

Exploring the impacts of climate change on fisheries resources within the NAFO Convention Area

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Abstract

Climate change is impacting marine species, populations, ecosystems, and the fisheries and communities they support. While there is broad agreement that climate change should be considered when assessing the status of exploited stocks and making harvest decisions, there is little consensus on how to do so. This study aims to increase knowledge and awareness of climate change and its impacts on fisheries and ecosystems across the Northwest Atlantic Fisheries Organization (NAFO) Convention Area, following NAFO's 2023 resolution to address the effects of climate change on NAFO fisheries and to provide guidance on adaptation and mitigation in support of climate-resilient fisheries. A comprehensive literature review was undertaken, supplemented by analyses of projected climate change and its ecological impacts across the NAFO Convention Area. Various climate changes are observed and projected, including surface and bottom warming, deoxygenation, acidification, reduced sea ice, and altered mixing and nutrient flux. These climate changes are associated with a range of ecological shifts, including altered productivity and mortality rates, geographic range shifts toward more northerly and/or deeper waters, earlier ages at maturity but reduced body sizes, shifted phenology, and trophic mismatches, with disproportionate impacts on high-trophic species. Half of the species examined in the NAFO Convention Area are at high risk of being adversely affected by anthropogenic climate change over the next 75 years. In many areas, climate impacts on fisheries living resources are already occurring or are projected within the next few decades. However, a notable lack of information on climate change impacts was observed for some species, leading to uncertainty in climate risk assessments. Interpreting these findings within the NAFO fisheries management context and in light of its ecosystem approach to fisheries roadmap, several approaches to addressing the impacts of climate change on NAFO fisheries are discussed.

Keywords: Northwest Atlantic Ocean, climate change, climate vulnerability, climate risk, fisheries, fisheries management, Northwest Atlantic Fisheries Organization, climate impacts

Introduction

The ocean climate varies naturally at seasonal, decadal, and multidecadal scales, but for the past century, it has been systematically changing due to human activities (IPCC, 2019). Seasonal and decadal-to-multidecadal climate variation and its effects on marine life can be immense but short-lived (Behrenfeld *et al.*, 2006; Martinez *et al.*, 2009; Boyce *et al.*, 2010). In contrast, longer-term, anthropogenically driven climate changes tend to be of smaller magnitude year over year but can cause abrupt, unanticipated and lasting effects on marine life (Scheffers *et al.*, 2016). Further, shorter-term climate variation and longer-term climate changes are increasingly interacting to create shifting patterns of seasonality and more frequent and extreme climate fluctuations (Nin *et al.*, 2009; Wang *et al.*, 2019; Shin *et al.*, 2022).

These climate changes affect marine life through a complex web of pathways, 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.*, 2020a). Climate change is expected to have significant effects on the distribution, yield, and productivity of marine fishing (Bryndum-Buchholz *et al.*, 2018; Free *et al.*, 2019; Lotze *et al.*, 2019; Boyce *et al.*, 2020a). Nevertheless, studies also suggest that appropriate management can improve fisheries status (Gaines *et al.*, 2018; Hilborn *et al.*, 2020) and offset adverse climate change effects—in some situations, compensating for harmful effects and amplifying positive effects (*e.g.*, Le Bris *et al.*, 2018). There is an urgent need to account for both short-term variability and long-term trends in the climate system when assessing and managing

marine fisheries to achieve sustainable outcomes now and in the future. This is particularly challenging for the Northwest Atlantic, one of the most dynamic regions of the global ocean that exhibits huge seasonal and decadal-to-multidecadal variation (Visbeck *et al.*, 2001) and is a hotspot of climate change (Hurrell *et al.*, 2006; Delworth *et al.*, 2016).

The extent to which fisheries management strategies in the North Atlantic account for climate change varies but is generally low (*e.g.*, Boyce *et al.*, 2021; Kulka *et al.*, 2022; Pepin *et al.*, 2022). The limited climate consideration in the North Atlantic, and elsewhere, may contribute to the shortcomings of many fisheries management approaches worldwide (Garcia and Grainger 1997; Worm *et al.*, 2009; Brander 2010; Pershing *et al.*, 2015) and associated fish population collapses and delayed recoveries (Baum *et al.*, 2003; Myers and Worm 2003, 2005; Worm *et al.*, 2009; Hutchings *et al.*, 2010). Delays in implementing climate adaptation measures are expected to exacerbate these risks (Melvin *et al.*, 2016), and there is an urgency to understand how fisheries can be managed in a climate-considered manner (Lawler *et al.*, 2010; Pinsky and Mantua 2014; Gattuso *et al.*, 2015; Busch *et al.*, 2016; Ojea *et al.*, 2017; Holsman *et al.*, 2019). As a result, the 2021 United Nations (UN) General Assembly Sustainable Fisheries Resolution A/RES/76/71 calls on regional fisheries management organizations (RFMOs) to consider the profound implications of climate change for fisheries, as well as the science and adaptive management actions likely to be required in the future. Likewise, at the 35th meeting of the United Nations Food and Agriculture Organization's (FAO) Committee on Fisheries (COFI), an emphasis was placed on the need to increase the knowledge and awareness of climate change impacts in fisheries and aquaculture and the need to be able to provide climate-resilient fisheries advice and management. In 2023, NAFO adopted a resolution (NAFO/COM 23-13) on addressing the impacts of climate change (NAFO, 2023); (see [SI](#) for details of the resolution). To paraphrase, the resolution outlined NAFO efforts to summarize and evaluate current and projected climate changes and their impacts on ecosystems, as well as target and non-target species across the Northwest Atlantic region, paying specific attention to the Northwest Atlantic Fisheries Organization (NAFO) Convention Area (Fig. 1); consider how climate change could be more explicitly considered in decision-making via the NAFO Ecosystem Roadmap; and identify data gaps and research needs as they relate to climate impacts and adaptation within NAFO.

This study supports this work by 1) reviewing the scientific basis for climate change and its impacts on Northwest Atlantic fisheries resources, 2) conducting a targeted assessment of climate impacts and risks on fisheries living resources within the NAFO Convention Area, 3) proposing pathways for increasing climate change considerations within Northwest Atlantic Fisheries Organization

(NAFO) assessments and management measures, and 4) exploring how climate variability and change could be more explicitly integrated within NAFO's current EAF management system (Koen-Alonso *et al.*, 2019). To our knowledge, this is the first synthesis of current and future climate changes and their impacts, explicitly focused on advancing climate resilience within NAFO.

Our study focuses on Northwest Atlantic ecosystems and the 14 species (hereafter referred to as 'NAFO species') for which NAFO's Scientific Council has previously provided advice, either as part of a recurring assessment schedule, as one-off requests, or as advice of their own accord (*i.e.* not requested). For some species, many stocks are defined within the Convention Area. Some stocks are managed by NAFO (*e.g.*, when distributed in whole or in part outside national EEZs), whereas others are managed by the Coastal States. We focus on the complete distribution of species within the NAFO Convention Area, hereafter referred to as the NW Atlantic, rather than the stock structure. By examining the potential impacts of climate change at a large spatial scale, it is possible to infer effects at smaller scales (*e.g.*, at the stock level) and monitor the potential south-to-north progression of these impacts.

Climate change and its impacts on NW Atlantic ecosystems: past trends and future outlook

This study reviews over 800 publications on the impacts of climate change on fisheries living resources—species, populations, and ecosystems (see [Supplementary Information and Table S1](#) for search criteria and summary tables); it organizes them into climate change, climate impacts, and climate futures.

Climate changes: A physical and biogeochemical basis

The NW Atlantic is a climate change hotspot (Boyce *et al.*, 2010, 2020b; Hutchings *et al.*, 2012; Loder *et al.*, 2013; Niemi *et al.*, 2019; Alexander *et al.*, 2020; DFO 2022). Since 1900, surface waters across the NW Atlantic have warmed more rapidly (0.93°C; S.D. = 0.47°C) than the global average (Boyce *et al.*, 2020b), with 2012 and 2023 being anomalously warm (Bernier *et al.*, 2023). Rapid warming has occurred in the Gulf of Maine, particularly between 2005 and 2015 (Pershing *et al.*, 2015). Bottom temperatures have also risen in some areas of the NW Atlantic, albeit more modestly (Hutchings *et al.*, 2012b; Loder *et al.*, 2013; Niemi *et al.*, 2019; IPCC, 2019; Cyr and Galbraith 2021; DFO 2022; du Pontavice *et al.*, 2023). In other areas, such as the Newfoundland and Labrador shelf and the Eastern Arctic, strong natural fluctuations at decadal timescales may also influence the thermal habitat of benthic species (Cyr *et al.*, 2025).

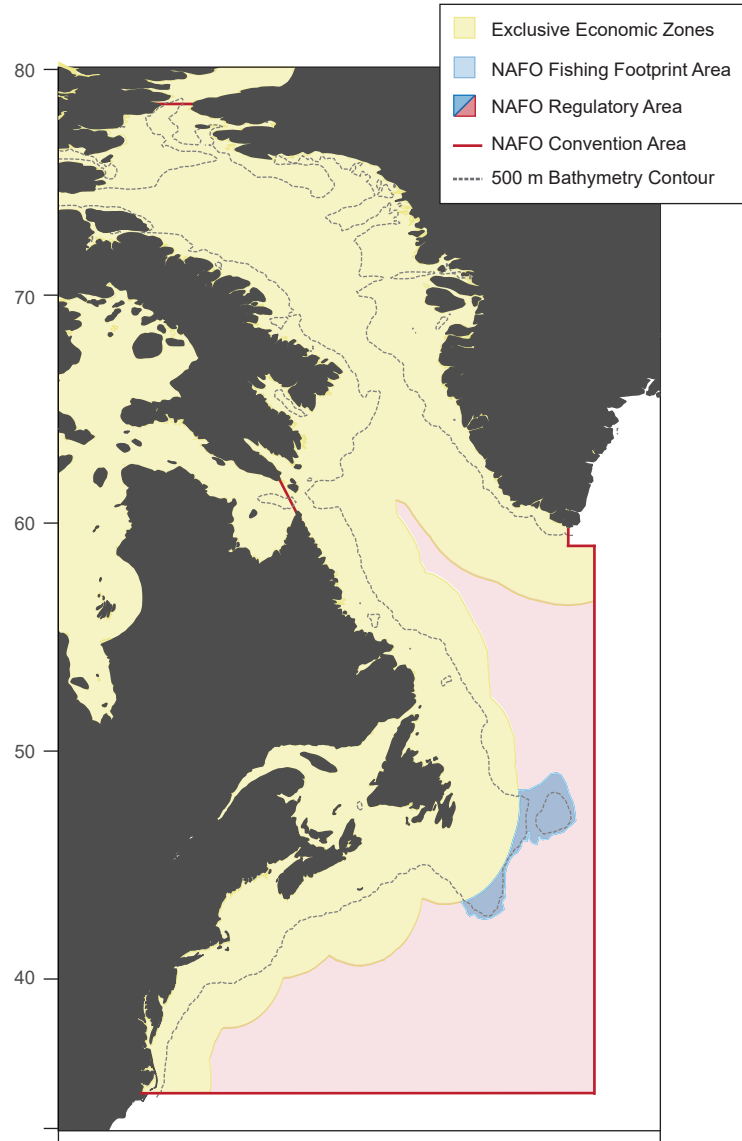


Fig. 1: The NAFO convention area (red lines), regulatory area (red shaded area and blue shaded area) and exclusive economic zones (yellow shading). The gray dashed line depicts the 500 bathymetric contour.

Winter warming across the Northwest Atlantic is associated with reduced sea-ice volume and shorter sea-ice seasons. Arctic sea ice cover in both summer and winter has been declining since 1979, with the September sea ice extent declining by 12% per decade and a projected ice-free Arctic by the fall of 2071 (Hutchings *et al.*, 2012a). Arctic sea ice thickness declined by 48% between 1980 and 2008 (Kwok and Rothrock, 2009). Linearly declining sea ice extent and thickness were also 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

(Hutchings *et al.*, 2012a). Sea ice volume and duration have declined in Newfoundland and Labrador since 1969, with the third-lowest value recorded in 2021 (Cyr *et al.*, 2022).

In conjunction with rising temperatures, climate change is a primary driver of ocean deoxygenation (Hutchings *et al.*, 2012b; Stendaro and Gruber, 2012; Loder *et al.*, 2013; FAO 2018; Niemi *et al.*, 2019; IPCC, 2019; Borggaard *et al.*, 2020; Bernier *et al.*, 2023). Dissolved oxygen declined in almost all regions of the North Atlantic, including the northwest Atlantic, between 1960 and 2009 (Stendaro and Gruber, 2012). Globally,

warming is estimated to account for approximately 50% of the oxygen loss in the upper 1 000 m of the ocean (Breitburg *et al.*, 2018). Warming-driven stratification and reduced nutrient supply in conjunction with increasing frequency and magnitude of phytoplankton blooms (Dai *et al.*, 2023) have exacerbated reductions in dissolved oxygen and 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.*, 2023). Such deoxygenation reduces the quality and quantity of marine habitats and, in extreme conditions, can even result in mass die-offs and “dead zones” that are largely devoid of marine life.

Increasing carbon dioxide emissions are absorbed by the upper oceans, lowering their pH, a process known as acidification. Acidification in the Northwest Atlantic is increasing faster than in most other oceans (Hutchings *et al.*, 2012b; IPCC, 2019; Boyce *et al.*, 2020b; Bernier *et al.*, 2023). Significant acidification has also been reported in coastal areas near large estuaries and cold-water currents (Peck and Pinnegar, 2018). Acidification is especially relevant at high latitudes because CO_2 solubility is higher in colder waters, and the aragonite saturation horizon shoals with depth (Fabry *et al.*, 2008), leading to an earlier onset of undersaturation. 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).

Climate change is associated with increased frequency and intensity of climate extremes (Meehl and Tebaldi, 2004; IPCC *et al.*, 2012; Thompson *et al.*, 2013; Oliver *et al.*, 2018). For instance, Oliver *et al.*, (2018) reported that the average frequency and duration of marine heatwaves have significantly increased by 34% and 17% since 1925. Notable marine heatwaves occurred in the Northwest Atlantic in 2012 (Chen *et al.*, 2014; Mills *et al.*, 2024); for instance, in the northeast U.S., more frequent marine heatwaves were associated with distributional shifts, altered growth patterns, and thermal stress (Mills *et al.*, 2024).

Surface warming is linked with reduced mixing, enhanced vertical stratification and reduced nutrient availability (Behrenfeld *et al.*, 2006; Polovina *et al.*, 2008; Boyce *et al.*, 2010, 2014; Lewandowska *et al.*, 2014) and a decline in phytoplankton concentration across the Northwest Atlantic ($-0.6\% \text{ yr}^{-1}$; 1911–2010) and the Arctic ($-0.4\% \text{ yr}^{-1}$; 1899–2005) oceans over the past century (Boyce *et al.*, 2010, 2014) and in the NW Atlantic between 1999 and 2016 (Bernier *et al.*, 2023). However, while phytoplankton concentrations are declining overall, coastal blooms are becoming more frequent and intense (Dai *et al.*, 2023). Warming, stratification, and reduced nutrient concentrations have been associated with increases in picophytoplankton ($<0.2 \mu\text{m}$) across the North Atlantic (Morán *et al.*, 2009) and shifts in phytoplankton species groups, including diatoms, dinoflagellates,

and coccolithophores (Cermeno *et al.*, 2008; Hinder *et al.*, 2012; Barton *et al.*, 2016) and rapid poleward and eastward shifts in many species in the North Atlantic Ocean (Barton *et al.*, 2016).

Climate-related changes in the cyclic seasonal development (phenology) of phytoplankton occurred in the NW Atlantic between 1999 and 2016, with considerable variability in the magnitude and timing of the spring bloom and a gradual decline in its duration (Bernier *et al.*, 2023). The decline in spring bloom duration in the NW Atlantic is comparable to reports that the duration of the phytoplankton growing season has declined at temperate-polar latitudes ($35\text{--}65^\circ\text{N}$) between 1998 and 2007, coincident with surface temperature changes (Racault *et al.*, 2012). Seasonal changes in the environment and in the abundance of marine organisms have also been observed in the Gulf of Maine (GoM). Record *et al.*, (2019) reported that spring and autumn blooms had shifted later by 1–9 days per decade since 1960, associated with changes in temperature, nutrients, and salinity. Alternatively, a review of 20 studies in the GoM found that spring onset had generally shifted earlier, autumn onset later, and event duration had increased (Staudinger *et al.*, 2019). These studies highlight that the impact of changing phenology is often challenging to capture and can be highly species- and driver-specific. Despite strong interannual variability in phytoplankton bloom timing on the Newfoundland shelf, no long-term changes have been detected (Cyr *et al.*, 2024).

Zooplankton shifts have also been documented, with an increase in small warm-water zooplankton and a reduction in the large, energy-rich copepod *Calanus finmarchicus* (Bernier *et al.*, 2023). *C. finmarchicus* has been declining across the NW Atlantic since 2009. Alternatively, smaller copepods such as *Pseudocalanus* spp. have increased, particularly on the Newfoundland Shelf (Bernier *et al.*, 2023).

Alongside long-term climate changes, interdecadal to multidecadal climate variability is significant across the NW Atlantic. The North Atlantic Oscillation (NAO) is a dominant signature of climate variability, with the lower frequency Atlantic Multidecadal Oscillation (AMO) being of secondary importance (Visbeck *et al.*, 2001; Hurrell and Deser, 2009; Martinez *et al.*, 2009; Boyce *et al.*, 2010; Delworth *et al.*, 2016). The NAO causes abrupt changes in temperature, wind, and other climate fields that have a wide range of impacts throughout marine ecosystems, affecting fisheries (Parsons and Lear, 2001; Ottersen *et al.*, 2001). The NAO has low predictability and is poorly represented in climate models, making its impacts on fish stocks difficult to anticipate.

Climate impacts on marine life

Distributional shifts are a common ecological response to climate change, with species often shifting into either

deeper or more northern waters, presumably in search of more thermally suitable habitat (Dulvy *et al.*, 2008; Pinsky *et al.*, 2013; Cheung *et al.*, 2016a; Kleisner *et al.*, 2017), 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; Mills *et al.*, 2024), North Sea (Perry *et al.*, 2005), and the Denmark Strait (MacKenzie *et al.*, 2014). For example, Nye *et al.*, (2009) reported poleward shifts in 17 of 36 commercial fish stocks between 1968 and 2007 in US waters associated with ocean warming. Climate change has also been associated with a northward expansion of bluefin tuna outside their usual range and into the subpolar waters near Greenland (MacKenzie *et al.*, 2014).

DFO has recently noted an increasing number of exotic warm-water species reported on the Scotian Shelf and Bay of Fundy (Bernier *et al.*, 2023), as well as a rapid increase in the abundance of some temperate species, such as silver hake, off southern Newfoundland (DFO 2025). 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). It is unclear how the introduction of new species and the emigration of others will affect marine ecosystems and fisheries in the NW Atlantic.

Delayed timing of seasonal plankton blooms can affect larval fish survivorship, affecting adult productivity (Cushing 1969, 1990). Platt *et al.*, (2003) reported reduced survivorship of larval haddock on the Eastern Scotian Shelf, where the spring phytoplankton bloom was delayed. Koeller *et al.*, (2009) reported that shrimp (*Pandalus borealis*) 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, associated with seasonal temperature changes (Asch, 2015).

Ocean warming is associated with changes in growth rates and reduced sizes of plankton, fish, and invertebrates (Drinkwater, 2005; Li *et al.*, 2009; Shackell *et al.*, 2010; Sheridan and Bickford, 2011; Cheung *et al.*, 2013a). Shackell *et al.*, (2010) reported a 60% decline in the average body mass of predatory fish and invertebrate species between 1970 and 2008, coinciding with increasing temperatures, stratification, and size-selective harvesting. 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, on trophic interactions, and on ecosystem structure.

Increases in smaller-sized plankton and reductions in

larger, energy-rich ones (Bernier *et al.*, 2023) likely affect energy flow and fisheries production. Due to 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 food web instead of being 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 strongly affect the amount of organic matter exported to support deep-sea ecosystems and fisheries.

Temperature affects predator-prey (trophic) interactions globally (Boyce *et al.*, 2015b) and across the NW Atlantic ocean (Frank *et al.*, 2006, 2007; Petrie *et al.*, 2009). However, understanding how temperature changes influence trophic dynamics is notoriously challenging, as effects can operate through direct and indirect pathways and be time-lagged. Shackell *et al.*, (2010) reported that while predator biomass remained constant over time, reductions in their average size eroded their predation efficiency, leading to a 300% increase in prey biomass between 1990 and 2008. Warming can also decouple predators' and prey's metabolic demands, affecting predation intensity. For example, Grady *et al.*, (2019) 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. In contrast, those of warm-blooded endotherms (*e.g.*, mammals, some tunas, sharks, and billfish) would remain constant. Consequently, ectotherms would benefit from consuming more available prey than endotherms. Resolving the biological impacts of warming on marine species is one of the critical uncertainties and limitations to projecting the effects of climate on marine species and ecosystems (Taucher and Oschlies, 2011; Lotze *et al.*, 2019).

Reduced oxygen, combined with warming and associated changes in metabolism, can reduce fish size (Shackell *et al.*, 2010; Cheung *et al.*, 2012) and reproductive output (Barneche *et al.*, 2018). Hypoxia has been associated with mass mortality events in marine species and is known to adversely affect growth, reproduction, and distribution (Diaz and Rosenberg, 2008; Altieri *et al.*, 2017).

Acidification adversely affects the ability of plankton, molluscs, crustaceans, and corals to form calcium carbonate skeletons. Ocean pH can be spatiotemporally variable (Gibb *et al.*, 2023). Acidification can cause tissue damage in larval Atlantic cod, increasing susceptibility to infection (Frommel *et al.*, 2012).

While poorly resolved, climate-driven shifts in bacteria, viruses and infection rates are likely to impact marine ecosystems and fisheries profoundly (Cavicchioli *et al.*, 2019). Increases in storm surges and sea level rise are projected to expand bacteria's geographic and seasonal

ranges (Burge *et al.*, 2014). Climate-driven warming and salinity changes have already been associated with a poleward range shift of outbreaks of *Vibrio*, a bacterium that can have devastating effects on fish (Ina-Salwany *et al.*, 2019), in the North Atlantic, the North Sea, the Baltic Sea, and Alaska (Burge *et al.*, 2014; Vezzulli *et al.*, 2016). Climate change may also render some species more susceptible to infection. In the Arctic, warming is projected to increase disease transmission among species in the Eastern and Western Arctic ecosystems. Disease outbreaks can also cause mass mortality of keystone species such as sea stars and urchins, leading to cascading ecosystem effects (Harvell *et al.*, 2019). Given the potentially severe consequences for fisheries productivity, monitoring for changes in disease transmission and infection rates is vital to managing fisheries under climate change.

Climate extremes, including marine heatwaves, have been associated with habitat loss (Wernberg *et al.*, 2016; Hughes *et al.*, 2017), reduced primary production and harmful algal blooms (Jöhnk *et al.*, 2008; 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). Conversely, a recent study found that the ecological impacts of marine heatwaves on demersal fish were minimal and indistinguishable from natural variability (Fredston *et al.*, 2023).

The current review highlighted that understanding the impacts of climate on marine life is complex and challenging (Table 1 and Fig. 2). Impacts are often mediated through multiple stressors (*e.g.*, temperature, oxygen, pH, or ocean circulation; Fig. 2A) and operate through several direct (*e.g.*, metabolic rates, egg incubation time, survival) and indirect (*e.g.*, altered prey availability or predation) pathways that can affect species synergistically or antagonistically and can vary depending on the life history stage and geographic location (Fig. 3C). Coincident impacts, such as exploitation, can further obscure the detection of climate effects. Notwithstanding the variety and complexity of climate impacts, some general patterns have emerged (Table 1 and Fig. 2), including warming-driven increases in growth rates and associated reductions in body sizes and earlier ages at maturity (Drinkwater, 2005; Li *et al.*, 2009; Shackell *et al.*, 2010; Sheridan and Bickford, 2011; Cheung *et al.*, 2013a); disproportionate climate impacts on high relative to low trophic species (Kirby and Beaugrand, 2009; Kwiatkowski *et al.*, 2019; Lotze *et al.*, 2019); metabolic decoupling leading to increased grazing rates on phytoplankton (O'Connor *et al.*, 2009; Lewandowska *et al.*, 2014); competitive advantages of ectothermic species over endothermic (Grady *et al.*, 2019); and shifts in species distributions to more northern and deeper ocean waters (Nye *et al.*, 2011; Shackell *et al.*, 2012; Pinsky *et al.*, 2013; MacKenzie *et al.*, 2014; Walsh *et al.*, 2015; Morley *et al.*, 2018; Mullaney *et al.*, 2023).

North Atlantic climate futures

Ocean warming is projected to continue at higher-than-average rates throughout the NW Atlantic over the next century (Saba *et al.*, 2016; Boyce *et al.*, 2020b). These changes are expected to increase fisheries catch potential in higher latitudes and 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.*, 2020a; Bryndum-Buchholz *et al.*, 2020); (Table S4). 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 (Niemi *et al.*, 2019; Lotze *et al.*, 2019; Boyce *et al.*, 2020a; Bryndum-Buchholz *et al.*, 2020) and nearshore waters of the northwest Atlantic, with uncertainty varying by emission scenario (IPCC, 2019b).

Boyce *et al.*, (2020b) reported that marine animal biomass is projected to decline across most of the southern NW Atlantic (<~60°N), with increases in the Arctic under high emissions (Fig. 5.2 in Boyce *et al.*, 2020b). These projections broadly agree with reports that under high emissions, 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 ($\pm 29.5\%$); (Bryndum-Buchholz *et al.*, 2020).

Across the NW Atlantic, waters that supported the highest fishery landings during 2000–2018 were projected to lose the greatest marine animal biomass due to climate change, regardless of the emission scenario (Fig. 5.5 in Boyce *et al.*, 2020b). This suggests that ongoing climate change will disrupt fisheries across the NW Atlantic and that fisheries will either need to track the spatial redistribution of fish biomass or experience reduced catch. Either way, a significant disruption to the fishing industry is likely, particularly under high-emissions scenarios. This report further noted that areas projected to experience the largest climate-driven losses in marine animal biomass are subjected to many additional stressors, such as pollution, fishing pressure, shipping traffic, and acidification, indicating that there may well be unanticipated synergies between the impacts of climate change on fisheries and the effects of other human activities.

Climate-driven species redistributions (Nye *et al.*, 2009; Pinsky *et al.*, 2013; MacKenzie *et al.*, 2014) are projected to continue (Morley *et al.*, 2018; Allyn *et al.*, 2020). Under high emissions, 23% of transboundary fish stocks—those that move across the exclusive economic zones of two or more countries—are expected to shift by 2030, with 45% shifting by 2100 (Palacios-Abrantes *et al.*, 2022). Such projected shifts in species distributions are particularly apparent across the northwest Atlantic. Shackell *et al.*, (2014) predicted changes in the thermal habitat of 46 marine species in the Northwest Atlantic (~35°N to ~48°N), reporting that by 2060, most species (55%)

Table 1. Observed climate trends and their effects on marine life within the NW Atlantic. Table references are in the [supplementary materials](#).

Phenomenon	Pattern or Trend	References
Range expansion or contraction	- By 2060, 55% of species are projected to lose thermal habitat, 21% gain and 24% remain constant.	(Nye <i>et al.</i> , 2009, 2011; Cheung <i>et al.</i> , 2013b; Pinsky <i>et al.</i> , 2013; Shackell <i>et al.</i> , 2014; Morley <i>et al.</i> , 2018; Allyn <i>et al.</i> , 2020; Mills <i>et al.</i> , 2024)
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 north-eastern US; mostly northward	(Nye <i>et al.</i> , 2011; Shackell <i>et al.</i> , 2012; Pinsky <i>et al.</i> , 2013; MacKenzie <i>et al.</i> , 2014; Walsh <i>et al.</i> , 2015; Kleisner <i>et al.</i> , 2017; Morley <i>et al.</i> , 2018)
Depth distribution	- A shift towards inhabiting deeper, colder waters	(Shackell <i>et al.</i> , 2012; Pinsky <i>et al.</i> , 2013; Morley <i>et al.</i> , 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 <i>et al.</i> , 2014; Bernier <i>et al.</i> , 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 - Trophic mismatch between phytoplankton spring bloom and larval haddock and shrimp.	(Platt <i>et al.</i> , 2003; Edwards <i>et al.</i> , 2004; Koeller <i>et al.</i> , 2009; Walsh <i>et al.</i> , 2015; Niemi <i>et al.</i> , 2019; Record <i>et al.</i> , 2019; Staudinger <i>et al.</i> , 2019)
Trophic amplification	- Increased zooplankton grazing - Increased predation of ectotherms relative to endotherms - A shift towards resource control of marine ecosystems - Stronger adverse climate impacts on high trophic species relative to low	(Frank <i>et al.</i> , 2006, 2007; Kirby and Beaugrand, 2009; Petrie <i>et al.</i> , 2009; Boyce <i>et al.</i> , 2015; Grady <i>et al.</i> , 2019; Kwiatkowski <i>et al.</i> , 2019; Lotze <i>et al.</i> , 2019)
Size structure	- Reduction in size of primary and secondary producers	(Drinkwater, 2005; Li <i>et al.</i> , 2009; Shackell <i>et al.</i> , 2010; Sheridan and Bickford, 2011; Cheung <i>et al.</i> , 2013a)
Temperature	- Warming almost everywhere - Rapid warming in the Gulf of Maine, Gulf of St. Lawrence, Scotian Shelf - Increasing frequency and severity of marine heatwaves	(Hutchings <i>et al.</i> , 2012; Saba <i>et al.</i> , 2016; Frölicher <i>et al.</i> , 2018; Oliver <i>et al.</i> , 2018, 2019; Greenan <i>et al.</i> , 2019; Cheung and Frölicher, 2020; Amaya <i>et al.</i> , 2023)
Freshwater flux	- Increased at high latitudes from hydrological cycle intensification	(Durack and Wijffels, 2010; Durack <i>et al.</i> , 2012)
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 <i>et al.</i> , 2012; Hutchings <i>et al.</i> , 2012; Stroeve <i>et al.</i> , 2012; Bernier <i>et al.</i> , 2018; Niemi <i>et al.</i> , 2019)
Stratification	- Increased, especially at low latitudes - Associated with nutrient limitations at low to mid-latitudes	(Behrenfeld <i>et al.</i> , 2006; Polovina <i>et al.</i> , 2008)
Acidification	- Increasing, especially in the Gulf of St. Lawrence and Arctic - Negative effects on calcifying species	(Doney <i>et al.</i> , 2009; Steinacher <i>et al.</i> , 2009; Wanninkhof <i>et al.</i> , 2015; Bernier <i>et al.</i> , 2018; Peck and Pinnegar, 2018; Niemi <i>et al.</i> , 2019)
Deoxygenation	- Follows the global deoxygenation trends with widespread spatial variability driven by natural oscillations. - Deoxygenation is driven by the retreat of the Labrador Current and a slowdown of the Atlantic Meridional Overturning Circulation.	(Johnson and Gruber, 2007; Frölicher <i>et al.</i> , 2009; Hoegh-Guldberg and Bruno, 2010; Stando and Gruber, 2012; Stramma <i>et al.</i> , 2012; Bernier <i>et al.</i> , 2018; Claret <i>et al.</i> , 2018; Niemi <i>et al.</i> , 2019)
Primary production	- Spatially variable but declining, especially at low latitudes - Complex responses in the Arctic, including changes from ice algae to phytoplankton, moderate declines in some areas but increases in others - More frequent, intense, and widespread blooms.	(Gregg <i>et al.</i> , 2003; Behrenfeld <i>et al.</i> , 2006; Boyce <i>et al.</i> , 2010, 2014; Niemi <i>et al.</i> , 2019; Dai <i>et al.</i> , 2023)
Disease transmission	- Increased, especially at high latitudes.	(Ward and Lafferty, 2004; Frommel <i>et al.</i> , 2012; Burge <i>et al.</i> , 2014; Vezzulli <i>et al.</i> , 2016)
Growth and demography	- Faster growth - Earlier age at maturity	(Atkinson, 1994; Ohlberger, 2013; Niu <i>et al.</i> , 2023)

Notes: “Borealization” = Northward expansion or increased dominance of species adapted to boreal (cold-temperate) conditions into Arctic or high-latitude ecosystems. “Tropicalization” = An increase in warm-water (tropical or subtropical) species or expansion of their ranges into temperate ecosystems. “Deepening” = The downward movement of marine species into deeper, cooler waters. “Species invasion” = The arrival, establishment, and spread of species into new regions.

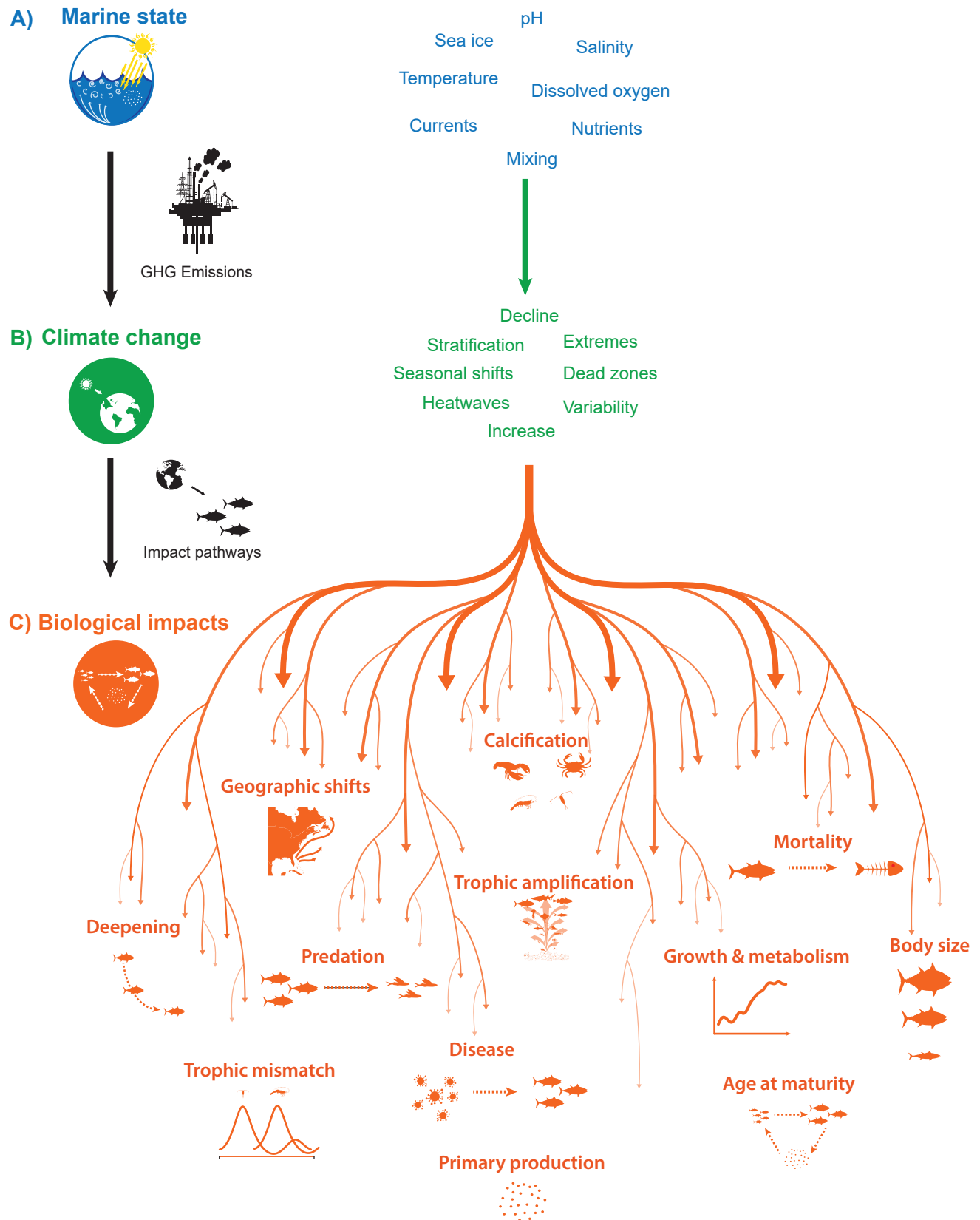


Fig. 2: Complex, multifaceted climate impact pathways on marine life. The marine environment is characterized by several state variables (A; blue) that, due to anthropogenic greenhouse gas (GHG) emissions, are undergoing diverse temporal shifts (B; green). The large number of climate change pathways creates a complex, multifaceted array (orange arrows) through which climate change can affect marine species, populations, ecosystems, and fisheries (C; orange). Note: “trophic amplification” = The process by which climate-driven environmental changes produce increasingly larger ecological impacts at higher trophic levels than at lower ones.

would lose thermal habitat, with 21% gaining and 24% remaining constant; in the US, 65% of species lost thermal habitat, with 20% gaining and 15% remaining constant. Planktivores such as herring, sand lance, and capelin were predicted to lose significant habitat in 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.

Biodiversity patterns, too, are projected to shift under climate change. Reygondeau *et al.*, (2020) projected shifts in the geographic distribution of 56 biogeochemical provinces (*i.e.* “Longhurst provinces”)—coherent biogeochemical environments that shape the distribution and abundance of marine biodiversity—between 1950 and 2100 under high and low emission scenarios. The study reported poleward shifts in the distribution of

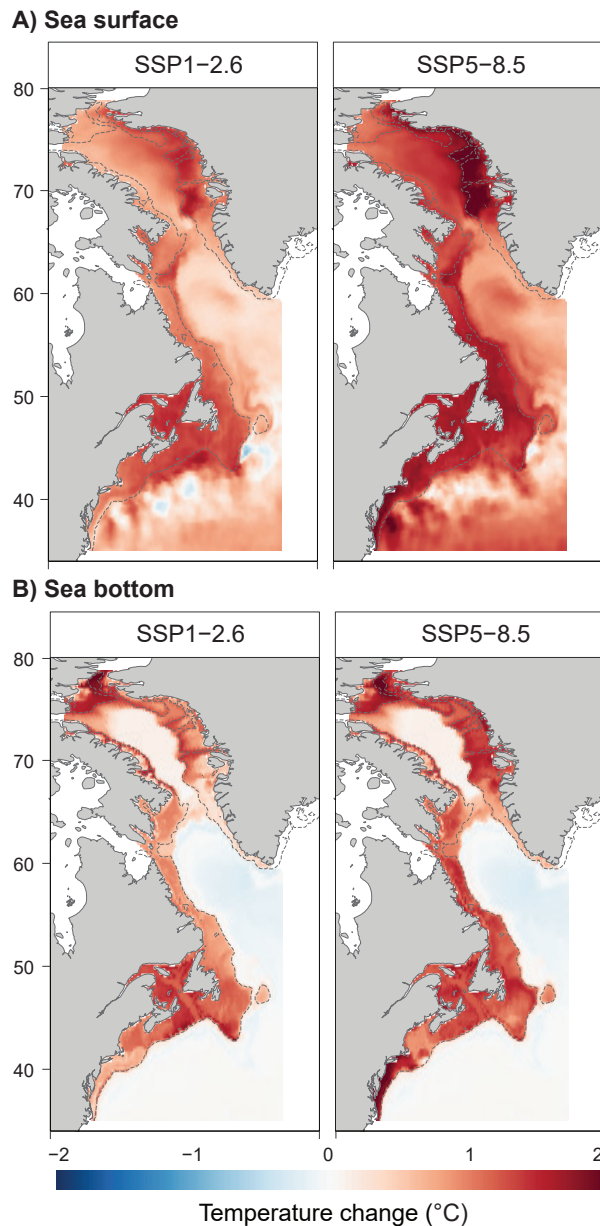


Fig. 3: Climate projections to 2050 across the NW Atlantic from two CMIP6 climate models. Projected future change in average temperature at the sea surface (A) and bottom (B) between 2014–2024 and 2045–2055 under low (left columns) and high (right columns) emissions scenarios. Red depicts warming, and blue depicts cooling.

biogeographic provinces by an average of 18.4 km per decade and the emergence of novel biogeochemical provinces by 2040, which will encompass 1.2% of the global ocean by 2100.

Climate impacts on 14 NAFO species: A semi-quantitative risk evaluation

Approach and data

A literature review of 175 peer-reviewed articles and 12 stock assessments was combined with quantitative analyses of species' projected climate exposure from the Climate Risk Index for Biodiversity (CRIB) framework (Boyce *et al.*, 2022) to arrive at a semi-quantitative climate risk score for the 14 NAFO species (low, medium, high). CRIB climate exposure indices included the species' projected time of climate emergence (yr) and thermal habitat loss (%). The projected timing of climate emergence denotes the anticipated onset of thermal stress for a species. It is calculated as the year in which the projected temperature is projected to exceed the species' thermal niche. Projected thermal habitat loss quantifies the magnitude of anticipated climate impacts on a species and the potential for climate-driven shifts in its geographic range. It was calculated as the proportion of a species' present geographic range over which the projected climate will exceed its thermal niche.

These metrics were calculated for each NAFO species using its geographic distribution predicted by species distribution models (SDMs), thermal niches compiled from a literature review (Table S1), and ocean temperature projections from Earth System Models.

Native geographic distributions for NAFO species were obtained from AquaMaps (Kesner-Reyes *et al.*, 2016). AquaMaps predicts marine species' spatial distribution using environmental niche models validated using independent survey observations (Ready *et al.*, 2010) and evaluated against alternative methodologies and independent datasets (Jones *et al.*, 2012). The native geographic distributions on their 0.5° global grid were statistically rescaled to a 0.25° grid using nearest-neighbour interpolation, as described by Boyce *et al.* (2024).

Climate models were used to project the climate exposure of NAFO species. For pelagic NAFO species, including capelin (*Mallotus villosus*) and shortfin squid (*Illex illecebrosus*), projected sea surface temperatures were used. Projected bottom temperatures were used for demersal species. Monthly sea-surface (SST) and bottom temperature (°C) projections (2015–2100) were obtained from two published Global Earth System Climate Models in the Coupled Model Intercomparison Project Phase 6 (CMIP6) archive to evaluate projected temperature trends across the Northwest Atlantic through 2050. Projections were harmonized onto a regular 0.25°

grid across the NW Atlantic under high (SSP5–8.5) and low (SSP1–2.6) emission scenarios (Meinshausen *et al.*, 2020). While there is ongoing debate about the most likely emission scenario, we evaluated SSP5–8.5 and SSP1–2.6 as the extremes of the most plausible scenarios. Surface and bottom temperature changes were calculated as the difference between the average temperature in the current decade (2014–2024) and 2050 (2045–2055) within each 0.25° grid cell across the NAFO Convention Area. Changes were calculated for each model projection before averaging.

Surface waters are projected to warm across nearly the entire NAFO Convention Area, particularly under high-emissions scenarios and along continental shelves (Fig. 3A). The average surface warming across both emission scenarios in the NW Atlantic was 1°C, with some regions experiencing larger magnitude warming under high emissions (2.5°C) and others slightly cooling under low emissions (-0.8°C). Most of the bottom-water warming occurs within the 500 m isobath, with slight cooling in some deeper offshore waters (Fig. 3B). The average bottom warming across both emission scenarios in the NW Atlantic was 0.45°C, with some regions warming by up to 2.1°C under high emissions or cooling by up to -0.37°C under low emissions. Contrary to expectation, some parts of the Grand Banks experience more significant warming on the seafloor than at its surface.

Climate risk

Together, this analysis and literature review (Table 2) provided a semi-quantitative basis for evaluating climate risk (low, moderate, or high) for each species across the NW Atlantic (Figs. 4 and 5) and also helped to pinpoint where additional information may be required. Boyce *et al.*, (2022) present the peer-reviewed rationale for defining climate risk in relation to thermal habitat loss and climate emergence (*e.g.*, Table S4). In short, species were assessed at high risk if a majority (>50%) of the available studies showed harmful climate impacts, and/or the projected thermal habitat loss to 2050 was over 10%, and/or the average year of climate emergence was early (2060–2090) and highly geographically variable (SD>20 years). Species were at moderate risk if some (~10–50%) of the available studies showed adverse climate impacts, and/or the projected thermal habitat loss to 2050 was ~5–10%, and/or the average year of climate emergence was later (2090s) and moderately geographically variable (SD 15–20 years). Species were at low risk if few (<~10%) or none of the available studies showed adverse climate impacts, and/or the projected thermal habitat loss to 2050 was <5%, and/or the average year of climate emergence was late (2090s) with low geographical variance (SD<15 years).

Half of the fourteen species were assessed to be at high climate risk across the NW Atlantic, including Atlantic

Table 2. Studies into the climate impacts on NAFO-managed species. Habitat loss: The proportion of the species native geographic range projected to become thermally unsuitable. Emergence: The average year when the temperature is projected to exceed the thermal niche of the species across its native geographic range. Risk: The climate risk for the species, considering its projected habitat loss, emergence time, and the available published climate impact studies. Table references are in the [supplementary materials](#).

Highlights	Habitat loss	Emergence	Risk
Atlantic wolffish (<i>Anarhichas lupus</i>)			
<ul style="list-style-type: none"> - Relatively narrow thermal range (-1°C–10°C); (Beese and Kandler, 1969; Albikovskaya, 1982; O’Dea and Haedrich, 2000). - Significantly affected by warming and deoxygenation (Dutil <i>et al.</i>, 2014; Bianucci <i>et al.</i>, 2016; Brennan <i>et al.</i>, 2016; Árnason <i>et al.</i>, 2019; Bluemel <i>et al.</i>, 2022; Lavin <i>et al.</i>, 2022). - Optimal temperature for adult growth is 6.6°C to 8°C for adults (Immsland <i>et al.</i>, 2006; Lamarre <i>et al.</i>, 2009), and 11.5°C for juveniles (Hansen and Falk-Petersen, 2002). - Altered distribution northward and into deeper waters in response to warming (McCarthy <i>et al.</i>, 1999) and shifted migration routes (Orlov <i>et al.</i>, 2023). 	11%	2087±24	High
Capelin (<i>Mallotus villosus</i>)			
<ul style="list-style-type: none"> - Moderately wide thermal range (-1.5°C–14°C) with a preference for waters between -1°C and 6°C (Rose, 2005). - In the late 1980s, cooling led to an extension of capelin distribution into the southern Gulf of St. Lawrence and eastern Scotian Shelf (Gregoire <i>et al.</i>, 2005; Rose, 2005). - Rose (2005) reported temperature changes as small as 1°C associated with changes in distribution over scales of hundreds of kilometers; temperature changes may result in much larger displacements, including the establishment of new spawning sites. - Orlova <i>et al.</i> (2005) reported several indirect effects of climate on capelin distribution and energy reserves involving the abundance and species of copepod prey. - Warming affects vertical migration (Davoren and Montevecchi, 2003) and behaviour (Frank <i>et al.</i>, 2016) and linked to changes in spawning timing (Murphy <i>et al.</i>, 2021). - Climate-driven sea ice reductions affect primary production and prey availability (Buren <i>et al.</i>, 2019). - Limited information about the impacts of changing oxygen and pH. 	17%	2082±30	High
Greenland halibut (<i>Reinhardtius hippoglossoides</i>)			
<ul style="list-style-type: none"> - Moderately wide thermal range (-1.89°C–15°C) with preferred temperatures between 0 and 7°C (Shackell <i>et al.</i>, 2013; Boje <i>et al.</i>, 2014; Ruth <i>et al.</i>, 2023). - Optimal temperature for aerobic scope of 2.4°C (Ruth <i>et al.</i>, 2023), with decreased survival and growth above 7.5°C (Ghinter <i>et al.</i>, 2021). - Temperature affects genomic variation, affecting growth and migration patterns (Ferchaud <i>et al.</i>, 2022). - Warming associated with vertical distribution shifts to maintain preferred temperatures, with younger individuals showing the largest shifts (Wheeland and Morgan, 2020). - Bottom temperature warming between 1993 and 2003 led to increased growth rates of juveniles of 1.6cm°C⁻¹ (Sünksen <i>et al.</i>, 2010). - Experiments indicate that juvenile halibut are sensitive to even small reductions in dissolved oxygen, with severe hypoxia reducing the maximum metabolic rate by 55% (Dupont-Prinet <i>et al.</i>, 2013a). - Juveniles are more sensitive to hypoxia than adults (Dupont-Prinet <i>et al.</i>, 2013a). - Warming and deoxygenation in the Gulf of St. Lawrence projected to reduce the highest density halibut aggregations by 55%; oxygen levels are already at the species limit (Stortini <i>et al.</i>, 2017). 	4%	2094±15	Moderate
Northern shrimp (<i>Pandalus borealis</i>)			
<ul style="list-style-type: none"> - Narrow thermal range (1°C–6°C) with a preferred range of 1–4°C (Allen, 1959; Shumway <i>et al.</i>, 1985; Apollinio <i>et al.</i>, 1986; Colbourne and Orr, 2005) with optimum for larvae is reported to be 9°C. One anomalous study reported an upper thermal limit for shrimp of 12°C (Bjork, 1913). - Warming adversely affects recruitment (Wieland and Siegstad, 2012; Jónsdóttir <i>et al.</i>, 2013). - Warming decreases growth rates, possibly due to increased metabolic demands, leading to reduced body size (Koeller <i>et al.</i>, 2007). - Warming will significantly affect shrimp hatching and recruitment, including altered timing of hatching (Brillon <i>et al.</i>, 2005; Koeller <i>et al.</i>, 2009; Richards, 2012; Arnberg <i>et al.</i>, 2013). - Coherence between shrimp hatching times and phytoplankton seasonal blooms across the North Atlantic driven by bottom temperature (Koeller <i>et al.</i>, 2009), suggesting that climate change could lead to a phenological mismatch (Cushing, 1990) and poor recruitment (but see (Chang <i>et al.</i>, 2021) for an alternative hypothesis). - Relatively tolerant to hypoxia, with males being more tolerant on average than females (Dupont-Prinet <i>et al.</i>, 2013b). 	24%	2073±32	High

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Roughhead grenadier (<i>Macrourus berglax</i>)			
- narrow thermal range (-0.5°C–5.4°C).	31%	2065±31	High
Splendid alphonsino (<i>Beryx splendens</i>)			
- Moderate thermal range (-2°C–17°C).	28%	2072±35	High
Witch flounder (<i>Glyptocephalus cynoglossus</i>)			
- Moderately wide thermal range (-1°C–11.4°C), with 15°C an optimal for larval growth (Bidwell and Howell, 2001).	11%	2087±24	High
Yellowtail flounder (<i>Limanda ferruginea</i>)			
<ul style="list-style-type: none"> - Wide thermal range (-1°C–18°C). - Oxygen consumption declines at temperatures above 14°C (MacIsaac <i>et al.</i>, 1997). - Preferred temperature range is -1 to 5.8° C (Walsh, 1992a), while optimal feeding is between 6.8°C and 7.1°C (Hyun <i>et al.</i>, 2014). - Projected northward shifts from the Gulf of Maine in response to warming (Palacios-Abrantes <i>et al.</i>, 2020). - Temperature variation affects growth and development (Benoît and Pepin, 1999) as well as distribution (Pinhorn and Halliday, 2016) and movement (Hyun <i>et al.</i>, 2014). - Warming negatively affects recruitment variability (Robertson <i>et al.</i>, 2024). - Brodie <i>et al.</i>, (2010) reported positive effects of warming on yellowtail flounder on the Grand Bank, with cooling associated with stock declines and warming with recovery. - Distributions were relatively insensitive to temperature fluctuations (Walsh, 1992). 	7%	2091±20	High
Atlantic cod (<i>Gadus morhua</i>)			
<ul style="list-style-type: none"> - Wide thermal range (-1.5°C–19°C), yet studies have reported an optimal metabolic scope between 10 and 14.5°C (Tirsgaard <i>et al.</i>, 2015). - Optimal growth is higher (15.1°C) for smaller younger individuals (Bolton-Warberg <i>et al.</i>, 2015), and smaller cod have been experimentally found to prefer warmer temperatures (Lafrance <i>et al.</i>, 2005). - Experiments indicate that at 17°C, cod experience heightened immune activity indicative of stress (Lazado <i>et al.</i>, 2023), while at 18°C, they experience energetic limitations (Hu <i>et al.</i>, 2016). - At 9°C, cod have been found to experience erratic spawning frequencies (Kjesbu <i>et al.</i>, 2023). - Temperature significantly affects the geographic distribution of cod (Edvardsson <i>et al.</i>, 2022). - During warmer regimes, cod have been found to inhabit deeper, cooler waters, particularly larger older individuals, while cold regimes led to reduced activity and vertical movement (Freitas <i>et al.</i>, 2015; Nian <i>et al.</i>, 2021). - Winter <i>et al.</i> (2020, 2023) reported that warming exacerbated Allee effects, increasing the risk of population collapse and requiring a larger population size of recovery. - Severe tissue damage at higher CO₂ levels and that continuing increased ocean acidification could affect the survivorship and recruitment of cod (Dahlke <i>et al.</i>, 2022). - Controlled warming of 2°C and 4°C showed that warming might accelerate development and increase mortality in larval cod (Oomen <i>et al.</i>, 2022). - Holt and Jørgensen (Holt and Jørgensen, 2014) predicted that 2°C warming would lead to increased cod growth rates and larger asymptotic sizes, while others have reported increased cod growth and biomass in response to warming (Kjesbu <i>et al.</i>, 2014; Mullaney <i>et al.</i>, 2019; Sguotti <i>et al.</i>, 2023). - Context dependency of temperature effects: Mantzouni <i>et al.</i>, (2010) reported that warming effects were positive on cod recruitment at temperatures below 5°C but negative above it, while Lindmark <i>et al.</i> also reported a temperature threshold effect on cod condition (Lindmark <i>et al.</i>, 2023). - Cod can be sensitive to acidification, with elevated CO₂ levels altering gene expression, suggesting stress at the molecular level (Mittermayer <i>et al.</i>, 2019). - Bioeconomic modelling indicates the harmful effects of acidification on recruitment (Hänsel <i>et al.</i>, 2020). - Acidification can cause tissue damage in larval cod, leading to increased susceptibility to infection (Frommel <i>et al.</i>, 2012). - Shackell <i>et al.</i> (2013) reported that cod in the Canadian northwest Atlantic were impervious to pH changes within the range of values projected to 2100; however, results based on experiments involving Baltic rather than Atlantic cod (Frommel <i>et al.</i>, 2013). - Deoxygenation is associated with deteriorating health in cod (Cheung <i>et al.</i>, 2022; Lindmark <i>et al.</i>, 2023). - Recruitment is influenced by the North Atlantic Oscillation (NAO), with effects varying geographically and temporally. - Recruitment in European waters south of 62°N is particularly sensitive to climatic changes driven by the NAO when the spawning stock biomass is low (Brander, 2005). - The effect of NAO on recruitment is modulated by the existing population size of the stock. - Correlation between NAO and recruitment success evident in some time periods but not others (Solow, 2007). 	3%	2095±13	Moderate

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Redfish (<i>Sebastes</i> spp.)			
<ul style="list-style-type: none"> - Moderate thermal range (-0.8°C–13°C) with a reported core thermal habitat between 5.5°C and 8.5°C (Eriksen <i>et al.</i>, 2015). - Warming a major factor driving the spatial redistribution of redfish in the Irminger Sea (Pedchenko, 2005). - Warming linked to earlier spawning, altered prey, and trophic mismatch on the Flemish Cap (Anderson, 1994) and to reduced size at maturity in the Gulf of St. Lawrence (Brûlé <i>et al.</i>, 2024). - Acidification adversely affects survival and behaviour during early life stages. - Reported higher redfish fecundity under warming on the Flemish Cap between 1996 and 2020. (González-Carrión and Saborido-Rey, 2022) 	4%	2093±16	Moderate
Thorny skate (<i>Amblyraja radiata</i>)			
<ul style="list-style-type: none"> - Moderately broad thermal range (-0.5°C–12.5°C) (Pennino <i>et al.</i>, 2019; Kneebone <i>et al.</i>, 2020), with a preference for temperatures between -0.5°C and 3°C (Pennino <i>et al.</i>, 2019). - Shifted vertical distribution in response to temperature variation (Swain and Benoît, 2006), suggesting that temperature drives their distribution. - Warming is associated with increased metabolic demands in the Gulf of Maine and a reduced tolerance for hypoxia (Schwieterman <i>et al.</i>, 2019). - Positive relationship between thorny skate and snow crab distribution, suggesting that temperature-driven shifts in crab could impact skate abundance and distribution (Pennino <i>et al.</i>, 2019). 	6%	2092±18	Moderate
American plaice (<i>Hippoglossoides platessoides</i>)			
<ul style="list-style-type: none"> - Relatively wide range of temperatures (-1.3°C–14°C). - Optimal temperature range for growth and development is between 6 and 10°C (Howell and Caldwell, 1984). - Most common between -1°C and 5°C (Shackell <i>et al.</i>, 2013). - Temperature preference for plaice varies with their ration level (Morgan, 1993), suggesting that the productivity regime and prey availability could affect their climate sensitivity. - Temperature affects recruitment and survival rates either directly or by affecting prey availability, with effects being both positive and negative (Walsh, 1994; Swain <i>et al.</i>, 1998; Shepherd <i>et al.</i>, 2000). - Temperature affects swimming endurance, suggesting that temperature could affect their catchability (Winger <i>et al.</i>, 1999). - Little is known of the effects of hypoxia or pH on plaice. 	2%	2095±11	Low
White hake (<i>Urophycis tenuis</i>)			
<ul style="list-style-type: none"> - Wide thermal tolerance range (-0.6°C–21°C). - Temperature-driven northward shifts in white hake distribution across the northeast US continental shelf between 1968 and 2008, influenced by the position of the Gulf Stream and the Atlantic Multidecadal Oscillation (Frederich and Lancaster, 2024). 	1.4%	2096±9	Low
Shortfin squid (<i>Illex illecebrosus</i>)			
<ul style="list-style-type: none"> - Wide thermal range (0.5°C–27.3°C) with a preference between 4°C and 14°C (Bazzino <i>et al.</i>, 2005; Chiu <i>et al.</i>, 2017) and spawning associated with temperatures between 16°C and 18°C (Wang <i>et al.</i>, 2018). - Chang <i>et al.</i> (2015) and Ying <i>et al.</i> (2024) reported a squid preference for cooler water temperatures with adverse effects under warming. 	3%	2094±14	Low

wolffish (*Anarhichas lupus*), Capelin (*Mallotus villosus*), Northern shrimp (*Pandalus borealis*), Roughhead grenadier (*Macrourus berglax*), Splendid alfonsino (*Beryx splendens*), Witch flounder (*Glyptocephalus cynoglossus*), and Yellowtail flounder (*Myxopsetta ferruginea*). These species tended to have narrower thermal niches (Table S1), to experience greater projected thermal-habitat losses by 2050, and to experience thermal stress earlier across their geographic ranges. Many high-risk species are already experiencing thermal stress and habitat loss; the roughhead grenadier, splendid alfonsino, and northern shrimp have lost approximately 20% of their thermally suitable habitat, primarily around their southern range limits (Fig. 4). High-risk species experience climate impacts through several pathways, including, for instance, phenology effects and trophic mismatch on early life stages affecting

recruitment (*e.g.*, shrimp and capelin) (Koeller *et al.*, 2009; Murphy *et al.*, 2021), altered migration routes (*e.g.*, halibut and capelin) (Rose, 2005; Olafsdottir and Rose, 2012; Carscadden *et al.*, 2013; Ferchaud *et al.*, 2022), and changing sea ice conditions (*e.g.*, capelin); (Buren *et al.*, 2019). Climate effects on growth, recruitment, mortality, geographic distribution, and trophic interactions were among the most commonly reported impact pathways for these species. Few climate impact studies were available for the roughhead grenadier, splendid alfonsino, and witch flounder, making their assessment status less certain.

Four of the 14 species were assessed at moderate climate risk, including Atlantic cod (*Gadus morhua*), Greenland halibut (*Reinhardtius hippoglossoides*), redfish (*Sebastes* spp.), and thorny skate (*Amblyraja radiata*). These species

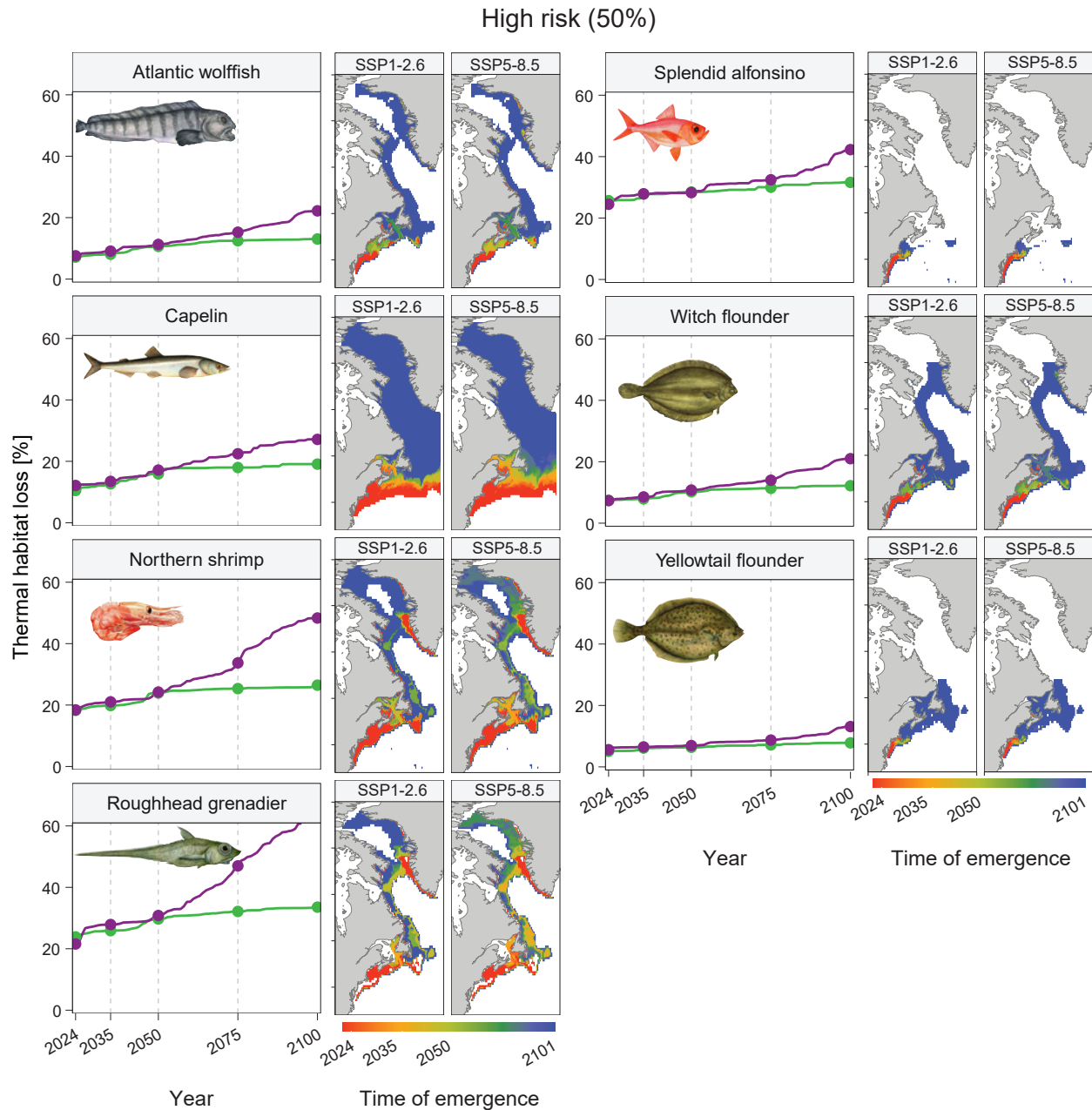


Fig. 4: Projected magnitude and timing of climate impacts on NAFO species assessed at high climate risk. (Left plots) The projected proportion of thermally suitable habitat loss across the NW Atlantic under high (purple) and low (green) emissions. Vertical lines denote years 2035, 2050, and 2075, respectively. (Right maps) The year when the temperature is projected to exceed the species' upper thermal limit across the NW Atlantic. Red depicts earlier, and blue late emergence.

tended to have broader thermal niches (Table S1) but were also experiencing thermal stress across portions of their geographic ranges, though more modest and primarily restricted to the southernmost extent of the NW Atlantic or to the Gulf of St. Lawrence (Fig. 5). In the US, areas where warming has exceeded the thorny skate thermal limit have already led to declines the warming effects are already underway (Kulka *et al.*, 2024).

Cod is among the most studied species, but fewer climate impact studies are available for redfish and thorny skate (Table 2). Most studies of cod and Greenland halibut have suggested adverse effects of climate change and significant responses to climate variability.

Three species were assessed at low climate risk. American plaice (*Hippoglossoides platessoides*), White hake

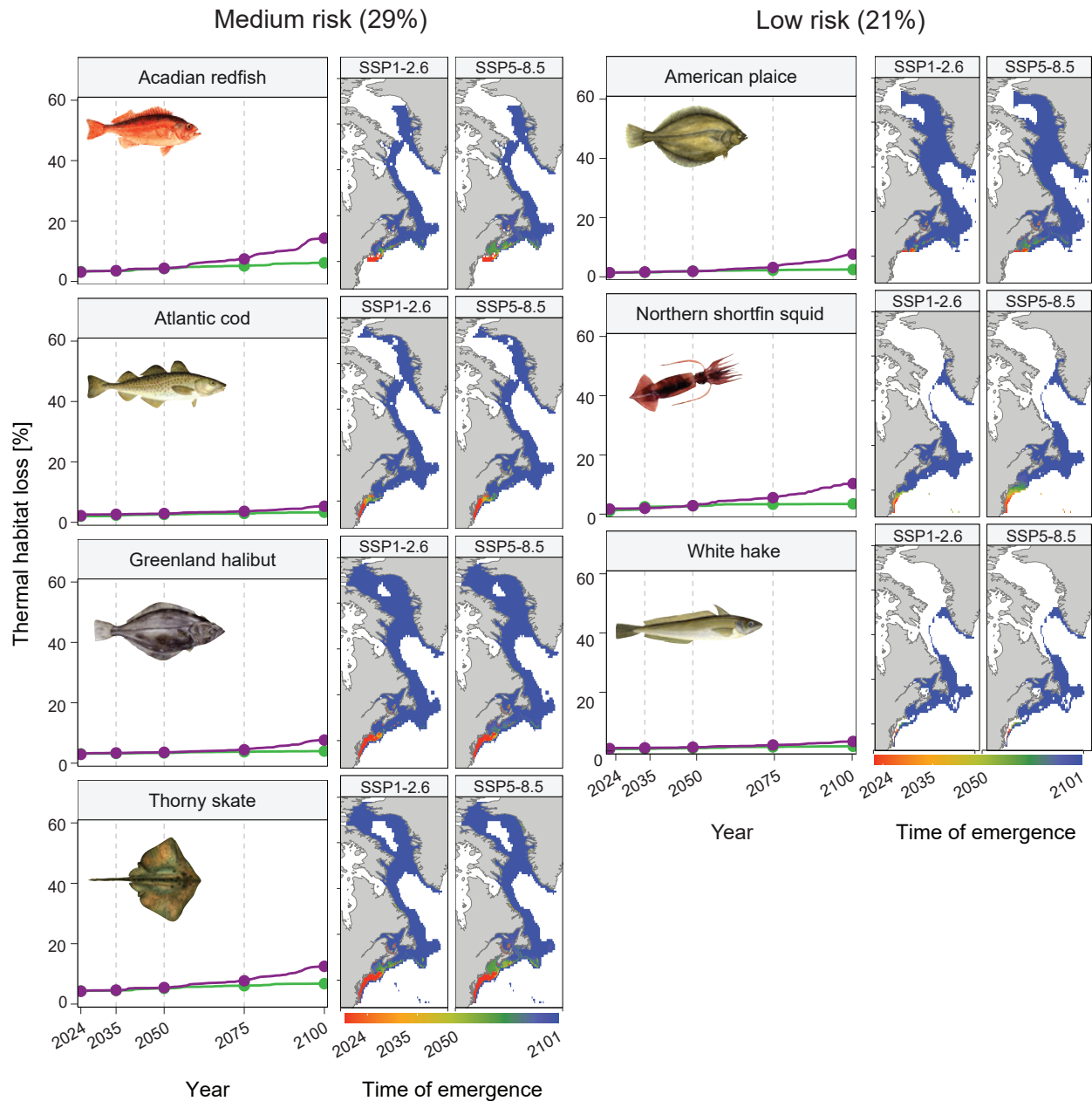


Fig. 5: Projected magnitude and timing of climate impacts on NAFO species assessed at moderate and low climate risk. (Left plots) The projected proportion of thermally suitable habitat loss across the NW Atlantic under high (purple) and low (green) emissions. Vertical lines denote years 2035, 2050, and 2075, respectively. (Right maps) The year when the temperature is projected to exceed the species' upper thermal limit across the NW Atlantic. Red depicts earlier, and blue late emergence.

(*Urophycis tenuis*), and Shortfin squid (*Illex illecebrosus*) tended to have broader thermal limits (Table S1), leading to later emergence times, reduced thermal habitat loss (Fig. 5), and lower climate risk. For white hake, additional climate pathways could also be important; climate-driven variability in the Labrador Current has been shown to affect larval dispersal, with consequences for settlement, recruitment, and resulting adult productivity (Han and Kulka, 2008). However, these assessments are highly

uncertain, as there are very few studies on the effects of climate on these species (Table 2).

Pathways to climate-informed NAFO fisheries

This section explores how to support climate resilience within NAFO fisheries, identifying three crucial elements to strengthen the integration of climate information into NAFO's ecosystem approach to fisheries: tracking and

projecting climate change, accessing integrated climate data products, and conducting climate-informed stock assessments.

Tracking and projecting climate change and its impacts

Disentangling anthropogenic climate change from natural climate variability is a challenging task that requires close ecosystem monitoring, including environmental changes, shifts in species distributions, phenology, and the emergence of pathogens and diseases. Regular environmental and ecological monitoring and dissemination, using standardized techniques, are thus key to properly tracking ongoing changes in an ecosystem. Government agencies are usually better resourced to perform these tasks and ensure continuity. In Atlantic Canada, DFO coordinates the Atlantic Zone Monitoring Program (AZMP) (Therriault *et al.*, 1998), which annually surveys and collects multidisciplinary oceanographic data that contribute to periodic state of the Atlantic Ocean reports (Bernier *et al.*, 2023) that summarize climate and ecosystem trends (see also the next section on integrated data products). In the U.S. Atlantic, NOAA provide annual State of the Ecosystem reports (NOAA, 2025). Long-term environmental and ecological datasets are instrumental in providing baseline information, and their continuity should be prioritized (Rosi *et al.*, 2022).

While species are generally expected to shift into more northern and deeper waters (Nye *et al.*, 2011; Shackell *et al.*, 2012; Pinsky *et al.*, 2013; Walsh *et al.*, 2015; Morley *et al.*, 2018), unexpected shifts have also been observed (Pinsky *et al.*, 2013), highlighting the species-specific nature of climate responses and the need for ongoing monitoring. Geographic range shifts pose several challenges for fisheries assessment and management, including transboundary disputes, increased effort and costs for fishers to track fish, new or increased bycatch species, and potential biases in stock assessments. For instance, many NAFO assessments rely on surveys that are often fixed in time and space; this fixed design can miss shifting species distributions, leading to biased abundance estimates that underlie fishing quotas.

Several avenues exist for monitoring shifting species distributions. Standardized ecological surveys are the gold standard for tracking species distributional shifts (Nye *et al.*, 2009, 2011; Cheung *et al.*, 2013b; Pinsky *et al.*, 2013; Shackell *et al.*, 2014; Morley *et al.*, 2018; Allyn *et al.*, 2020; Mills *et al.*, 2024), yet logistical challenges could arise in implementing them to track species shifts across the vast and remote NAFO Convention Area (Fig. 1). Alternatively, species distribution models (SDMs) offer a flexible and proactive approach (Kaschner *et al.*, 2019; Karp *et al.*, 2025; Reygondeau *et al.*, 2025). SDMs predict the relative probability of species occurrence and habitat suitability as functions of the environment. Most SDMs are temporally static, ignoring temporal variation,

and leverage historical relationships between species occurrences and environmental conditions to predict species presence.

To be useful for fisheries, SDMs must instead be dynamic, accounting for spatial and temporal variation in species occurrence and their environments. Dynamic SDMs are often more reliable and allow species distribution shifts to be tracked at a higher temporal frequency (El-Gabbas *et al.*, 2021). A rarely met requirement of such SDMs, however, is spatially and temporally matched species occurrences and environmental variables, and high-performance computing resources, which can limit routine operational use (Karp *et al.*, 2025).

Notwithstanding these challenges, dynamic SDMs could be developed for NAFO species using observations of species occurrence, for instance, from existing surveys, geolocated catch records, or animal tracking, and coincident temperature and other environmental observations, either sampled directly or inferred from independent data sources such as remote sensing or integrated data products. This process could be simplified using freely available statistical software packages (Dobson *et al.*, 2023). Ideally, and in light of NAFO's roadmap towards an ecosystem approach to fisheries (Koen-Alonso *et al.*, 2019), such models could eventually be developed as joint-dynamics SDMs that incorporate the correlated distributions of multiple species over time (Thorson *et al.*, 2016).

With such models, remote sensing observations could be used to estimate species distributions in real time, or to forecast climate conditions and predict where species will be months or years ahead (Tommasi *et al.*, 2017; Mills *et al.*, 2017). Notwithstanding the logistical and regulatory challenges, this information could be valuable for understanding where survey or fishing efforts should be deployed, anticipating shifts in stocks across management boundaries, and proactively addressing transboundary conflicts. Such tools offer a promising avenue for managing fisheries under climate change, yet they must be approached with sufficient outreach and engagement with NAFO Parties, fishing rights holders and stakeholders.

Diseases are rarely studied or considered in marine fisheries outside aquaculture, yet climate change is projected to expand bacteria's geographic and seasonal ranges (Burge *et al.*, 2014). Given the potentially severe consequences for fisheries productivity, monitoring for changes in disease transmission is vital to managing fisheries under climate change. While monitoring the fisheries' catch for signs of disease is one avenue, environmental DNA (eDNA) is another new data stream that would be useful for monitoring species occurrence, including invasive species and shifts in harmful bacteria and viruses (Stat *et al.*, 2017; Farrell *et al.*, 2021; Rishan *et al.*, 2023). eDNA helps monitor disease and pathogen prevalence in aquaculture (Peters *et al.*, 2018; Shea

et al., 2020) and could be a relatively low-cost means of monitoring invasive species and disease outbreaks in the Northwest Atlantic.

Seasonal shifts in fish distribution can substantially affect population productivity and fisheries, particularly by influencing recruitment and the success of early life stages (Platt *et al.*, 2003; Edwards *et al.*, 2004; Koeller *et al.*, 2009; Walsh *et al.*, 2015; Niemi *et al.*, 2019). Furthermore, seasonal shifts in the timing of species movements and key events can bias stock biomass estimates derived from surveys conducted at fixed times and locations. Developing indicators of seasonal environmental shifts, such as the timing and magnitude of the spring phytoplankton bloom, would help monitor climate-driven changes in phenology and their impacts on NAFO stocks. For instance, Brickman and Shackell (2024) developed a series of phenology indicators and explored their application for predicting ecological responses, for instance, in the timing of inshore lobster migration, spawning times for cod, egg development times for shrimp, thermal stress in herring, and habitat condition for halibut and snow crab. Such indicators can be incredibly valuable for evaluating climate-fisheries interactions and can be derived from daily or weekly remote sensing observations of chlorophyll concentrations or surface temperatures.

A notable yet vital information gap in understanding the impacts of climate change on fisheries' living resources is the lack of information on effects on early life stages, which are critical to fisheries productivity and sustainability. Early life stages (*e.g.*, juveniles, larvae) often have narrower environmental tolerances than adults, rendering them more sensitive to climate variability and change (Dahlke *et al.*, 2020). At the same time, they are often less well-monitored or studied than adults. Due to the general movement to deeper waters that occurs with increasing size or age in demersal fishes, *i.e.* Heincke's law (Heincke, 1913), understanding climate impacts on fish populations involves evaluating climate changes and their effects on bottom-dwelling adults, as well as individuals occupying the pelagic zone (Frank *et al.*, 2018). Despite these challenges, early-life-stage individuals could serve as sentinels of climate change, and monitoring them could provide early warnings of impending effects on adult biomass and productivity.

Climate vulnerability and risk assessments have been a priority focus for intergovernmental organizations (IPCC 2007, 2014) and are included in the US NMFS Fisheries Climate Science Strategy (Busch *et al.*, 2016; Hare *et al.*, 2016; Morrison *et al.*, 2016) and in development at Fisheries and Oceans Canada for its Atlantic fisheries (Boyce *et al.*, 2023). Hundreds of climate vulnerability assessments have been published (de los Ríos *et al.*, 2018). Building on these, quantitative methods, such as the CRIB, can provide standardized, spatially explicit climate

vulnerability and risk estimates for species in a flexible manner that could be useful to marine conservation and management (Lewis *et al.*, 2023), including fisheries (Boyce *et al.*, 2023, 2024). The CRIB assesses the likelihood of adverse consequences (IPCC, 2021) at individual locations within species' native geographic distributions to inform conservation and management efforts where they operate. Of particular relevance to NAFO's goal of an ecosystem approach to fisheries (Koen-Alonso *et al.*, 2019), the CRIB evaluates climate risk at both the species and ecosystem levels (Boyce *et al.*, 2022). Synoptic, spatially explicit climate vulnerability or risk estimates could support evidence-based decision-making under climate change, helping decision-makers to identify priorities for scientific and management efforts to implement proactive management measures, reduce impacts, increase resilience, and advance the adaptive capacity of fisheries.

Access to integrated climate data products.

The Marine Environmental Data Section (MEDS) of Fisheries and Oceans Canada provides environmental data to the NAFO Standing Committee on Fisheries Environment (STACFEN). These data primarily consist of temperature and salinity profiles collected by ships, underwater gliders, drifting buoys and floats, animal tags, and other platforms (Alcinov, 2023), which can be challenging to use. The observations are collected differently—some from standardized surveys, others opportunistically—and differ in measurement biases, sampling intensities and frequencies, and completeness. Significant effort is often required to prepare these data for use in fisheries assessments, thereby hindering their use. Integrating environmental data layers or time series would enable researchers to incorporate a more robust representation of climate variability and change into fisheries assessment and advice. The International Council for the Exploration of the Sea (ICES) Report on Ocean Climate (IROC) provides such time series on a public portal (<https://ocean.ices.dk/core/iroc>) together with their interpretation in a large report published every three years (González-Pola *et al.*, 2023).

In Atlantic Canada, the Newfoundland and Labrador Climate Index (NLCI) combines ten climate subindices into an annually updated time-series (1951–2025) representing the climate state of the Newfoundland and Labrador shelf (Cyr and Galbraith, 2021). Additional climate products exist (Belanger *et al.*, 2025) or are in development, including the Canadian Atlantic Bottom Temperature and Salinity (CABOTS) database that integrates *in situ* observations to provide seasonal values across the northwest Atlantic and eastern Arctic shelf regions from 1980 to 2023 (Coyne and Cyr, 2024). Providing similarly integrated spatiotemporal data layers for key climate variables (*e.g.*, pH, dissolved oxygen, sea ice, primary production, and vertical mixing), as

well as indicators of spatial and phenological shifts, climate projections, and forecasts (see below), would aid the integration of climate considerations into fisheries management. Some of these products are compiled and made available by STACFEN to NAFO scientists (Coyne *et al.*, 2025).

Remote sensing measurements of the surface oceans enable spatially resolved evaluations of SST, wind, sea ice, chlorophyll, and other fields at high sampling frequencies (*e.g.*, daily or monthly) in near-real time, with most data available since the 1970s. For instance, Copernicus, the Earth observation component of the European Union's Space program, merges observations from multiple sensors to provide daily measurements of the sea surface globally¹. Remote sensing observations are widely used in climate impact studies but remain underutilized for fisheries assessment and management in the Northwest Atlantic. Remote sensing observations would be a valuable resource for synoptic, real-time environmental monitoring, assessing species' geographic range shifts, and detecting seasonal shifts and trophic mismatches.

Climate projections and forecasts are increasingly used in fisheries assessment and management (A'Mar *et al.*, 2009; Hobday *et al.*, 2010; Bell *et al.*, 2020). The difference between climate projections and forecasts is subtle yet important. Whereas projections explore a range of plausible climate futures that may come to pass, forecasts evaluate the most likely climate future given present-day conditions; as a result, projections tend to be multi-decadal, whereas forecasts are often seasonal (Sillmann *et al.*, 2017). Despite the use of climate forecasts in fisheries in the US, Australia, and elsewhere, they are not yet used within NAFO. Several climate and/or Earth system models exist for the Northwest Atlantic (Lavoie *et al.*, 2016; Saba *et al.*, 2016; Wang *et al.*, 2018b; Laurent *et al.*, 2021), yet few are available at high spatial and temporal resolution across a plausible range of emission scenarios. Developing or supporting the creation of a high-resolution regional climate model for the Northwest Atlantic Ocean would be highly valuable for anticipating the impacts of climate change on NAFO living resources. Ideally, the model would forecast, rather than project, climate changes at a high resolution (~1–10 km²) across the NAFO convention area five to ten years ahead. Such a model would have numerous potential uses; it could be coupled to stock assessment operating models within a management strategy evaluation (MSE) to help determine harvest quotas under climate change; and combined within a dynamic species distribution model (see below) to predict likely geographic range shifts (El-Gabbas *et al.*, 2021); input into a seasonal model to anticipate potential phenological shifts and trophic mismatches; or used in climate risk assessments for species (Boyce *et al.*, 2022) and/or fisheries (Boyce *et al.*, 2023, 2024) to understand climate impacts on fisheries living resources.

The successful development of climate-considered fisheries will depend on understanding the complex pathways by which climate impacts operate. Consolidating the available scientific literature on climate change and its impacts on NAFO species, including their environmental niches, into a centralized database would facilitate a more robust understanding of which climate impact pathways are most important for stocks, how they operate, and how to mitigate them. Such a database could also help identify information gaps that require further investigation. This report and the literature summarized in [Tables S1–8](#) are a start, but should be enhanced and updated as new information becomes available.

Climate-informed stock assessments

Climate impacts can be directly incorporated into fisheries assessment models ([Table S8](#)), thereby enabling their explicit consideration when providing scientific advice on quota. Management strategy evaluation is a flexible modelling approach for establishing management procedures that are robust to a range of uncertainties associated with data limitations, species, ecosystem, model architecture, climate impacts, or other factors (Goethel *et al.*, 2019).

To achieve climate and ecosystem objectives in a precautionary manner, MSE can be implemented using multispecies models that incorporate species interactions and the effects of climate variability and change on them (Sainsbury *et al.*, 2000; Smith *et al.*, 2007; Dichmont *et al.*, 2008; Plagányi *et al.*, 2013; Goethel *et al.*, 2019; Merino *et al.*, 2019). Similarly, uncertainties related to past (Wang *et al.*, 2018a) or future (A'Mar *et al.*, 2009) climate change can be evaluated within MSE using observed or forecast climate time series under different emission scenarios (Merino *et al.*, 2019). For example, A'mar *et al.*, (2009) incorporated climate change factors dynamically into an MSE for walleye pollock (*Gadus chalcogrammus*) in the Gulf of Alaska. This approach enables the quantification of key climate-change impacts when estimating population dynamics and optimizing subsequent management strategies. MSE studies have shown that the stock-recruitment relationship for Pacific sardine (*Sardinops sagax*) varies with SST. Based on this, the average SST over the most recent three years establishes the sardine quota for the next year (PFMC, 2007).

Duplisea *et al.*, (2020) introduced a risk-based approach to incorporating climate change considerations into fisheries management in Canada through what the authors refer to as “climate change conditioning of science advice” (CCSA). CCSA requires information on how environmental factors affect the productivity dynamics of a resource and accounts for climate change when estimating the probability that a management objective will be met. The CCSA approach is based on risk equivalency, the concept of making management decisions of equal risk despite differences in, for instance, data availability, resource

¹ [ESA SST CCI and C3S reprocessed sea surface temperature analyses | Copernicus Marine Service](#)

dynamics, knowledge, assessment methods, and advisory contexts. Risk-equivalency approaches have been applied in the management of Australian fisheries and in the US (Fulton *et al.*, 2016). Like MSE, CCA evaluates climate change in terms of risk, but it is less widely used and less flexible.

Two-thirds (66%) of NAFO-managed stocks lack assessment models. In these situations, approaches for incorporating climate variability and change into the assessment and decision-making process are less well defined (Table S8). Understanding the nature and magnitude of climate impacts on a fishery, and when and where they will arise, is fundamental to setting quotas that ensure long-term sustainability. Synthesizing the available climate-impact literature on managed species and their environmental niche limits (Table S1 and Table S7) would provide a vital baseline for understanding species' responses to observed and anticipated environmental changes. Species often respond nonlinearly to the environment, and understanding species' environmental limits and optimal values would be valuable for resolving variable responses to environmental variability and change and for adjusting management decisions accordingly. Including climate risk assessments, as previously described, as a standard component of the NAFO ecosystem, along with multispecies and stock assessments, would allow for contextualized advice based on climate impacts. The California sardine, Peruvian anchovy, and Bering Sea snow crab fisheries described in the following paragraph provide real-world examples of how fisheries harvest control rules can be adjusted in response to changing climate conditions.

Interdecadal-to-multidecadal climate variability significantly affects fisheries across the NW Atlantic. Developing indices to represent this climate variability, such as the North Atlantic Oscillation (NAO), the NLCI, or the Atlantic Multidecadal Oscillation (AMO), may help understand and incorporate the effects of a changing climate on stock productivity. This could involve adjusting the fishing quota in near real time based on the magnitude, duration, or phase of these indices and their expected impacts on stocks. This approach is used in other fisheries subjected to similar decadal-to-multidecadal climate variability, such as the Pacific Decadal Oscillation (PDO) and El Niño Southern Oscillation (ENSO). For instance, due to the devastating effects of El Niño-ENSO-associated warming on anchovy populations in the Humboldt Current, Peru closes its fishery during El Niño events to limit additional fishing mortality (Oliveros-Ramos *et al.*, 2021). Marine species in the eastern Bering Sea experience alternating regime shifts driven by the PDO (Hare and Mantua 2000), and reference points for the snow crab (*Chionoecetes opilio*) fishery are estimated only after a climate shift has occurred (Szuwalski and Punt, 2013). Likewise, because California sardines (*Sardinops sagax*) are more productive when ocean temperatures are near

17.5°C (Jacobson and Maccall, 1995), 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). Adopting a similar approach in the Northwest Atlantic would require a working understanding of the effects of the NAO—or any comparable index—on specific stocks, real-time monitoring of the index, and agreed-upon guidelines for adjusting quotas based on its phases.

In addition to climate-informed stock assessment, integrative approaches such as the Resist–Accept–Direct (RAD) framework and forward-looking approaches such as scenario planning are complementary and can help fisheries management explicitly address climate-driven change and uncertainty (Lynch *et al.*, 2021; Schuurman *et al.*, 2022). Scenario planning explores a set of plausible future environmental and ecological conditions. In contrast, RAD provides a structured approach to determining whether management should resist change, accept unavoidable impacts, or actively direct systems toward more desirable future states. Together, they enhance climate consideration and resilience by making assumptions about change explicit and by supporting proactive, flexible decision-making under non-stationarity. These approaches could complement traditional stock assessments by informing reference points, harvest strategies, and spatial management with a forward-looking climate context, rather than relying solely on historical conditions.

A climate roadmap

Mapping climate

To successfully establish climate-informed NAFO fisheries, climate considerations must be integrated and harmonized within NAFO management frameworks, cycles, and governance structures, namely the NAFO Roadmap (Fig. 6A). The Roadmap is designed to guide the transition to an Ecosystem Approach to Fisheries, ensuring long-term ecosystem sustainability by incorporating ecological, social, and economic perspectives into fisheries management (Koen-Alonso *et al.*, 2019). It emphasizes the long-term health and stability of the ecosystem and is objective-driven, requiring clear management goals to achieve it. The Roadmap's key components include identifying ecosystem-based management units for tailored approaches, a hierarchical structure, setting exploitation rates at ecosystem, multispecies, and stock levels, ensuring sustainability across these scales, and considering the effects on non-target species and benthic communities. The Roadmap also seeks to assess adverse impacts on vulnerable marine ecosystems and of bycatch. The NAFO governance structure includes a Scientific Council (SC), which provides scientific

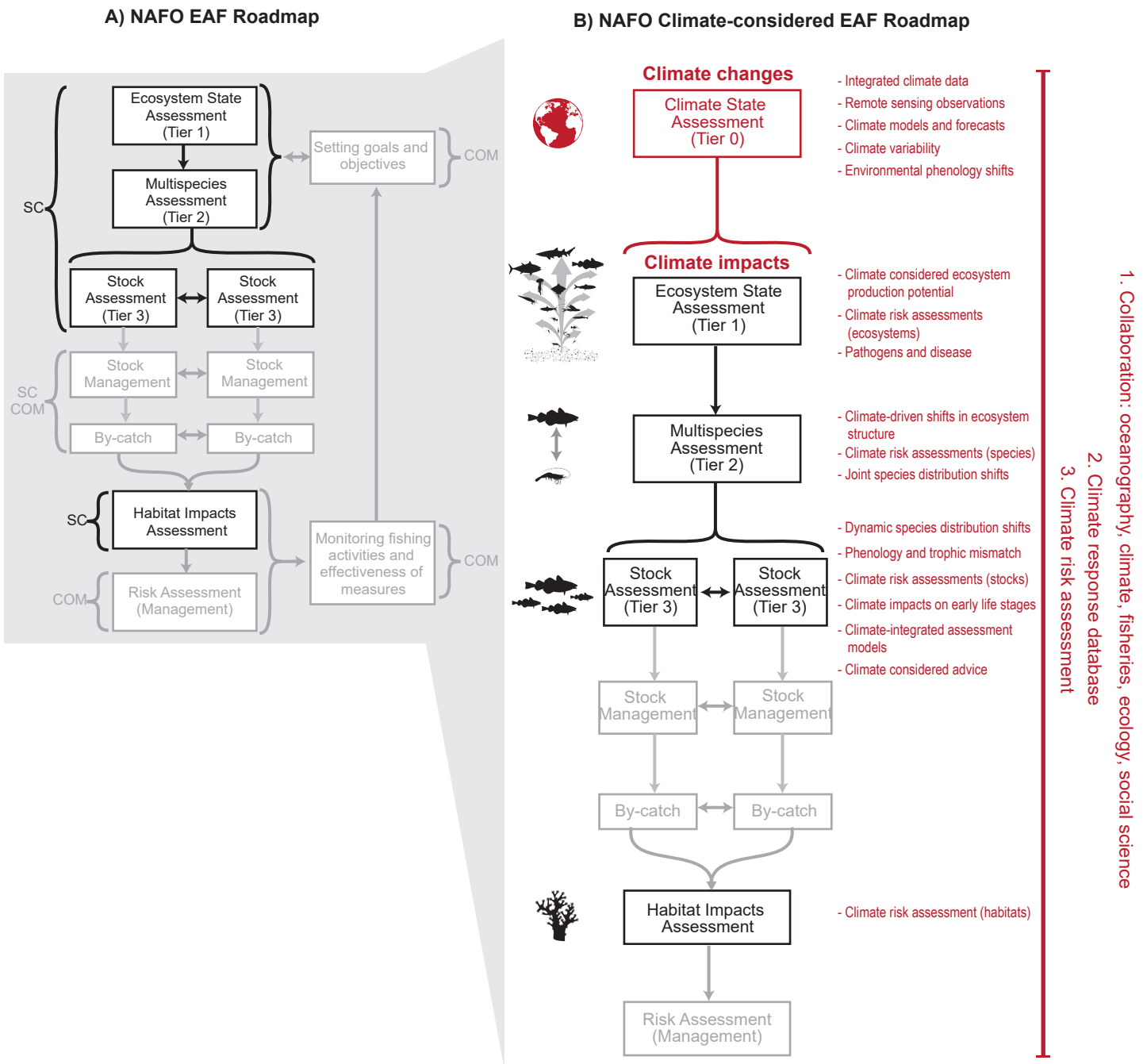


Fig. 6: NAFO climate-considered EAF roadmap. Current working template of the NAFO Roadmap (A) and steps to enhance its climate readiness (B; red text). SC: Scientific Council; COM: Commission.

advice, and a Commission (COM), which makes management decisions. The Roadmap progresses through stages, with the SC providing science support to COM by conducting ecosystem state assessments (Tier 1), multispecies assessments (Tier 2), and fisheries stock assessments (Tier 3). The following examines how the recommendations outlined above are integrated into the Roadmap and highlights potential avenues for improvement.

Climate state assessments

The analyses and development of methods to support the NAFO Roadmap are generally performed within the Scientific Council Working Group on Ecosystem Science and Assessment (WG-ESA), which reports back to SC. For example, WG-ESA has worked towards Ecosystem Production Potential (EPP) models and derived metrics such as Fisheries Production Potential (FPP) and Total Catch Indices (TCI); (see Koen-Alonso 2022 for a chronology of documents contributing to this work). The current NAFO Roadmap considers the broad-scale impacts of climate variability and change on ecosystem production within Tier 1—ecosystem assessments. For example, Tier 1 assesses the impacts of large-scale climate forcing on primary production and the limits this places on ecosystem carrying capacity—the assumption being that as climate-driven primary production declines, so too does cumulative ecosystem production (Koen-Alonso *et al.*, 2019). SC also has, as part of its core structure, a Standing Committee on Fisheries Environment (STACFEN) that compiles, assesses, and reports on environmental data (*e.g.*, Cyr and Belanger, 2025) that can be used to inform this aspect of the Roadmap. A previous review of NAFO’s Roadmap endorsed proposed approaches for the implementation of Tier 1 assessments as ‘sensible, reasonable, and even advisable’ (NAFO, 2022).

Here, we propose adding an overarching Tier 0 Climate State to the Roadmap. Such an addition would not alter any functionality of the Roadmap but could help incorporate important climate change and impact pathways highlighted in this report that are not currently considered in Tier 1. Where Tier 1 considers climate-driven impacts on cumulative ecosystem production, Tier 0 could provide the type of detailed foundational climate data needed to resolve climate impacts on, for instance, stock size structure, geographic distribution, or seasonal development, as well as impacts operating on populations or stocks (*e.g.*, Tier 3) rather than entire ecosystems. In short, Tier 0 could support the current Roadmap while furthering a more explicit integration of climate variability and change into ecosystem and fishery assessment and management processes at Tiers 1–3 (Fig. 6B).

Such an assessment would incorporate previous suggestions related to climate data products, including developing integrated data products of key oceanographic variables (*e.g.*, surface and bottom temperatures, dissolved

oxygen, chlorophyll) to evaluate climate trends, evaluating indices of changing phenology, assessing the onset and magnitude of climate variability (*e.g.*, climate indices), and forecasting or projecting how climate conditions will evolve. While the report would describe the past, current and future climate state across the NW Atlantic, a vital contribution would be the generation of integrated, quality-checked, and ready-to-use climate data products that could be deployed in other SC Roadmap assessments (*e.g.*, Tiers 1–3).

The International Council for the Exploration of the Sea (ICES) produces an annual report on ocean climate conditions across the North Atlantic (González-Pola *et al.*, 2023), NOAA provide annual State of the Ecosystem reports for the Northeast U.S. Shelf (NOAA, 2025), and DFO produces periodic reports on the state of the Atlantic Canadian Ocean (Galbraith *et al.*, 2025), providing examples of how such an assessment could be developed within the NAFO Roadmap. The ICES reports on ocean climate (IROCs) combine historical ocean observations to describe ocean conditions, trends, and variability across the North Atlantic Ocean and summarize and distribute climate data through an interactive, easy-to-use, publicly available web platform². While the IROCs focus on historical data and trends, a NAFO analogue ideally would include forecasted or projected trends.

Climate impacts on NAFO ecosystems and stocks

Within the ecosystem assessment (Tier 1), climate data from the climate state assessment (Tier 0) could be used to evaluate important climate impact pathways on ecosystems in addition to the currently considered impacts on bulk primary production and overall system carrying capacity. Studies suggest that ocean biogeochemical provinces that shape biodiversity and constrain ecosystem structure and fisheries productivity will shift under ongoing climate change (Reygondeau *et al.*, 2020), meaning that the ecosystem production units used in the Roadmap should also be monitored to detect climate-driven shifts in productivity and adjust fisheries quotas accordingly. Geographic patterns of ecosystem climate risk can be assessed and monitored using approaches such as the CRIB, which also allows for evaluating future climate scenarios and their ecological impacts (Boyce *et al.*, 2022, 2024). Catch limits for the ecosystem unit could be adjusted depending on climate-informed impact thresholds, as employed in other fisheries (Szuwalski and Punt, 2013; Pinsky and Mantua, 2014; Oliveros-Ramos *et al.*, 2021). Climate-driven shifts in disease and pathogens could also be monitored and assessed, for instance, using eDNA, as part of the ecosystem assessment (Baillie *et al.*, 2019; Abbott *et al.*, 2021).

Within the Roadmap, multispecies assessments (Tier 2) are a means of understanding species interactions and trends, the role of anthropogenic and environmental

² [ICES Oceanography - IROC](#)

drivers on ecosystem structure and dynamics, and defining multispecies reference points (Koen-Alonso *et al.*, 2019). Climate data from the climate state assessment provides a means to explore climate variability and change in multispecies dynamics and to adjust reference points accordingly. Dynamic joint SDMs could be used to examine climate-driven shifts in species distribution in real time (Thorson *et al.*, 2016), while climate risk assessment could evaluate spatial patterns in climate risks at the species level to mitigate them (Boyce *et al.*, 2022). The impacts of shifting environmental phenology on species interactions (*e.g.*, trophic mismatch) (Cushing 1990, 1995) could likewise be explored at this level. Fisheries and ecosystem models are becoming increasingly detailed and reliable, and could be explored to resolve the effects of projected or forecasted climate changes on the biomass of exploited species and ecological interactions (Tittensor *et al.*, 2018b, 2018a, 2021).

In the Roadmap, single species assessments (Tier 3) form the basis for stock-specific catch levels, and where quota decisions should also be informed by Tiers 1–2. Stock assessments represent the most detailed examination of trends and drivers in fish populations, and several recommendations discussed previously fall under their purview, including evaluating past and anticipated distribution shifts (*e.g.*, dynamic SDMs), phenology, trophic mismatch and its effects on recruitment, climate impacts on early life stages, climate risk analyses at the level of individual stocks, and developing climate-integrated assessment models. Evaluating climate impacts on each stock as a standard assessment practice would be a meaningful way to support climate-informed assessment and advice, particularly for the 66% of NAFO stocks that lack assessment models. Such an impact assessment would interpret population dynamics in the context of climate trends reported in the climate state assessment (Tier 0), integrate the available knowledge from the suggested climate impact database, and include a standardized climate risk assessment carried out for each stock, such as has been undertaken using the CRIB framework (Boyce *et al.*, 2023, 2024). Such vulnerability and risk analyses have been widely promoted as a means of developing climate-informed fisheries advice and are 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).

Overarching considerations

While fisheries scientists have traditionally been solely responsible for assessing stock status and providing advice, the Roadmap's objectives regarding the ecosystem approach to fisheries (EAF) and the integration of climate considerations within it are multidisciplinary, requiring expertise from climate scientists, oceanographers, ecologists, and social

scientists. Climate considerations pervade the Roadmap; therefore, including oceanographers and climate scientists at each level (Tiers 0–3) would support its integration into the assessment and management process.

Integrating climate considerations into the Roadmap more explicitly and fully will require a robust evidence base—a strong understanding of the pathways by which climate affects species, populations, and ecosystems. A climate impacts database that synthesizes the current state of knowledge on climate change and its effects on NAFO species and stocks, and that supports regular climate risk assessment at the species and ecosystem scales, would help support this process across all Tiers. Climate vulnerability and risk assessments can supplement this knowledge, providing objective evaluations of how the likelihood of climate impacts varies across taxa and geographies, and how this information could be incorporated into fisheries management.

The current Roadmap includes ecosystem considerations, requiring an expansion of the taxonomic scale of analysis. Explicitly including climate considerations will require greater temporal resolution in the assessments. Further, climate change can interact with seasonal and basin-scale climate variability to create large, abrupt climate changes. NAFO assessment cycles must be able to respond dynamically to abrupt, unanticipated climate changes.

Conclusions

This study suggests that the climate system across the Northwest Atlantic Ocean is dynamic, with substantial seasonal, decadal, and multidecadal variability overlaying long-term climate changes (Tables S2–3). Overall, the Northwest Atlantic Ocean is becoming warmer, more acidic, more hypoxic, more stratified, and more nutrient-depleted, with declining sea ice. These trends are expected to continue into the foreseeable future, with the magnitude of changes depending on emission trajectories.

Marine species within the NAFO Convention Area are already experiencing a range of climate impacts, which are likely to continue or intensify over the coming years (Tables S4–5). Direct effects of temperature are more frequently evaluated and described, particularly for well-studied species such as Atlantic cod. In contrast, indirect climate effects, such as altered predation, prey availability, shifting phenology, and disease transmission, are less commonly studied but are nonetheless likely to occur and be important. Indirect climate impacts can be exceedingly challenging to pinpoint, as they often co-occur with other drivers such as fishing, competition, or anthropogenic stressors. Across species, early life stages appear to be more sensitive to climate impacts consistently, and juveniles and smaller individuals commonly have narrower thermal limits than adults, highlighting the importance of considering life history in climate impact evaluations (Dahlke *et al.*, 2020). Notwithstanding

these challenges, several avenues exist for incorporating climate variability and change into fisheries management to strengthen the resilience and the productivity of fish stocks (Table S8). Understanding both the impacts of climate change on fisheries within the NAFO Convention Area and the pathways to integrate the information into science assessments and the NAFO Roadmap will better equip NAFO Parties to address climate impacts in support of healthy oceans and sustainable fisheries.

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