEMENT SCIENCE, 1200 NEW YORK AVE, NW, WASHINGTON, DC 20005 USA, NW, WASHINGTON, DC 20005 USA.

Grafton, R. Q., Kompas, T., McLoughlin, R., and Rayns, N. 2007. Benchmarking for fisheries governance. Marine Policy, 31: 470–479.

Grafton, R. Q., and Quentin Grafton, R. 2010. Adaptation to climate change in marine capture fisheries. MARINE POLICY, 34: 606–615. Elsevier.

Greenan, B. J. W., Shackell, N. L., Ferguson, K., Greyson, P., Cogswell, A., Brickman, D., Wang, Z., *et al.* 2019. Climate Change Vulnerability of American Lobster Fishing Communities in Atlantic Canada. Frontiers in Marine Science, 6. Frontiers Media, Lausanne, Switzerland.

Gregg, R. M., Score, A., Pietri, D., and Hansen, L. 2016. The state of climate adaptation in US marine fisheries management. Bainbridge Island, WA, USA. 110 pp. http://www.cakex.org/sites/default/files/documents/EcoAdapt_%0AMarineFisheriesAdaptation_August 2016_1.pdf.

Gregg, W. W., Conkright, M. E., Ginoux, P., O'Reilly, J. E., and Casey, N. W. 2003. Ocean primary production and climate: Global decadal changes. Geophysical Research Letters, 30: 1809. http://www.ncbi.nlm.nih.gov/pubmed/15800621%5Cnhttp://doi.wiley.com/10.1029/2003GL016889.

Griffith, D. M., Veech, J. A., and Marsh, C. J. 2016. cooccur: Probabilistic Species Co-Occurrence Analysis in R. Journal of Statistical Software, 69: 1–17.

Gruber, N. 2011. Warming up, turning sour, losing breath: ocean biogeochemistry under global change. PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A-MATHEMATICAL PHYSICAL AND ENGINEERING SCIENCES, 369: 1980–1996.

Guinotte, J. M., Orr, J., Cairns, S., Freiwald, A., Morgan, L., and George, R. 2006. Will human-induced changes in seawater chemistry alter the distribution of deep-sea scleractinian corals? FRONTIERS IN ECOLOGY AND THE ENVIRONMENT, 4: 141–146.

Gunderson, L., Peterson, G., and Holling, C. S. 2008. Practicing adaptive management in complex social-ecological systems. *In* Complexity Theory for a Sustainable Future, pp. 223–245. Ed. by J. Norberg and G. S. Cumming. Columbia University Press, New York.

Hall-Spencer, J. M., Rodolfo-Metalpa, R., Martin, S., Ransome, E., Fine, M., Turner, S. M., Rowley, S. J., *et al.* 2008. Volcanic carbon dioxide vents show ecosystem effects of ocean acidification. NATURE, 454: 96–99.

Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, K. V, Micheli, F., D'Agrosa, C., Bruno, J. F., *et al.* 2008. A global map of human impact on marine ecosystems. Science, 319: 948–952. http://www.sciencemag.org/content/319/5865/948.short (Accessed 6 November 2013).

Hamilton, L. C., and Butler, M. J. 2001. Outport adaptations: social indicators through Newfoundland's cod crisit. Human Ecology Review, 8: 1–11.

Hamilton, L. C. C., Haedrich, R. L. L., and Duncan, C. M. M. 2004. Above and below the water: social/ecological transformation in the northwest Newfoundland. Population and Environment, 25: 195–215.

Hare, J. A., Morrison, W. E., Nelson, M. W., Stachura, M. M., Teeters, E. J., Griffis, R. B., Alexander, M. A., *et al.* 2016. A vulnerability assessment of fish and invertebrates to climate change on the northeast u.s. continental shelf. PLoS ONE, 11: 1–30. http://dx.doi.org/10.1371/journal.pone.0146756.

Hare, S. R., and Mantua, N. J. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography, 47: 103–145. https://linkinghub.elsevier.com/retrieve/pii/S0079661100000331.

Harvell, C. D., Mitchell, C. E., Ward, J. R., Altizer, S., Dobson, A. P., Ostfeld, R. S., and Samuel, M. D. 2002. Ecology - Climate warming and disease risks for terrestrial and marine biota. SCIENCE, 296: 2158–2162. http://www.sciencemag.org/cgi/content/abstract/296/5576/2158.

Harvell, C. D., Montecino-Latorre, D., Caldwell, J. M., Burt, J. M., Bosley, K., Keller, A., Heron, S. F., *et al.* 2019. Disease epidemic and a marine heat wave are associated with the continental-scale collapse of a pivotal predator (Pycnopodia helianthoides). SCIENCE ADVANCES, 5.

Haward, M. 2000. Outstanding issues with regimes for oceans governance. *In* Oceans Governance and Maritime Strategy, pp. 121–128. Ed. by D. Wilson and R. Sherwood. Allen & Unwin, Sydney, Australia.

Hazen, E. L., Scales, K. L., Maxwell, S. M., Briscoe, D. K., Welch, H., Bograd, S. J., Bailey, H., *et al.* 2018. A dynamic ocean management tool to reduce bycatch and support sustainable fisheries. Science Advances, 4: 1–8.

Heithaus, M. R., Wirsing, A. J., and Dill, L. M. 2012. The ecological importance of intact top-predator populations: a synthesis of 15 years of research in a seagrass ecosystem. MARINE AND FRESHWATER RESEARCH, 63: 1039–1050.

Henson, S. A., Beaulieu, C., Ilyina, T., John, J. G., Long, M., Séférian, R., Tjiputra, J., *et al.* 2017. Rapid emergence of climate change in environmental drivers of marine ecosystems. Nature Communications, 8: 1–9.

Henson, S. a. A., Sarmiento, J. L. L., Dunne, J. P. P., Bopp, L., Lima, I., Doney, S. C. C., John, J., *et al.* 2010. Detection of anthropogenic climate change in satellite records of ocean chlorophyll and productivity. BIOGEOSCIENCES, 7: 621–640.

Hicks, C. C., Cohen, P. J., Graham, N. A. J., Nash, K. L., Allison, E. H., Lima, C. D., Mills, D. J., *et al.* 2019. Harnessing global fisheries to tackle micronutrient deficiencies. Science, 574: 95–98.

Hilborn, R., and Walters, C. J. 1992. Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty. Chapman and Hall, New York.

Hilborn, R., Quinn, T. P., Schindler, D. E., and Rogers, D. E. 2003. Biocomplexity and fisheries sustainability. Proc. Natl. Acad. Sci. USA, 100: 6564–6568. http://www.pnas.org/cgi/content/abstract/100/11/6564.

Hilborn, R., Amoroso, R. O., Anderson, C. M., Baum, J. K., Branch, T. A., Costello, C., De Moor, C. L., *et al.* 2020. Effective fisheries management instrumental in improving fish stock status. Proceedings of the National Academy of Sciences of the United States of America, 117: 2218–2224.

Hill, J. K., Griffiths, H. M., and Thomas, C. D. 2011. Climate Change and Evolutionary Adaptations at Species' Range Margins. *In* ANNUAL REVIEW OF ENTOMOLOGY, VOL 56, pp. 143–159. Ed. by Berenbaum, MR and Carde, RT and Robinson, GE.

Hinder, S. L., Hays, G. C., Edwards, M., Roberts, E. C., Walne, A. W., and Gravenor, M. B. 2012. Changes in marine dinoflagellate and diatom abundance under climate change. Nature Climate Change, 2: 271–275. Nature Publishing Group. http://www.nature.com/doifinder/10.1038/nclimate1388.

Hobday, A. J., and Hartmann, K. 2006. Near real-time spatial management based on habitat predictions for a longline bycatch species. FISHERIES MANAGEMENT AND ECOLOGY, 13: 365–380.

Hobday, A. J. 2010. Ensemble analysis of the future distribution of large pelagic fishes off Australia. PROGRESS IN OCEANOGRAPHY, 86: 291–301.

Hobday, A. J., Hartog, J. R., Timmiss, T., and Fielding, J. 2010. Dynamic spatial zoning to manage southern bluefin tuna (Thunnus maccoyii) capture in a multi-species longline fishery. FISHERIES OCEANOGRAPHY, 19: 243–253.

Hobday, A. J., Smith, A. D. M., Stobutzki, I. C., Bulman, C., Daley, R., Dambacher, J. M., Deng, R. A., *et al.* 2011. Ecological risk assessment for the effects of fishing. FISHERIES RESEARCH, 108: 372–384.

Hobday, A. J., and Hartog, J. R. 2014. Derived ocean features for dynamic ocean management. Oceanography, 27: 134–145.

Hobday, A. J., Spillman, C. M., Eveson, P. J., and Hartog, J. R. 2016. Seasonal forecasting for decision support in marine fisheries and aquaculture. Fisheries Oceanography, 25: 45–56.

Hoegh-Guldberg, O., Mumby, P. J., Hooten, A. J., Steneck, R. S., Greenfield, P., Gomez, E., Harvell, C. D., *et al.* 2007. Coral reefs under rapid climate change and ocean acidification. SCIENCE, 318: 1737–1742.

Hoegh-Guldberg, O., and Bruno, J. F. 2010. The Impact of Climate Change on the World's Marine Ecosystems. SCIENCE, 328: 1523–1528.

Hofmann, M., and Schellnhuber, H.-J. 2009. Oceanic acidification affects marine carbon pump and triggers extended marine oxygen holes. PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA, 106: 3017–3022.

Holbrook, S. J., Schmitt, R. J., and Stephens, J. S. 1997. Changes in an assemblage of temperate reef fishes associated with a climate shift. ECOLOGICAL APPLICATIONS, 7: 1299–1310.

Hollowed, A. B., Bond, N. A., Wilderbuer, T. K., Stockhausen, W. T., A'Mar, Z. T., Beamish, R. J., Overland, J. E., *et al.* 2009. A framework for modelling fish and shellfish responses to future climate change. ICES Journal of Marine Science, 66: 1584–1594.

Hollowed, A. B., Barange, M., Beamish, R. J., Brander, K., Cochrane, K., Drinkwater, K., Foreman, M. G. G., *et al.* 2013. Projected impacts of climate change on marine fish and fisheries. ICES JOURNAL OF MARINE SCIENCE, 70: 1023–1037.

Holsman, K. K., Ianelli, J. N., and Aydin, K. 2017. 2017 Multi-species Stock Assessment for walleye pollock, Pacificcod, and arrowtooth flounder in the Eastern Bering Sea.

Holsman, K. K., Hazen, E. L., Haynie, A., Gourguet, S., Hollowed, A., Bograd, S. J., Samhouri, J. F., *et al.* 2019a. Towards climate resiliency in fisheries management. ICES Journal of Marine Science, 76: 1368–1378.

Holsman, K. K., Ianelli, J. N., Aydin, K., and Spies, I. 2019b. 2019 Climate-Enhanced Multi-Species Stock Assessment for Walleye Pollock, Pacific Cod, and Arrowtooth Flounder in the Eastern Bering Sea. *In* NPFMC Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Bering Sea/Aleutian Islands Regions, p. 43.

Holsman, K. K., Haynie, A. C., Hollowed, A. B., Reum, J. C. P., Aydin, K., Hermann, A. J., Cheng, W., *et al.* 2020. Ecosystem-based fisheries management forestalls climate-driven collapse. Nature Communications, 11: 4579. http://www.nature.com/articles/s41467-020-18300-3.

Howard, J., Babij, E., Griffis, R., Helmuth, B., Himes-Cornell, A., Niemier, P., Orbach, M., *et al.* 2013. OCEANS AND MARINE RESOURCES IN A CHANGING CLIMATE. *In* OCEANOGRAPHY AND MARINE BIOLOGY: AN ANNUAL REVIEW, VOL 51, pp. 71–192. Ed. by Hughes, RN and Hughes, DJ. CRC PRESS-TAYLOR & FRANCIS GROUP, 6000 BROKEN SOUND PARKWAY NW, STE 300, BOCA RATON, FL 33487-2742 USA.

Howell, D., and Begley, J. 2004. An overview of Gadget, the Globally applicable Area-Disaggregated General Ecosystem Toolbox. ICES.

Hsieh, C., Reiss, C. S., Hunter, J. R., Beddington, J. R., May, R. M., and Sugihara, G. 2006. Fishing elevates variability in the abundance of exploited species. NATURE, 443: 859–862.

Hughes, T. P., Kerry, J. T., Alvarez-Noriega, M., Alvarez-Romero, J. G., Anderson, K. D., Baird, A. H., Babcock, R. C., *et al.* 2017. Global warming and recurrent mass bleaching of corals. NATURE, 543: 373+.

Hunt, G., and Roy, K. 2006. Climate change, body size evolution, and Cope's Rule in deep-sea ostracodes. PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA, 103: 1347–1352.

Hurrell, J. W., Visbeck, M., Busalacchi, A., Clarke, R. A., Delworth, T. L., Dickson, R. R., Johns, W. E., *et al.* 2006. Atlantic climate variability and predictability: A CLIVAR perspective. JOURNAL OF CLIMATE, 19: 5100–5121.

Hutchings, J. A., and Myers, R. A. 1993. Effect of age on the seasonality of maturation and spawning of Atlantic cod, Gadus morhua, in the Northwest Atlantic. Canadian Journal of Fisheries and Aquatic Science, 50: 2468–2474.

Hutchings, J. A., Minto, C., Ricard, D., Baum, J. K., and Jensen, O. P. 2010. Trends in the abundance of marine fishes. Canadian Journal of Fisheries and Aquatic Sciences, 67: 1205–1210.

Hutchings, J. A., and Rangeley, R. W. 2011. Correlates of recovery for Canadian Atlantic cod (Gadus morhua) 1. Canadian Journal of Zoology, 89: 386–400.

Hutchings, J. A., Cote, I. M., Dodson, J. J., Fleming, I. A., Jennings, S., Mantua, N. J., Peterman, R. M., *et al.* 2012. Climate change, fisheries, and aquaculture: trends and consequences for Canadian marine biodiversity. Environmental Reviews, 20: 220–311.

Ikerd, J. E. 1990. Agriculture's search for sustainability and profitability. Journal of soil and water conservation, 45: 18–23.

Iles, T. D., and Sinclair, M. 1982. Atlantic Herring: Stock Discreteness and Abundance. Science, 215: 627–633. http://www.sciencemag.org/cgi/doi/10.1126/science.215.4533.627.

IPBES. 2019. Chapter 4: Plausible futures of nature, its contributions to people and their good quality of life. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES Global Assessment on Biodiversity and Ecosystem Services.

IPCC. 2007. Climate change 2007: synthesis report. Summary for policymakers. Fourth Assessment Report. Intergovernmental Panel on Climate Change, Gland, Switzerland.

IPCC, Field, C. B., Barros, V., Stocker, T. F., Qin, D., Dokken, D. J., Ebi, K. L., *et al.* 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation - SREX Summary for Policymakers. Cambridge University Press, Cambridge, U.K., New York, USA. 1–19 pp.

IPCC. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland. 151 pp.

IPCC. 2019. Chapter 5: Changing ocean, marine ecosystems, and dependent communities. Intergovernmental Panel of Climate Change. IPCC Special Report for the Ocean and Cryosphere in the Changing Climate.

JACOBSON, L. D., and MACCALL, A. D. 1995. STOCK-RECRUITMENT MODELS FOR PACIFIC SARDINE (SARDINOPS-SAGAX). CANADIAN JOURNAL OF FISHERIES AND AQUATIC SCIENCES, 52: 566–577.

Jennings, S., Pinnegar, J. K., Polunin, N. V. C., and Warr, K. J. 2001. Impacts of trawling disturbance on the trophic structure of benthic invertebrate communities. Marine Ecology Progress Series, 213: 127–142.

Jennings, S., and Collingridge, K. 2015. Predicting consumer biomass, size-structure, production, catch potential, responses to fishing and associated uncertainties in the world's marine ecosystems. PLoS ONE, 10: 1–28.

Johnson, K. H., Vogt, K. A., Clark, H. J., Schmitz, O. J., and Vogt, D. J. 1996. Biodiversity and the productivity and stability of ecosystems. TREE, 11: 373–377.

Jones, M. C., Dye, S. R., Pinnegar, J. K., Warren, R., and Cheung, W. W. L. 2012. Modelling commercial fish distributions: Prediction and assessment using different approaches. Ecological Modelling, 225: 133–145. Elsevier B.V. http://dx.doi.org/10.1016/j.ecolmodel.2011.11.003.

Jones, P. J. S., and Burgess, J. 2005. Building partnership capacity for the collaborative management of marine protected areas in the UK: A preliminary analysis. Journal of Environmental Management, 77: 227–243.

Jurado-Molina, J., Livingston, P. A., and Ianelli, J. N. 2005. Incorporating predation interactions in a statistical catch-at-age model for a predator-prey system in the eastern Bering Sea. Canadian Journal of Fisheries and Aquatic Sciences, 62: 1865–1873. http://www.nrcresearchpress.com/doi/10.1139/f05-110.

Kaariainen, J. I., and Bett, B. J. 2006. Evidence for benthic body size miniaturization in the deep sea. JOURNAL OF THE MARINE BIOLOGICAL ASSOCIATION OF THE UNITED KINGDOM, 86: 1339–1345.

Kasperski, S., and Holland, D. S. 2013. Income diversification and risk for fishermen. PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA, 110: 2076–2081.

Keith, D. A., Martin, T. G., McDonald-Madden, E., and Walters, C. 2011. Uncertainty and adaptive management for biodiversity conservation. Biological Conservation, 144: 1175–1178.

Kelmo, F., and Hallock, P. 2013. Responses of foraminiferal assemblages to ENSO climate patterns on bank reefs of northern Bahia, Brazil: A 17-year record. ECOLOGICAL INDICATORS, 30: 148–157.

Kennedy, V. S. 1990. Anticipated Effects of Climate Change on Estuarine and Coastal Fisheries. Fisheries, 15: 16–24. http://doi.wiley.com/10.1577/1548-8446(1990)015%3C0016:AEOCCO%3E2.0.CO;2.

Kiceniuk, J. W., and Colbourne, E. 1997. Relating oxygen levels in the Newfoundland offshore waters to the physiology of Atlantic cod. Canadian Journal of Fisheries and Aquatic Sciences, 54: 81–87.

King, J. R., McFarlane, G. A., and Punt, A. E. 2015. Shifts in fisheries management: adapting to regime shifts. PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B-BIOLOGICAL SCIENCES, 370.

KINZEY, D., and PUNT, A. E. 2008. MULTISPECIES AND SINGLE-SPECIES MODELS OF FISH POPULATION DYNAMICS: COMPARING PARAMETER ESTIMATES. Natural Resource Modeling, 22: 67–104. http://doi.wiley.com/10.1111/j.1939-7445.2008.00030.x.

Knowlton, N., and Jackson, J. B. C. 2008. Shifting baselines, local impacts, and global change on coral reefs. PLoS biology, 6: e54. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=2253644&tool=pmcentrez&rendertype=abstract (Accessed 28 January 2013).

Koch, M., Bowes, G., Ross, C., and Zhang, X.-H. 2013. Climate change and ocean acidification effects on seagrasses and marine macroalgae. GLOBAL CHANGE BIOLOGY, 19: 103–132.

Koeller, P., Fuentes-Yaco, C., Platt, T., Sathyendranath, S., Richards, a, Ouellet, P., Orr, D., *et al.* 2009. Basin-scale coherence in phenology of shrimps and phytoplankton in the North Atlantic Ocean. Science, 324: 791–3. http://www.ncbi.nlm.nih.gov/pubmed/19423827 (Accessed 29 January 2013).

Koen-Alonso, M., Pepin, P., Fogarty, M. J., Kenny, A., and Kenchington, E. 2019. The Northwest Atlantic Fisheries Organization Roadmap for the development and implementation of an Ecosystem Approach to Fisheries: structure, state of development, and challenges. Marine Policy, 100: 342–352. Elsevier Ltd.

Kofinas, G. P. 2009. Adaptive Co-management in Social-Ecological Governance. *In* Principles of Ecosystem Stewardship: Resilience-Based Natural Resource Management in a Changing World, pp. 77–101. Ed. by F. S. Chapin, G. P. Kofinas, and C. Folke. Springer, New York.

Kopke, K., and O'Mahoney, C. 2011. Preparedness of key coastal and marine sectors in Ireland to adapt to climate change. Marine Policy, 35: 800–809.

Koslow, J. A., Goericke, R., Lara-Lopez, A., and Watson, W. 2011. Impact of declining intermediate-water oxygen on deepwater fishes in the California Current. MARINE ECOLOGY PROGRESS SERIES, 436: 207–218.

Koubrak, O., VanderZwaag, D. L., and Worm, B. 2020. Saving the North Atlantic right whale in a changing ocean: Gauging scientific and law and policy responses. Ocean and Coastal Management: 1–16.

Kroeker, K. J., Kordas, R. L., Crim, R. N., and Singh, G. G. 2010. Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. ECOLOGY LETTERS, 13: 1419–1434.

Kuhnlein, H. V., and Receveur, O. 2007. Local cultural animal food contributes high levels of nutrients for Arctic Canadian Indigenous adults and children. Journal of Nutrition, 137: 1110–4.

Kurihara, H., Shimode, S., and Shirayama, Y. 2004. Sub-lethal effects of elevated concentration of CO2 on planktonic copepods and sea urchins. JOURNAL OF OCEANOGRAPHY, 60: 743–750.

Kuroyanagi, A., da Rocha, R. E., Bijma, J., Spero, H. J., Russell, A. D., Eggins, S. M., and Kawahata, H. 2013. Effect of dissolved oxygen concentration on planktonic foraminifera through laboratory culture experiments and implications for oceanic anoxic events. MARINE MICROPALEONTOLOGY, 101: 28–32.

Kwok, R., and Rothrock, D. A. 2009. Decline in Arctic sea ice thickness from submarine and ICESat records: 1958-2008. Geophysical Research Letters, 36: L15501.

Laurent, A., Fennel, K., and Kuhn, A. (n.d.). An observation-based evaluation and ranking of historical Earth System Model simulations for regional downscaling in the northwest North Atlantic Ocean. Biogeosciences Discussions.

Lavoie, D., Lambert, N., and Gilbert, D. 2019. Projections of Future Trends in Biogeochemical Conditions in the Northwest Atlantic Using CMIP5 Earth System Models. Atmosphere - Ocean, 57: 18–40.

Lawler, J. J., Tear, T. H., Pyke, C., Shaw, R. M., Gonzalez, P., Kareiva, P., Hansen, L., *et al.* 2010. Resource management in a changing and uncertain climate. Frontiers in Ecology and the Environment, 8: 35–43.

Lawn, J., and Harvey, D. 2003. Nutrition and food security in Kugaaruk, Nunavut: baseline survey for the food mail pilot project. Ottawa: Department of Indian Affairs and Northern Development.

Le Bris, A., Pershing, A. J., Hernandez, C. M., Mills, K. E., and Sherwood, G. D. 2015. Modelling the effects of variation in reproductive traits on fish population resilience. ICES JOURNAL OF MARINE SCIENCE, 72: 2590–2599.

Le Bris, A., Mills, K. E., Wahle, R. A., Chen, Y., Alexander, M. A., Allyn, A. J., Schuetz, J. G., *et al.* 2018. Climate vulnerability and resilience in the most valuable North American fishery. Proceedings of the National Academy of Sciences of the United States of America, 115: 1831–1836.

Lefcheck, J. S., Byrnes, J. E. K., Isbell, F., Gamfeldt, L., Griffin, J. N., Eisenhauer, N., Hensel, M. J. S., *et al.* 2015. Biodiversity enhances ecosystem multifunctionality across trophic levels and habitats. Nature Communications, 6: 6936. Nature Publishing Group. http://dx.doi.org/10.1038/ncomms7936%5Cnhttp://www.nature.com/doifinder/10.1038/ncomms7936.

Lester, S. E., McLeod, K. L., Tallis, H., Ruckelshaus, M., Halpern, B. S., Levin, P. S., Chavez, F. P., *et al.* 2010. Science in support of ecosystem-based management for the US West Coast and beyond. Biological Conservation, 143: 576–587.

Levin, L. A. 2003. Oxygen minimum zone benthos: Adaptation and community response to hypoxia. *In* OCEANOGRAPHY AND MARINE BIOLOGY, VOL 41, pp. 1–45. Ed. by Gibson, RN and Atkinson, RJA.

Lewandowska, A. M., Boyce, D. D. G. D., Hofmann, M., Matthiessen, B., Sommer, U., and Worm, B. 2014. Effects of sea surface warming on marine plankton. Ecology Letters, 17: 614–623. http://www.ncbi.nlm.nih.gov/pubmed/24575918 (Accessed 2 March 2014).

Lewison, R. L., Hobday, A. J., Maxwell, S., Hazen, E., Hartog, J. R., Dunn, D. C., Briscoe, D., *et al.* 2015. Dynamic Ocean Management: Identifying the Critical Ingredients of Dynamic Approaches to Ocean Resource Management. Bioscience, 65: 486–498.

Li, W. K. W., McLaughlin, F. a, Lovejoy, C., and Carmack, E. C. 2009. Smallest algae thrive as the Arctic Ocean freshens. Science (New York, N.Y.), 326: 539. http://www.ncbi.nlm.nih.gov/pubmed/19900890 (Accessed 29 January 2013).

Lindegren, M., Checkley, D. M., Rouyer, T., MacCall, A. D., and Stenseth, N. C. 2013. Climate, fishing, and fluctuations of sardine and anchovy in the California Current. Proceedings of the National Academy of Sciences, 110: 13672–13677. http://www.pnas.org/cgi/doi/10.1073/pnas.1305733110.

Lindegren, M., and Brander, K. 2018. Adapting Fisheries and Their Management To Climate Change: A Review of Concepts, Tools, Frameworks, and Current Progress Toward Implementation. Reviews in Fisheries Science and Aquaculture, 26: 400–415. Taylor & Francis.

Lindstrøm, U., Smout, S., Howell, D., and Bogstad, B. 2009. Modelling multi-species interactions in the Barents Sea ecosystem with special emphasis on minke whales and their interactions with cod, herring and capelin. Deep Sea Research Part II: Topical Studies in Oceanography, 56: 2068–2079. https://linkinghub.elsevier.com/retrieve/pii/S0967064508003950.

Link, J., Overholtz, W., O'Reilly, J., Green, J., Dow, D., Palka, D., Legault, C., *et al.* 2008. The Northeast US continental shelf Energy Modeling and Analysis exercise (EMAX): Ecological network model development and basic ecosystem metrics. JOURNAL OF MARINE SYSTEMS, 74: 453–474.

Link, J. S., Griffis, R., and Busch, S. (Eds). 2015. NOAA Fisheries Climate Science Strategy. NOAA Technical Memorandum NMFS-F/SPO-155. 70 pp.

Little, A. S., Needle, C. L., Hilborn, R., Holland, D. S., and Marshall, C. T. 2015. Real-time spatial management approaches to reduce bycatch and discards: experiences from Europe and the United States. FISH AND FISHERIES, 16: 576–602.

Loder, J. W., Han, G., Galbraith, P. S., Chassé, J., and Editors, A. V. D. B. 2013. Aspects of climate change in the Northwest Atlantic off Canada. Canadian Manuscript Report of Fisheries and Aqautic Sciences, 3045: 190.

Loder, J. W., and van der Baaren, A. 2013. Climate change projections for the Northwest Atlantic from six CMIP5 Earth System Models. Can. Tech. Rep. Hydrogr. Ocean. Sci., 286: 112.

Loder, J. W., van der Baaren, A., and Yashayaev, I. 2015. Climate Comparisons and Change Projections for the Northwest Atlantic from Six CMIP5 Models. Atmosphere - Ocean, 53: 529–555.

Longhurst, A. 2007. Ecological geography of the sea. Elsevier Inc., Burlington, MA. 542 pp.

Lotze, H. K., and Milewski, I. 2004. Two centuries of multiple human impacts and successive changes in a North Atlantic food web. Ecological Applicaitons, 14: 1428–1447.

Lotze, H. K., Tittensor, D. P., Bryndum-Buchholz, A., Eddy, T. D., Cheung, W. W., Galbraith, E. D., Barange, M., *et al.* 2019. Ensemble projections of global ocean animal biomass with climate change. Proceedings of the National Academy of Sciences: 1–6. https://www.biorxiv.org/content/early/2018/11/09/467175.

Lowitt, K. 2013. Examining fisheries contributions to community food security: Findings from a household seafood consumption survey on the west coast of Newfoundland. Journal of Hunger & Environment, 8: 221–241.

Lynn, K., Daigle, J., Hoffman, J., Lake, F., Michelle, N., Ranco, D., Viles, C., *et al.* 2013. The impacts of climate change on tribal traditional foods. CLIMATIC CHANGE, 120: 545–556.

MacKenzie, B. R., Payne, M. R., Boje, J., Hoyer, J. L., Siegstad, H., H??yer, J. L., and Siegstad, H. 2014. A cascade of warming impacts brings bluefin tuna to Greenland waters. GLOBAL CHANGE BIOLOGY, 20: 2484–2491.

Manno, C., Morata, N., and Bellerby, R. 2012. Effect of ocean acidification and temperature increase on the planktonic foraminifer Neogloboquadrina pachyderma (sinistral). POLAR BIOLOGY, 35: 1311–1319.

Marshall, A. G., Hudson, D., Wheeler, M. C., Hendon, H. H., and Alves, O. 2012. Simulation and prediction of the Southern Annular Mode and its influence on Australian intra-seasonal climate in POAMA. CLIMATE DYNAMICS, 38: 2483–2502.

Mather, C. 2013. From cod to shellfish and back again? The new resource geography and Newfoundland's fish economy. Applied Geography, 45: 402–409.

Maury, O. 2010. An overview of APECOSM, a spatialized mass balanced 'Apex Predators ECOSystem Model' to study physiologically structured tuna population dynamics in their ecosystem. Progress in Oceanography, 84: 113–117. Elsevier Ltd.

Maxwell, S. M., Hazen, E. L., Lewison, R. L., Dunn, D. C., Bailey, H., Bograd, S. J., Briscoe, D. K., *et al.* 2015. Dynamic ocean management: Defining and conceptualizing real-time management of the ocean. Marine Policy, 58: 42–50.

Maynard, J. A., Johnson, J. E., Marshall, P. A., Eakin, C. M., Goby, G., Schuttenberg, H., and Spillman, C. M. 2009. A Strategic Framework for Responding to Coral Bleaching Events in a Changing Climate. ENVIRONMENTAL MANAGEMENT, 44: 1–11.

McCarty, J. P. 2001. Ecological consequences of recent climate change. CONSERVATION BIOLOGY, 15: 320–331.

McClain, C. R., Allen, A. P., Tittensor, D. P., and Rex, M. a. 2012. Energetics of life on the deep seafloor. Proceedings of the National Academy of Sciences, 109: 15366–15371. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3458337&tool=pmcentrez&rendertype=abstract.

McClatchie, S., Hendy, I. L., Thompson, A. R., and Watson, W. 2017. Collapse and recovery of forage fish populations prior to commercial exploitation. Geophysical Research Letters, 44: 1877–1885.

McClenachan, L., Scyphers, S., and Grabowski, J. H. 2020. Views from the dock: Warming waters, adaptation, and the future of Maine's lobster fishery. Ambio, 49: 144–155. http://link.springer.com/10.1007/s13280-019-01156-3.

McDonald, J., and Styles, M. C. 2014. Legal Strategies for Adaptive Management under Climate Change. Journal of Environmental Law, 26: 25–53.

McIlgorm, A., Hanna, S., Knapp, G., Le Floc'H, P., Millerd, F., and Pan, M. 2010. How will climate change alter fishery governance? Insights from seven international case studies. MARINE POLICY, 34: 170–177.

McKenzie, R. A., and Skud, B. E. 1958. Herring Migrations in the Passarnaguoddy Regionl. Journal of the Fisheries Research Board of Canada, 15: 1329–1343.

McKenzie, R. A., and Tibbo, S. N. 1960. Herring fishery in southern New Brunswick. Journal of the Fisheries Research Board of Cananda, 17: 133–168.

Meehl, G. A., and Tebaldi, C. 2004. More intense, more frequent, and longer lasting heat waves in the 21st century. SCIENCE, 305: 994–997.

Melnychuk, M. C., Banobi, J. A., and Hilborn, R. 2014. The adaptive capacity of fishery management systems for confronting climate change impacts on marine populations. Reviews in Fish Biology and Fisheries, 24: 561–575.

Melnychuk, M. C., Essington, T. E., Branch, T. A., Heppell, S. S., Jensen, O. P., Link, J. S., Martell, S. J. D., *et al.* 2016. Which design elements of individual quota fisheries help to achieve management objectives? Fish and Fisheries, 17: 126–142.

Melvin, A. M., Larsen, P., Boehlert, B., Neumann, J. E., Chinowski, P., Espinet, X., Martinich, J., *et al.* 2016. Climate change damages to Alaska public infrastructure and the economics of proactive adaptation. Proceedings of the National Academy of Sciences of the United States of America, 114: E122–E131.

Merino, G., Arrizabalaga, H., Arregui, I., Santiago, J., Murua, H., Urtizberea, A., Andonegi, E., *et al.* 2019. Adaptation of North Atlantic Albacore Fishery to Climate Change: Yet Another Potential Benefit of Harvest Control Rules. Frontiers in Marine Science, 6: 1–14.

Michaelidis, B., Ouzounis, C., Paleras, A., and Portner, H. O. 2005. Effects of long-term moderate hypercapnia on acid-base balance and growth rate in marine mussels Mytilus galloprovincialis. MARINE ECOLOGY PROGRESS SERIES, 293: 109–118.

Minto, C., and Worm, B. 2012. Interactions between small pelagic fish and young cod across the North Atlantic. Ecology, 93: 2139–2154.

Mishra, A. K., El-Osta, H. S., Morehard, M., Johnson, J., and Hopkins, J. 2002. Income, Wealth, and the Economic Well-Being of Farm Households. Washington, D.C. 77 pp.

Moffitt, E. A., Punt, A. E., Holsman, K., Aydin, K. Y., Ianelli, J. N., and Ortiz, I. 2016. Moving towards ecosystem-based fisheries management: Options for parameterizing multi-species biological reference points. Deep Sea Research Part II: Topical Studies in Oceanography, 134: 350–359. https://linkinghub.elsevier.com/retrieve/pii/S0967064515002763.

Molnár, P. K., Bitz, C. M., Holland, M. M., Kay, J. E., Penk, S. R., and Amstrup, S. C. 2020. Fasting season length sets temporal limits for global polar bear persistence. Nature Climate Change. https://doi.org/10.1038/s41558-020-0818-9.

Mora, C., and Ospina, A. F. 2001. Tolerance to high temperatures and potential impact of sea warming on reef fishes of Gorgona Island (tropical eastern Pacific). MARINE BIOLOGY, 139: 765–769.

Mora, C., and Ospina, A. F. 2002. Experimental effect of cold, La Nina temperatures on the survival of reef fishes from Gorgona Island (eastern Pacific Ocean). MARINE BIOLOGY, 141: 789–793.

Mora, C., and Robertson, D. R. 2005. Causes of latitudinal gradients in species richness: A test with fishes of the Tropical Eastern Pacific. ECOLOGY, 86: 1771–1782.

Mora, C. 2008. A clear human footprint in the coral reefs of the Caribbean. PROCEEDINGS OF THE ROYAL SOCIETY B-BIOLOGICAL SCIENCES, 275: 767–773.

Mora, C. 2009. Degradation of Caribbean coral reefs: focusing on proximal rather than ultimate drivers. Reply to Rogers. PROCEEDINGS OF THE ROYAL SOCIETY B-BIOLOGICAL SCIENCES, 276: 199–200.

Mora, C., Myers, R. A., Coll, M., Libralato, S., Pitcher, T. J., Sumaila, R. U., Zeller, D., *et al.* 2009. Management Effectiveness of the World's Marine Fisheries. PLoS Biology, 7: e1000131. https://dx.plos.org/10.1371/journal.pbio.1000131.

Mora, C., Aburto-Oropeza, O., Ayala Bocos, A., Ayotte, P. M., Banks, S., Bauman, A. G., Beger, M., *et al.* 2011. Global Human Footprint on the Linkage between Biodiversity and Ecosystem Functioning in Reef Fishes. PLOS BIOLOGY, 9: e1000606. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3071368&tool=pmcentrez&rendertype=abstract (Accessed 28 January 2013).

Mora, C., Wei, C.-L., Rollo, A., Amaro, T., Baco, A. R., Billett, D., Bopp, L., *et al.* 2013a. Biotic and human vulnerability to projected changes in ocean biogeochemistry over the 21st century. PLoS biology, 11: 1–14. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3797030&tool=pmcentrez&rendertype=abstract (Accessed 29 May 2014).

Mora, C., Frazier, A. G., Longman, R. J., Dacks, R. S., Walton, M. M., Tong, E. J., Sanchez, J. J., *et al.* 2013b. The projected timing of climate departure from recent variability. NATURE, 502: 183+. Nature Publishing Group. http://www.ncbi.nlm.nih.gov/pubmed/24108050 (Accessed 6 November 2013).

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

Morrison, W. E., Nelson, M. W., Griffis, R. B., and Hare, J. A. 2016. Methodology for Assessing the Vulnerability of Marine and Anadromous Fish Stocks in a Changing Climate. Fisheries, 41: 407–409.

Myers, R. A., and Worm, B. 2003. Rapid worldwide depletion of predatory fish communities. Nature, 423: 280–3. http://www.ncbi.nlm.nih.gov/pubmed/12748640.

Myers, R. A., and Worm, B. 2005. Extinction, survival, or recovery of large predatory fishes. Phil. Trans. R. Soc. Lond. B, 360: 13–20.

Narayanaswamy, B. E., Renaud, P. E., Duineveld, G. C. A., Berge, J., Lavaleye, M. S. S., Reiss, H., and Brattegard, T. 2010. Biodiversity Trends along the Western European Margin. PLOS ONE, 5.

Neira, S., and Arancibia, H. 2013. Food web and fish stock changes in central Chile: comparing the roles of jumbo squid (Dosidicus gigas) predation, the environment, and fisheries. DEEP-SEA RESEARCH PART II-TOPICAL STUDIES IN OCEANOGRAPHY, 95: 103–112.

Nesis, K. N. 1997. Gonatid squids in the subarctic North Pacific: Ecology, biogeography, niche diversity and role in the ecosystem. *In* ADVANCES IN MARINE BIOLOGY, VOL 32: THE BIOGEOGRAPHY OF THE OCEANS, pp. 243–324. Ed. by Blaxter, JHS and Southward, AJ.

Neubauer, P., Jensen, O. P., Hutchings, J. a, and Baum, J. K. 2013. Resilience and Recovery of Overexploited Marine Populations. Science, 340: 347–349. https://www.sciencemag.org/lookup/doi/10.1126/science.1230441 (Accessed 22 May 2013).

Nielsen, J. R., Degnbol, P., Viswanathan, K. K., Ahmed, M., Hara, M., and Abdullah, N. M. R. 2004. Fisheries co-management - an institutional innovation? lessons from South East Asia and Southern Africa. Marine Policy, 28: 151–160.

Niemi, A., Ferguson, S., Hedges, K., Melling, H., Michel, C., Ayles, B., Azetsu-scott, K., *et al.* 2019. State of Canada's Arctic Seas. Can. Tech. Rep. Fish. Aquat. Sci., 3344: 189.

NOAA. 2015. NOAA Federal Advisory Committees.

NOAA. 2019. 2017-2019 North Atlantic right whale unusual mortality event.

NOAA National Centers for Environmental information. 2020. Climate at a Glance: Global Time Series, published September 2020. https://www.ncdc.noaa.gov/cag/ (Accessed 5 September 2020).

Northwest Atlantic Fisheries Organization. 2019. Northwest Atlantic Fisheries Organization Scientific Council Reports 2019. Halifax, Canada. 451 pp. www.nafo.int.

NRC. 2011. Climate stabilization targets: emissions, concentrations, and impacts over decades to millennia. National Academies Press, Washington, D.C.

Nye, J. A., Link, J. S., Hare, J. A., and Overholtz, W. J. 2009. Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United States continental shelf. Marine Ecology Progress Series, 393: 111–129.

Nye, J. A., Joyce, T. M., Kwon, Y.-O., and Link, J. S. 2011. Silver hake tracks changes in Northwest Atlantic circulation. Nature Communications, 2: 1–6.

O'Connor, M. I., Piehler, M. F., Leech, D. M., Anton, A., and Bruno, J. F. 2009. Warming and resource availability shift food web structure and metabolism. Plos Biology, 7: 1–6.

O'Gorman, E. J., Enright, R. A., and Emmerson, M. C. 2008. Predator diversity enhances secondary production and decreases the likelihood of trophic cascades. OECOLOGIA, 158: 557–567.

Ogier, E. M., Davidson, J., Fidelman, P., Haward, M., Hobday, A. J., Holbrook, N. J., Hoshino, E., *et al.* 2016. Fisheries management approaches as platforms for climate change adaptation: Comparing theory and practice in Australian fisheries. Marine Policy, 71: 82–93.

Ojea, E., Pearlman, I., Gaines, S. D., and Lester, S. E. 2017. Fisheries regulatory regimes and resilience to climate change. Ambio, 46: 399–412. Springer Netherlands.

Okey, T. A. 2003. Membership of the eight Regional Fishery Management Councils in the United States: are special interests over-represented? Marine Policy, 27: 193–206.

Oliver, E. C. J., Benthuysen, J. A., Bindoff, N. L., Hobday, A. J., Holbrook, N. J., Mundy, C. N., and Perkins-Kirkpatrick, S. E. 2017. The unprecedented 2015/16 Tasman Sea marine heatwave. NATURE COMMUNICATIONS, 8.

Oliver, E. C. J., Donat, M. G., Burrows, M. T., Moore, P. J., Smale, D. A., Alexander, L. V., Benthuysen, J. A., *et al.* 2018. Longer and more frequent marine heatwaves over the past century. Nature Communications, 9: 1–12. Springer US. http://dx.doi.org/10.1038/s41467-018-03732-9.

Olsson, P., Folke, C., and Berkes, F. 2004. Adaptive comanagement for building resilience in social-ecological systems. ENVIRONMENTAL MANAGEMENT, 34: 75–90.

Ottersen, G., Hjermann, D. O., and Stenseth, N. C. 2006. Changes in spawning stock structure strengthen the link between climate and recruitment in a heavily fished cod (Gadus morhua) stock. Fisheries Oceanography, 15: 230–243.

Pacifici, M., Foden, W. B., Visconti, P., Watson, J. E. M., Butchart, S. H. M., Kovacs, K. M., Scheffers, B. R., *et al.* 2015. Assessing species vulnerability to climate change. Nature Climate Change, 5: 215–225.

Palmer, C., and Sinclair, P. 1997. When the fish are gone: Ecological disaster and the fishers of northwest Newfoundland. Fernwood Pub, Halifax, Nova scotia, Canada, Nova scotia, Canada. 103 pp.

Pauly, D., Christensen, V., Dalsgaard, J., Froese, R., and Torres Jr., F. 1998. Fishing down marine food webs. Science, 279: 860–863.

Pawlowski, J., Kelly-Quinn, M., Altermatt, F., Apothéloz-Perret-Gentil, L., Beja, P., Boggero, A., Borja, A., *et al.* 2018. The future of biotic indices in the ecogenomic era: Integrating (e)DNA metabarcoding in biological assessment of aquatic ecosystems. Science of the Total Environment, 637–638: 1295–1310.

Peck, M., and Pinnegar, J. K. 2018. Chapter 5: Climate change impact, vulnerabilities and adaptations: North Atlantic and Atlantic Arctic marine fisheries. *In* Impacts of climate change on fisheries and aquaculture Synthesis of current knowledge, adaptation and mitigation options. Food and Agriculture Organization of the United Nations, Rome, Italy.

Pendleton, D., Sullivan, P., Brown, M., Cole, T., Good, C., Mayo, C., Monger, B., *et al.* 2012. Weekly predictions of North Atlantic right whale *Eubalaena glacialis* habitat reveal influence of prey abundance and seasonality of habitat preferences. Endangered Species Research, 18: 147–161. http://www.int-res.com/abstracts/esr/v18/n2/p147-161/.

Pepin, P., King, J., Holt, C., Gurney-Smith, H., Shackell, N., Hedges, K., and Bundy, A. 2020. Incorporating climate, oceanographic and ecological change considerations into population assessments: A review of Fisheries and Oceans Canada's science advisory pr. DFO Can. Sci. Advis. Sec. Res. Doc., 2019/043: 66.

Pérez-Rodríguez, A., Howell, D., Casas, M., Saborido-Rey, F., and Ávila-De Melo, A. 2017. Dynamic of the Flemish cap commercial stocks: Use of a gadget multispecies model to determine the relevance and synergies among predation, recruitment, and fishing. Canadian Journal of Fisheries and Aquatic Sciences, 74: 582–597.

Perovich, D. K., and Richter-Menge, J. a. 2009. Loss of Sea Ice in the Arctic. Annual Review of Marine Science, 1: 417–441.
http://www.annualreviews.org/doi/abs/10.1146/annurev.marine.010908.163805 (Accessed 12 August 2013).

Perry, A. L., Low, P. J., Ellis, J. R., and Reynolds, J. D. 2005. Climate change and distribution shifts in marine fishes. Science, 308: 1912–1915.

Pershing, A. J., Alexander, M. A., Hernandez, C. M., Kerr, L. A., Le Bris, A., Mills, K. E., Nye, J. A., *et al.* 2015. Slow adaptation in the face of rapid warming leads to collapse of the Gulf of Maine cod fishery. Science, 350: 809–812.
https://www.sciencemag.org/lookup/doi/10.1126/science.aac9819.

Peterman, R. M., Pyper, B. J., and Grout, J. A. 2000. Comparison of parameter estimation methods for detecting climate-induced changes in productivity of Pacific salmon (Oncorhynchus spp.). CANADIAN JOURNAL OF FISHERIES AND AQUATIC SCIENCES, 57: 181–191.

PETERMAN, R. M., and STEER, G. J. 1981. RELATION BETWEEN SPORT-FISHING CATCHABILITY COEFFICIENTS AND SALMON ABUNDANCE. TRANSACTIONS OF THE AMERICAN FISHERIES SOCIETY, 110: 585–593.

Petrie, B., Yeats, P., and Strain, P. 1999. Nitrate, silicate, and phosphate atlas for the Scotian Shelf and the Gulf of Maine. Canadian Technical Report of Hydrography and Ocean Sciences, 203: 96.

Petrie, B., and Yeats, P. 2000. Annual and interannual variability of nutrients and their estimated fluxes in the Scotian Shelf - Gulf of Maine region. CANADIAN JOURNAL OF FISHERIES AND AQUATIC SCIENCES, 57: 2536–2546.

Petrie, B., Pettipas, R. G., Petrie, W. M., and Soukhovtsev, V. V. 2009a. Physical oceanographic conditions on the Scotian Shelf and in the Gulf of Maine during 2009.

Petrie, B., Frank, K. T., Shackell, N. L., and Leggett, W. C. 2009b. Structure and stability in exploited marine fish communities: quantifying critical transitions. FISHERIES OCEANOGRAPHY, 18: 83–101. WILEY, 111 RIVER ST, HOBOKEN 07030-5774, NJ USA.

PFMC. 2007. Status of the Pacific Coast Coastal Pelagic Species Fishery and Recommended Acceptable Biological Catches. Stock Assessment and Fishery Evaluation—2007. Pacific Fishery Management Council (PFMC), Portland. 126 pp.

Pinkerton, E. 1989. Co-operative Management of Local Fisheries: New Directions for Improved Management and Community Development. University of British Columbia Press, Vancouver, B.C., Canada. 313 pp.

Pinnegar, J. K., Trenkel, V. M., and Blanchard, J. L. 2008. 80 years of multispecies fisheries modelling: significant advances and continuing challenges. *In* Advances in fisheries science: 50 years on from Beverton and Holt, pp. 325–357. Ed. by A. Payne, J. Cotter, and T. Potter. Blackwell Publishing.

Pinsky, M. L., and Fogarty, M. 2012. Lagged social-ecological responses to climate and range shifts in fisheries. Climatic Change, 115: 883–891.

Pinsky, M. L., Worm, B., Fogarty, M. J., Sarmiento, J. L., and Levin, S. A. 2013. Marine Taxa Track Local Climate Velocities. SCIENCE, 341: 1239–1242. http://www.sciencemag.org/content/341/6151/1239%5Cnhttp://www.ncbi.nlm.nih.gov/pubmed/24031017%5Cnhttp://www.sciencemag.org/content/341/6151/1239.abstract.

Pinsky, M. L., and Mantua, N. J. 2014. Emerging Adaptation Approaches for Climate-Ready Fisheries Management. Oceanography, 27: 146–159.

Pinsky, M. L., Eikeset, A. M., McCauley, D. J., Payne, J. L., and Sunday, J. M. 2019. Greater vulnerability to warming of marine versus terrestrial ectotherms. Nature. Springer US. http://dx.doi.org/10.1038/s41586-019-1132-4.

Plaganyi, E. E., Punt, A. E., Hillary, R., Morello, E. B., Thebaud, O., Hutton, T., Pillans, R. D., *et al.* 2014. Multispecies fisheries management and conservation: tactical applications using models of intermediate complexity. FISH AND FISHERIES, 15: 1–22.

Plagányi, E. E. 2007. Models for an ecosystem approach to fisheries. 108 pp.

Plagányi, É. E., Skewes, T. D., Dowling, N. A., Haddon, M., Plaganyi, E. E., Skewes, T. D., Dowling, N. A., *et al.* 2013. Risk management tools for sustainable fisheries management under changing climate: A sea cucumber example. Climatic Change, 119: 181–197.

Platt, T., Fuentes-Yaco, C., and Frank, K. T. 2003. Spring algal bloom and larval fish survival. Nature, 423: 398–399.

Plourde, S., Lehoux, C., Johnson, C. L., Perrin, G., and Lesage, V. 2019. North Atlantic right whale (Eubalaena glacialis) and its food: (I) a spatial climatology of Calanus biomass and potential foraging habitats in Canadian waters. Journal of Plankton Research, 41: 667–685. Oxford University Press, Oxford, U.K.

Plummer, R., Crona, B., Armitage, D. R., Olsson, P., Tengoe, M., Yudina, O., Plummer, M., *et al.* 2012. Adaptive co-management: a systematic review and analysis. Ecology and Society, 17: 1–11.

Poertner, H.-O. 2008. Ecosystem effects of ocean acidification in times of ocean warming: a physiologist's view. MARINE ECOLOGY PROGRESS SERIES, 373: 203–217.

Poertner, H.-O. 2010. Oxygen- and capacity-limitation of thermal tolerance: a matrix for integrating climate-related stressor effects in marine ecosystems. JOURNAL OF EXPERIMENTAL BIOLOGY, 213: 881–893.

Poertner, H. O., and Knust, R. 2007. Climate change affects marine fishes through the oxygen limitation of thermal tolerance. SCIENCE, 315: 95–97.

Polacheck, T. 1999. An initial evaluation of management strategies for the southern bluefin tuna fishery. ICES Journal of Marine Science, 56: 811–826. https://academic.oup.com/icesjms/article-lookup/doi/10.1006/jmsc.1999.0554.

Poloczanska, E. S., Brown, C. J., Sydeman, W. J., Kiessling, W., Schoeman, D. S., Moore, P. J., Brander, K., *et al.* 2013. Global imprint of climate change on marine life. Nature Climate Change, 3: 919–925. internal-pdf://209.126.227.87/Poloczanska-2013-Global imprint of cl.pdf%5Cn%3CGo to ISI%3E://WOS:000326818800020
http://www.nature.com/nclimate/journal/v3/n10/pdf/nclimate1958.pdf.

Poloczanska, E. S., Burrows, M. T., Brown, C. J., García Molinos, J., Halpern, B. S., Hoegh-Guldberg, O., Kappel, C. V, *et al.* 2016. Responses of Marine Organisms to Climate Change across Oceans. Frontiers in Marine Science, 3: 62.
http://journal.frontiersin.org/Article/10.3389/fmars.2016.00062/abstract.

Polovina, J. J., Howell, E. A., and Abecassis, M. 2008. Ocean's least productive waters are expanding. Geophysical Research Letters, 35: L03618.

Pomeroy, R. 2007. Conditions for successful fisheries and coastal resources management: Lessons learned in Asia, Africa, and the wider Caribbean. *In* Adaptive co-management: Collaboration, learning and multi-level governance, pp. 172–187. Ed. by D. R. Armitage, F. Berkes, and N. Doubleday. UBC Press, Vancouver, B.C., Canada.

Pomeroy, R., Cinner, J. E., and Nielsen, J. R. 2011. Conditions for successful co-management: lessons learned in Asia, Africa, the Pacific and the wider Caribbean. *In* Small Fisheries Management: Frameworks and Approaches for the Developing World, pp. 115–131. Ed. by R. Pomeroy and N. L. Andrew. CABI International, USA.

Pomeroy, R. S. 1994. Community management and common property of coastal fisheries in Asia an dthe Pacific: concepts, methods and experiences. ICLARM Conference Proceedings, 45: 189.

Pondella II, D. J., and Allen, L. G. 2008. The decline and recovery of four predatory fishes from the Southern California Bight. MARINE BIOLOGY, 154: 307–313.

Power, M. J., Clark, K. J., Fife, F. J., Knox, D., Melvin, G. D., Stephenson, R. L., Annis, L. M., *et al.* 2006. 2006 Evaluation of 4VWX Herring. DFO Canaidan Science Advisory Secretariat Research Document, 2006/49: 142. Ottawa, Canada.

Prince, E. D., Luo, J., Goodyear, C. P., Hoolihan, J. P., Snodgrass, D., Orbesen, E. S., Serafy, J. E., *et al.* 2010. Ocean scale hypoxia-based habitat compression of Atlantic istiophorid billfishes. FISHERIES OCEANOGRAPHY, 19: 448–462.

Punt, A. E., A'mar, T., Bond, N. A., Butterworth, D. S., de Moor, C. L., De Oliveira, J. A. A., Haltuch, M. A., *et al.* 2014. Fisheries management under climate and environmental uncertainty: control rules and performance simulation. ICES JOURNAL OF MARINE SCIENCE, 71: 2208–2220.

Punt, A. E., Butterworth, D. S., de Moor, C. L., De Oliveira, J. A. A., and Haddon, M. 2016. Management strategy evaluation: best practices. Fish and Fisheries, 17: 303–334.

Purcell, J. E. 2012. Jellyfish and Ctenophore Blooms Coincide with Human Proliferations and Environmental Perturbations. *In* ANNUAL REVIEW OF MARINE SCIENCE, VOL 4, p. 209+. Ed. by Carlson, CA and Giovannoni, SJ.

Pyper, B. J., and Peterman, R. M. 1998. Comparison of methods to account for autocorrelation in correlation analyses of fish data. Canadian Journal of Fisheries and Aquatic Sciences, 55: 2127–2140. http://www.nrc.ca/cgi-bin/cisti/journals/rp/rp2_abst_e?cjfas_f98-104_55_ns_nf_cjfas55-98.

R Core Team. 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. R Foundation for Statistical Computing, Vienna, Austria. https://www.r-project.org/.

Racault, M. F., Le Quéré, C., Buitenhuis, E., Sathyendranath, S., and Platt, T. 2012. Phytoplankton phenology in the global ocean. Ecological Indicators, 14: 152–163. Elsevier Ltd. http://dx.doi.org/10.1016/j.ecolind.2011.07.010.

Rademeyer, R. A., and Butterworth, D. S. 2011. Technical details underlying the Management Strategy Evaluation process leading to selection of a management procedure for Western Component (4Xopqrs5) pollock. DFO Canadian Scientific Advisory Secretariat Research Document, 2011/nnn.

RAM Legacy Stock Assessment Database. 2018. Version 4.44-assessment-only. Released 2018-12-22.

Randall, C. J., and van Woesik, R. 2017. Some coral diseases track climate oscillations in the Caribbean. SCIENTIFIC REPORTS, 7.

Reusch, T. B. H., Ehlers, A., HÃ¤mmerli, A., and Worm, B. 2005. Ecosystem recovery after climatic extremes enhanced by genotypic diversity. Proc. Natl. Acad. Sci. USA, 102: 2826â€“2831.

Rex, M. A., Etter, R. J., Morris, J. S., Crouse, J., McClain, C. R., Johnson, N. A., Stuart, C. T., *et al.* 2006. Global bathymetric patterns of standing stock and body size in the deep-sea benthos. MARINE ECOLOGY PROGRESS SERIES, 317: 1–8.

Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., Kindermann, G., *et al.* 2011. RCP 8.5-A scenario of comparatively high greenhouse gas emissions. Climatic Change, 109: 33–57.

Ricard, D., Minto, C. C., Jensen, O. P., and Baum, J. K. 2012. Examining the knowledge base and status of commercially exploited marine species with the RAM Legacy Stock Assessment Database. FISH AND FISHERIES, 13: 380–398. http://doi.wiley.com/10.1111/j.1467-2979.2011.00435.x (Accessed 21 January 2014).

Riebesell, U., Schulz, K. G., Bellerby, R. G. J., Botros, M., Fritsche, P., Meyerhöfer, M., Neill, C., *et al.* 2007. Enhanced biological carbon consumption in a high CO2 ocean. Nature, 450: 545–8. http://www.ncbi.nlm.nih.gov/pubmed/17994008 (Accessed 29 January 2013).

Roe, E. 2001. Varieties of issue incompleteness and coordination: An example from ecosystem management. Policy Sciences, 34: 111–133.

Rosol, R., Huet, C., Wood, M., Lennie, C., Osborne, G., and Egeland, G. M. 2011. Prevalence of affirmative responses to questions of food insecurity: International Polar Year Inuit Health Survey, 2007_ 2008. International Journal of Circumpolar Health, 70: 488–97.

Rothschild, B. J., and Yiao, Y. 2011. Characterizing Uncertainty in Fish Stock Assessments: the Case of the Southern New England–Mid-Atlantic Winter Flounder. Transactions of the American Fisheries Society, 140: 557–569.

Ruhl, H. A., Ellena, J. A., Smith, K. L., and Smith Jr., K. L. 2008. Connections between climate, food limitation, and carbon cycling in abyssal sediment communities. PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA, 105: 17006–17011.

Saba, V. S., Griffies, S. M., Anderson, W. G., Winton, M., Alexander, M. A., Delworth, T. L., Hare, J. A., *et al.* 2016. Enhanced warming of the Northwest Atlantic Ocean under climate change. JOURNAL OF GEOPHYSICAL RESEARCH-OCEANS, 121: 118–132.

Sabine, C. L., Feely, R. A., Gruber, N., Key, R. M., Lee, K., Bullister, J. L., Wanninkhof, R., *et al.* 2004. The oceanic sink for anthropogenic CO2. Science, 305: 367–371. http://arxiv.org/abs/gr-qc/9809069%5Cnhttp://www.tandfonline.com/doi/abs/10.1080/01422419908228843%5Cnhttp://www.sciencemag.org/cgi/doi/10.1126/science.1097403%5Cnhttp://www.sciencemag.org/cgi/doi/10.1126/science.1097403 (Accessed 29 January 2013).

Saenz-Arroyo, A., Roberts, C. M., Torre, J., Carino-Olvera, M., and Enriquez-Andrade, R. R. 2005. Rapidly shifting environmental baselines among fishers of the Gulf of California. PROCEEDINGS OF THE ROYAL SOCIETY B-BIOLOGICAL SCIENCES, 272: 1957–1962.

SAFM. 2020. South Atlantic Fishery Management Council Citizen Science Program. https://safmc.net/citizen-science-program/.

Sainsbury, K. J., Punt, A. E., and Smith, A. D. M. 2000. Design of operational management strategies for achieving fishery ecosystem objectives. ICES JOURNAL OF MARINE SCIENCE, 57: 731–741.

Sandin, S. A., Smith, J. E., DeMartini, E. E., Dinsdale, E. A., Donner, S. D., Friedlander, A. M., Konotchick, T., *et al.* 2008. Baselines and Degradation of Coral Reefs in the Northern Line Islands. PLOS ONE, 3.

Scheffers, B. R., De Meester, L., Bridge, T. C. L. L., Hoffmann, A. A., Pandolfi, J. M., Corlett, R. T., Butchart, S. H. M. M., *et al.* 2016. The broad footprint of climate change from genes to biomes to people. SCIENCE, 354.

Schewe, J., Gosling, S. N., Reyer, C., Zhao, F., Ciais, P., Elliott, J., Francois, L., *et al.* 2019. State-of-the-art global models underestimate impacts from climate extremes. Nature Communications, 10: 1–14. http://www.nature.com/articles/s41467-019-08745-6.

Schindler, D. E., Hilborn, R., Chasco, B., Boatright, C. P., Quinn, T. P., Rogers, L. a, and Webster, M. S. 2010. Population diversity and the portfolio effect in an exploited species. NATURE, 465: 609–612. Nature Publishing Group. http://www.ncbi.nlm.nih.gov/pubmed/20520713 (Accessed 29 January 2013).

Schmidt, D. N., Renaud, S., Bollmann, J., Schiebel, R., and Thierstein, H. R. 2004. Size distribution of Holocene planktic foraminifer assemblages: biogeography, ecology and adaptation. MARINE MICROPALEONTOLOGY, 50: 319–338.

SCHNUTE, J. T. 1994. A GENERAL FRAMEWORK FOR DEVELOPING SEQUENTIAL FISHERIES MODELS. CANADIAN JOURNAL OF FISHERIES AND AQUATIC SCIENCES, 51: 1676–1688.

Schrank, W. E., Skoda, B., Parsons, P., and Roy, N. 1995. The Cost to Government of Maintaining a Commercially Unviable Fishery: The Case of Newfoundland 1981/82 to 1990/91. Ocean Development & International Law, 26: 357–390.

Schumacher, S., Jorissen, F. J., Dissard, D., Larkin, K. E., and Gooday, A. J. 2007. Live (Rose Bengal stained) and dead benthic foraminifera from the oxygen minimum zone of the Pakistan continental margin (Arabian Sea). MARINE MICROPALEONTOLOGY, 62: 45–73.

Sen, S., and Nielsen, J. R. 1996. Fisheries co-management: A comparative analysis. Marine Policy, 20: 405–418.

Sethi, S. A., Dalton, M., and Hilborn, R. 2012. Quantitative risk measures applied to Alaskan commercial fisheries. CANADIAN JOURNAL OF FISHERIES AND AQUATIC SCIENCES, 69: 487–498.

Shackell, N., and Frank, K. 2007. Compensation in exploited marine fish communities on the Scotian Shelf, Canada. Marine Ecology Progress Series, 336: 235–247. http://www.int-res.com/abstracts/meps/v336/p235-247/.

Shackell, N. L., Frank, K. T., Fisher, J. A. D., Petrie, B., and Leggett, W. C. 2010. Decline in top predator body size and changing climate alter trophic structure in an oceanic ecosystem. Proceedings of the Royal Society B-Biological Sciences, 277: 1353–1360. ROYAL SOC, London, UK.

Shackell, N. L., Bundy, A., Nye, J. A., and Link, J. S. 2012. Common large-scale responses to climate and fishing across Northwest Atlantic ecosystems. ICES JOURNAL OF MARINE SCIENCE, 69: 151–162. OXFORD UNIV PRESS, GREAT CLARENDON ST, OXFORD OX2 6DP, ENGLAND.

Shackell, N. L., Ricard, D., and Stortini, C. 2014. Thermal habitat index of many Northwest Atlantic temperate species stays neutral under warming projected for 2030 but changes radically by 2060. PLOS ONE, 9.

Sheridan, J. A., and Bickford, D. 2011. Shrinking body size as an ecological response to climate change. NATURE CLIMATE CHANGE, 1: 401–406.

Shi, D. L., Xu, Y., Hopkinson, B. M., and Morel, F. M. M. 2010. Effect of Ocean Acidification on Iron Availability to Marine Phytoplankton. SCIENCE, 327: 676–679.

Short, F. T., and Neckles, H. A. 1999. The effects of global climate change on seagrasses. AQUATIC BOTANY, 63: 169–196.

Singleton, S. 2000. Co-operation or capture? The paradox of co-management and community participation in natural resource management and environmental policy-making. Environmental Politics, 9: 1–21.

Smith, A. D. M., Fulton, E. J., Hobday, A. J., Smith, D. C., and Shoulder, P. 2007. Scientific tools to support the practical implementation of ecosystem-based fisheries management. ICES JOURNAL OF MARINE SCIENCE, 64: 633–639.

Smith, C. R., De Leo, F. C., Bernardino, A. F., Sweetman, A. K., and Arbizu, P. M. 2008. Abyssal food limitation, ecosystem structure and climate change. TRENDS IN ECOLOGY & EVOLUTION, 23: 518–528.

Soomai, S. S., Wells, P. G., and MacDonald, B. H. 2011. Multi-stakeholder perspectives on the use and influence of “grey” scientific information in fisheries management. Marine Policy, 35: 50–62. https://linkinghub.elsevier.com/retrieve/pii/S0308597X10001417.

Spalding, M. D., Fox, H. E., Allen, G. R., Davidson, N., Ferdaña, Z. a., Finlayson, M., Halpern, B. S., *et al.* 2007. Marine Ecoregions of the World: A Bioregionalization of Coastal and Shelf Areas. BioScience, 57: 573. http://bioscience.oxfordjournals.org/cgi/doi/10.1641/B570707.

Spillman, C. M., and Alves, O. 2009. Dynamical seasonal prediction of summer sea surface temperatures in the Great Barrier Reef. CORAL REEFS, 28: 197–206.

Spillman, C. M. 2011. Advances in Forecasting Coral Bleaching Conditions for Reef Management. BULLETIN OF THE AMERICAN METEOROLOGICAL SOCIETY, 92: 1586–1591.

Stanley, R. R. E., Dibacco, C., Lowen, B., Beiko, R. G., Jeffery, N. W., Wyngaarden, M. Van, Bentzen, P., *et al.* 2018. A climate-associated multispecies cryptic cline in the northwest Atlantic. Science Advances. http://advances.sciencemag.org/cgi/content/short/4/3/eaaq0929.

Starr, P. J., Breen, P. A., Hilborn, R. H., and Kendrick, T. H. 1997. Evaluation of a management decision rule for a New Zealand rock lobster substock. Marine and Freshwater Research, 48: 1093. http://www.publish.csiro.au/?paper=MF97171.

Steinacher, M., Joos, F., Froelicher, T. L., Plattner, G.-K., and Doney, S. C. 2009. Imminent ocean acidification in the Arctic projected with the NCAR global coupled carbon cycle-climate model. BIOGEOSCIENCES, 6: 515–533.

Stendardo, I., and Gruber, N. 2012. Oxygen trends over five decades in the North Atlantic. JOURNAL OF GEOPHYSICAL RESEARCH-OCEANS, 117.

Steneck, R., Graham, M., Bourque, B., Corbett, D., Erlandson, J., and Estes, J. 2002. Kelp Forest Ecosystems: Biodiversity, Stability, Resilience and Future. Environmental Conservation, 29: 436–459.

Steneck, R. S., Hughes, T. P., Cinner, J. E., Adger, W. N., Arnold, S. N., Berkes, F., Boudreau, S. A., *et al.* 2011. Creation of a Gilded Trap by the High Economic Value of the Maine Lobster Fishery. CONSERVATION BIOLOGY, 25: 904–912.

Stephenson, R. L., Power, M. J., Laffan, S. W., and Suthers, I. M. 2015. Tests of larval retention in a tidally energetic environment reveal the complexity of the spatial structure in herring populations. Fisheries Oceanography, 24: 553–570. WILEY, 111 RIVER ST, HOBOKEN 07030-5774, NJ USA.

Stobo, W. T., and Fowler, G. M. 2009. Herring Tagging in the Vicinity of the Scotian Shelf and Gulf of St. Lawrence by the Maritimes Region, 1973-1982. DFO Canadian Technical Report of Fisheries and Aquatic Sciences 2851: 69 p.

Stortini, C. H., Shackell, N. L., Tyedmers, P., and Beazley, K. 2015. Assessing marine species vulnerability to projected warming on the Scotian Shelf, Canada. ICES Journal of Marine Science, 72: 1713–1743.

Stramma, L., Schmidtko, S., Levin, L. A., and Johnson, G. C. 2010. Ocean oxygen minima expansions and their biological impacts. DEEP-SEA RESEARCH PART I-OCEANOGRAPHIC RESEARCH PAPERS, 57: 587–595.

Stramma, L., Prince, E. D., Schmidtko, S., Luo, J., Hoolihan, J. P., Visbeck, M., Wallace, D. W. R., *et al.* 2012. Expansion of oxygen minimum zones may reduce available habitat for tropical pelagic fishes. NATURE CLIMATE CHANGE, 2: 33–37. Nature Publishing Group. http://www.nature.com/doifinder/10.1038/nclimate1304 (Accessed 29 January 2013).

Stroeve, J. C., Kattsov, V., Barrett, A., Serreze, M., Pavlova, T., Holland, M., and Meier, W. N. 2012. Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. Geophysical Research Letters, 39: L16502. http://dx.doi.org/10.1029/2012GL052676.

Sumalia, U. R., and Cheung, W. W. L. 2010. Cost of Adapting Fisheries to Climate Change. Development and Climate Change, Discussion Paper No. 5 World Bank.

Swimmer, Y., Gutierrez, A., Bigelow, K., Barceló, C., Schroeder, B., Keene, K., Shattenkirk, K., *et al.* 2017. Sea Turtle Bycatch Mitigation in U.S. Longline Fisheries. Frontiers in Marine Science, 4. http://journal.frontiersin.org/article/10.3389/fmars.2017.00260/full.

Syamsuddin, M. L., Saitoh, S., Hirawake, T., Bachri, S., and Harto, A. B. 2013. Effects of El Nino-Southern Oscillation events on catches of Bigeye Tuna (Thunnus obesus) in the eastern Indian Ocean off Java. FISHERY BULLETIN, 111: 175–188.

Szuwalski, C. S., and Punt, A. E. 2013. Fisheries management for regime-based ecosystems: a management strategy evaluation for the snow crab fishery in the eastern Bering Sea. ICES JOURNAL OF MARINE SCIENCE, 70: 955–967.

Szuwalski, C. S., Vert-Pre, K. A., Punt, A. E., Branch, T. A., and Hilborn, R. 2015. Examining common assumptions about recruitment: a meta-analysis of recruitment dynamics for worldwide marine fisheries. Fish and Fisheries, 16: 633–648.

Taucher, J., and Oschlies, A. 2011. Can we predict the direction of marine primary production change under global warming? Geophysical Research Letters, 38: 1–6.

Taylor, D. L., and Peck, M. A. 2004. Daily energy requirements and trophic positioning of the sand shrimp Crangon septemspinosa. MARINE BIOLOGY, 145: 167–177.

Tecchio, S., Ramirez-Llodra, E., Sarda, F., Company, J. B., Palomera, I., Mecho, A., Pedrosa-Pamies, R., *et al.* 2011. Drivers of deep Mediterranean megabenthos communities along longitudinal and bathymetric gradients. MARINE ECOLOGY PROGRESS SERIES, 439: 181-U219.

Thompson, R. M., Beardall, J., Beringer, J., Grace, M., and Sardina, P. 2013. Means and extremes: building variability into community-level climate change experiments. ECOLOGY LETTERS, 16: 799–806.

Tittensor, D. P., Baco, A. R., Hall-Spencer, J. M., Orr, J. C., and Rogers, A. D. 2010a. Seamounts as refugia from ocean acidification for cold-water stony corals. MARINE ECOLOGY-AN EVOLUTIONARY PERSPECTIVE, 31: 212–225.

Tittensor, D. P., Rex, M. a, Stuart, C. T., McClain, C. R., and Smith, C. R. 2011. Species-energy relationships in deep-sea molluscs. Biology letters, 7: 718–22. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3169037&tool=pmcentrez&rendertype=abstract (Accessed 29 January 2013).

Tittensor, D. P., Eddy, T. D., Lotze, H. K., Galbraith, E. D., Cheung, W., Barange, M., Blanchard, J. L., *et al.* 2018a. ISIMIP2a Simulation Data from Fisheries & Marine Ecosystems (Fish-MIP; Global) Sector. Potsdam Institute for Climate Impact Research.GFZ Data Services. http://doi.org/10.5880/PIK.2018.005. Deposited 31 January 2018.

Tittensor, D. P., Eddy, T. D., Lotze, H. K., Galbraith, E. D., Cheung, W., Barange, M., Blanchard, J. L., *et al.* 2018b. A protocol for the intercomparison of marine fishery and ecosystem models: Fish-

MIP v1.0. Geoscientific Model Development, 11: 1421–1442. https://gmd.copernicus.org/articles/11/1421/2018/.

Tittensor, D. P., Beger, M., Boerder, K., Boyce, D. G., Cavanagh, R. D., Cosandey-Godin, A., Crespo, G. O., *et al.* 2019. Integrating climate adaptation and biodiversity conservation in the global ocean. Science Advances, 5: 1–16.

Tittensor, D. P. D. D. P., Mora, C., Jetz, W., Lotze, H. H. K. H., Ricard, D., Berghe, E. Vanden, Worm, B., *et al.* 2010b. Global patterns and predictors of marine biodiversity across taxa. NATURE, 466: 1098-U107. Nature Publishing Group. http://apps.isiknowledge.com/full_record.do?product=WOS&search_mode=GeneralSearch&qid=1&SID=4BgP8I2e1BlmMG7pMb4&page=1&doc=1.

Tompkins, E. L., and Adger, W. N. 2004. Does adaptive management of natural resources enhance resilience to climate change? ECOLOGY AND SOCIETY, 9.

Trijoulet, V., Fay, G., Curti, K. L., Smith, B., and Miller, T. J. 2019. Performance of multispecies assessment models: insights on the influence of diet data. ICES Journal of Marine Science, 76: 1938–1938. https://academic.oup.com/icesjms/article/76/6/1938/5511587.

Trijoulet, V., Fay, G., and Miller, T. J. 2020. Performance of a state-space multispecies model: What are the consequences of ignoring predation and process errors in stock assessments? Journal of Applied Ecology, 57: 121–135.

Trisos, C. H., Merow, C., and Pigot, A. L. 2020. The projected timing of abrupt ecological disruption from climate change. Nature, 580: 1–6. Springer US. http://www.nature.com/articles/s41586-020-2189-9.

Tsou, T.-S., and Collie, J. S. 2001. Estimating predation mortality in the Georges Bank fish community. Canadian Journal of Fisheries and Aquatic Sciences, 58: 908–922. http://www.nrc.ca/cgi-bin/cisti/journals/rp/rp2_abst_e?cjfas_f01-044_58_ns_nf_cjfas58-01.

Tuck, G. N. 2011. Are bycatch rates sufficient as the principal fishery performance measure and method of assessment for seabirds? Aquatic Conservation: Marine and Freshwater Ecosystems, 21: 412–422.

Tyrrell, M. C., Link, J. S., and Moustahfid, H. 2011. The importance of including predation in fish population models: Implications for biological reference points. FISHERIES RESEARCH, 108: 1–8.

van Nugteren, P., Herman, P. M. J., Moodley, L., Middelburg, J. J., Vos, M., and Heip, C. H. R. 2009a. Spatial distribution of detrital resources determines the outcome of competition between bacteria and a facultative detritivorous worm. LIMNOLOGY AND OCEANOGRAPHY, 54: 1413–1419.

van Nugteren, P., Moodley, L., Brummer, G.-J., Heip, C. H. R., Herman, P. M. J., and Middelburg, J. J. 2009b. Seafloor ecosystem functioning: the importance of organic matter priming. MARINE BIOLOGY, 156: 2277–2287.

van Oevelen, D., Soetaert, K., Garcia, R., de Stigter, H. C., Cunha, M. R., Pusceddu, A., and Danovaro, R. 2011. Canyon conditions impact carbon flows in food webs of three sections of the Nazare canyon. DEEP-SEA RESEARCH PART II-TOPICAL STUDIES IN OCEANOGRAPHY, 58: 2461–2476.

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., *et al.* 2011. The representative concentration pathways: An overview. Climatic Change, 109: 5–31.

Vaquer-Sunyer, R., and Duarte, C. M. 2011. Temperature effects on oxygen thresholds for hypoxia in marine benthic organisms. GLOBAL CHANGE BIOLOGY, 17: 1788–1797.

Vetter, E. W., Smith, C. R., and De Leo, F. C. 2010. Hawaiian hotspots: enhanced megafaunal abundance and diversity in submarine canyons on the oceanic islands of Hawaii. MARINE ECOLOGY-AN EVOLUTIONARY PERSPECTIVE, 31: 183–199.

Vezzulli, L., Grande, C., Reid, P. C., Helaouet, P., Edwards, M., Hoefle, M. G., Brettar, I., *et al.* 2016. Climate influence on Vibrio and associated human diseases during the past half-century in the coastal North Atlantic. PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA, 113: E5062–E5071.

Walsh, H. J., Richardson, D. E., Marancik, K. E., and Hare, J. A. 2015. Long-term changes in the distributions of larval and adult fish in the northeast U.S. shelf ecosystem. PLoS ONE, 10: 1–31. http://dx.doi.org/10.1371/journal.pone.0137382.

Walther, G.-R. R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T. J. C., Fromentin, J.-M. M., *et al.* 2002. Ecological responses to recent climate change. Nature, 416: 389–395. http://www.nature.com/cgi-taf/DynaPage.taf?file=/nature/journal/v416/n6879/full/416389a_fs.html.

Wang, Z., Lu, Y., Greenan, B., Brickman, D., and DeTracey, B. 2018. BNAM: An eddy-resolving North Atlantic Ocean model to support ocean monitoring. Can. Tech. Rep. Hydrogr. Ocean. Sci., 327: 18.

Wanninkhof, R., Barbero, L., Byrne, R., Cai, W.-J., Huang, W.-J., Zhang, J.-Z., Baringer, M., *et al.* 2015. Ocean acidification along the Gulf Coast and East Coast of the USA. Continental Shelf Research, 98: 54–71.

Weatherdon, L. V., Ota, Y., Jones, M. C., Close, D. A., and Cheung, W. W. L. L. 2016. Projected Scenarios for Coastal First Nations' Fisheries Catch Potential under Climate Change: Management Challenges and Opportunities. PLOS ONE, 11: 1–28.

Weijerman, M., Fulton, E. A., and Brainard, R. E. 2016. Management Strategy Evaluation Applied to Coral Reef Ecosystems in Support of Ecosystem-Based Management. PLOS ONE, 11: e0152577. https://dx.plos.org/10.1371/journal.pone.0152577.

Wernberg, T., Bennett, S., Babcock, R. C., de Bettignies, T., Cure, K., Depczynski, M., Dufois, F., *et al.* 2016. Climate-driven regime shift of a temperate marine ecosystem. Science, 353: 169–172. https://www.sciencemag.org/lookup/doi/10.1126/science.aad8745.

Whitney, C. K., and Ban, N. C. 2019. Barriers and opportunities for social-ecological adaptation to climate change in coastal British Columbia. Ocean and Coastal Management, 179.

Widdicombe, S., and Spicer, J. I. 2008. Predicting the impact of ocean acidification on benthic biodiversity: What can animal physiology tell us? JOURNAL OF EXPERIMENTAL MARINE BIOLOGY AND ECOLOGY, 366: 187–197.

Widdicombe, S., Dashfield, S. L., McNeill, C. L., Needham, H. R., Beesley, A., McEvoy, A., Oxnevad, S., *et al.* 2009. Effects of CO2 induced seawater acidification on infaunal diversity and sediment nutrient fluxes. MARINE ECOLOGY PROGRESS SERIES, 379: 59–75.

Wigham, B. D., Tyler, P. A., and Billett, D. S. M. 2003. Reproductive biology of the abyssal holothurian Amperima rosea: an opportunistic response to variable flux of surface derived organic matter? JOURNAL OF THE MARINE BIOLOGICAL ASSOCIATION OF THE UNITED KINGDOM, 83: 175–188.

Wijgerde, T., Jurriaans, S., Hoofd, M., Verreth, J. A. J., and Osinga, R. 2012. Oxygen and Heterotrophy Affect Calcification of the Scleractinian Coral Galaxea fascicularis. PLOS ONE, 7.

Williams, J. W., Jackson, S. T., and Kutzbacht, J. E. 2007. Projected distributions of novel and disappearing climates by 2100 AD. PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA, 104: 5738–5742.

Willis, C., and Bailey, M. 2020. Tuna trade-offs: Balancing profit and social benefits in one of the world's largest fisheries. Fish and Fisheries, 21: 740–759. https://onlinelibrary.wiley.com/doi/abs/10.1111/faf.12458.

Wilson, D. C. 2009. The Paradoxes of Transparency : Science and the Ecosystem Approach to Fisheries Management in Europe. Amsterdam University Press, Amsterdam. http://dare.uva.nl/aup/nl/record/323548.

WISHNER, K., LEVIN, L., GOWING, M., and MULLINEAUX, L. 1990. INVOLVEMENT OF THE OXYGEN MINIMUM IN BENTHIC ZONATION ON A DEEP SEAMOUNT. NATURE, 346: 57–59.

Wood, H. L., Spicer, J. I., and Widdicombe, S. 2008. Ocean acidification may increase calcification rates, but at a cost. PROCEEDINGS OF THE ROYAL SOCIETY B-BIOLOGICAL SCIENCES, 275: 1767–1773.

Worm, B., Lotze, H. K., Hillebrand, H., and Sommer, U. 2002. Consumer versus resource control of species diversity and ecosystem functioning. Nature, 417: 848–851.

Worm, B., and Duffy, J. E. 2003. Biodiversity, productivity, and stability in real food webs. Trends Ecol. Evol., 18: 628–632.

Worm, B., Barbier, E. B., Beaumont, N., Duffy, J. E., Folke, C., Halpern, B. S., Jackson, J. B. C., *et al.* 2006. Impacts of biodiversity loss on ocean ecosystem services. Science, 314: 787–90. http://www.ncbi.nlm.nih.gov/pubmed/17082450 (Accessed 29 January 2013).

Worm, B., Hilborn, R., Baum, J. K., Branch, T. a, Collie, J. S., Costello, C., Fogarty, M. J., *et al.* 2009. Rebuilding global fisheries. Science, 325: 578–85. http://www.ncbi.nlm.nih.gov/pubmed/19644114 (Accessed 28 January 2013).

Woulds, C., Cowie, G. L., Levin, L. A., Andersson, J. H., Middelburg, J. J., Vandewiele, S., Lamont, P. A., *et al.* 2007. Oxygen as a control on seafloor biological communities and their roles in sedimentary carbon cycling. LIMNOLOGY AND OCEANOGRAPHY, 52: 1698–1709.

Yasuhara, M., Hunt, G., Cronin, T. M., and Okahashi, H. 2009. Temporal latitudinal-gradient dynamics and tropical instability of deep-sea species diversity. PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA, 106: 21717–21720.

Yasuhara, M., Hunt, G., Cronin, T. M., Hokanishi, N., Kawahata, H., Tsujimoto, A., and Ishitake, M. 2012a. Climatic forcing of Quaternary deep-sea benthic communities in the North Pacific Ocean. PALEOBIOLOGY, 38: 162–179.

Yasuhara, M., Hunt, G., van Dijken, G., Arrigo, K. R., Cronin, T. M., and Wollenburg, J. E. 2012b. Patterns and controlling factors of species diversity in the Arctic Ocean. JOURNAL OF BIOGEOGRAPHY, 39: 2081–2088.

Yasuhara, M., Hunt, G., Breitburg, D., Tsujimoto, A., and Katsuki, K. 2012c. Human-induced marine ecological degradation: micropaleontological perspectives. ECOLOGY AND EVOLUTION, 2: 3242–3268.

Yool, A., Popova, E. E., and Coward, A. C. 2015. Future change in ocean productivity: Is the Arctic the new Atlantic? JOURNAL OF GEOPHYSICAL RESEARCH-OCEANS, 120: 7771–7790.