Informing a Strategic Approach to Address the Impacts of Climate Change on Wild Atlantic Salmon

A Report of a Theme-based Special Session of the Council of NASCO

Tuesday 6 June 2023

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Contents

Executive Summary

Climate change is altering the marine and freshwater ecosystems at an unprecedented rate and can be expected to impact Atlantic salmon at both the regional and Atlantic Ocean scale. Like many diadromous species, Atlantic salmon are particularly vulnerable to climate change with individuals experiencing the interactive effects of multiple direct and indirect changes across two very distinct, but connected, environments. Within the freshwater environment, the Atlantic salmon populations are adapted to the environmental conditions of their local river, which makes changes in environmental conditions particularly challenging. Changes such as increasing stream temperatures and alteration in flow regimes can directly affect life functions – for example, reproduction, growth and development, and impact survival. The marine environment for Atlantic salmon is extremely complex and expected changes will vary within regions of the North Atlantic used by this species. Rising temperatures, changing stratification and shifts in ocean currents will impact salmon directly through altered growth, maturation and survival schedules, as well as indirectly through spatial and temporal distribution shifts. The potential inability of wild Atlantic salmon across the species range to adapt to these predicted changes in a timely manner is particularly concerning.

Atlantic salmon are also exposed to several other human-induced stressors in both the freshwater and marine environment. For example, sea lice and infections related to fish farming, habitat alterations, invasive species, hydropower regulations, mitigation barriers, predators, watershed run off and escaped farmed salmon all pose particular threats to Atlantic salmon. These other stressors can directly and / or indirectly interact with climate change, further impacting salmon productivity and population growth. There is an urgent need to update our knowledge base and engage in cross-sectoral discussions to support the effective implementation of appropriate climate adaptive fisheries management across the species' range.

The North Atlantic Salmon Conservation Organization (NASCO) is a Regional Fisheries Management Organization whose mandate is to conserve, restore, enhance and rationally manage Atlantic salmon through international co-operation, taking account of best available scientific information. In 2021, the Council of NASCO agreed that a Theme-based Special Session (TBSS) would be held in 2023 on the theme of climate change, with the overarching goal to exchange information on the current and future impacts of climate change on salmon productivity in the North Atlantic and on management measures being implemented, to identify best practices and inform the development of a strategic approach by NASCO. The Steering Committee charged with organizing the TBSS tackled this via three targeted objectives:

1. **To summarise the current and predicted impacts of climate change on Atlantic salmon productivity across North Atlantic freshwater and marine environments.**
2. **To provide an overview of climate adaptive management actions undertaken by Parties / jurisdictions and other relevant countries to mitigate the negative impacts of climate change, with an assessment of the effectiveness of these actions and lessons learned.**
3. **To review the effectiveness of management actions, the challenges and knowledge gaps that are hindering climate adaptive management efforts across jurisdictions, to result in a set of tangible recommendations to NASCO.**

The TBSS took place on June 6, 2023, in Moncton, New Brunswick, Canada as part of the 40th NASCO Annual Meeting. Invited experts, Parties / jurisdictions and invited countries presented and partook in discussions to address the above three objectives. The Steering Committee presented a series of recommendations to the Council of NASCO setting out strategic actions that could be adopted by both NASCO and the Parties / jurisdictions to support the effective implementation of climate adaptive fisheries management for Atlantic salmon. These recommendations are to be considered by the NASCO Council in the coming year.

Introduction

Photo: Kai Benson Photography

Introduction

The scale of recent changes across the climate system is unprecedented over many centuries to many thousands of years[1]. In this era of undoubted human impact on the planet, with an already challenged environment for wild Atlantic salmon in both their freshwater and marine life stages, the potential inability of wild fish to adapt in a timely manner is particularly concerning. As such, there is an urgent need to update our knowledge base and engage in cross-sector discussions to support the effective implementation of climate adaptive fisheries management.

In 2021 the Council of NASCO agreed that a Theme-based Special Session (TBSS) would be held in 2023 on the overarching theme of climate change. NASCO's TBSS allow for greater exchange of information on a topic related to NASCO's Resolutions, Agreements and Guidelines. The Council agreed that:

> *'A Steering Committee would be established to consider the appropriate structure to ensure that tangible recommendations from the TBSS would be available to NASCO', CNL(21)62 (paragraph 5.20).'*

This TBSS would be NASCO's first on climate change.

NASCO and Climate Change

NASCO expressed concern about climate change as early as 1991 when 'Climate Change and Salmon Stocks' was on the Agenda of the Council Annual Meeting. The report, CNL(91)45, stated that:

> *'The Secretary presented a preliminary review, CNL(91)26 (Annex 23) on the possible implications of climate change for the wild salmon stocks. The salmon may be particularly vulnerable to global warming because of its life cycle which includes a phase in cold freshwater. The Council agreed that they should keep the evidence on climate change and its impacts on salmon stocks under review'.*

The introduction to the preliminary review referred to above, CNL(91)26, stated:

> *'At present detailed predictions of how climate change will affect salmon stocks are not possible. It is clear that all aspects of salmon biology could be affected by the predicted changes with implications for distribution changes*

[1] IPCC. 2021. Summary for Policymakers. *In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou. (Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 32 pp.

in freshwater and in the ocean and for management of the resource. The Council may therefore wish to be kept informed of developments in this field or consider holding a Special Session on this topic in the future.'

In 2012 the second performance review of NASCO reported (CNL(12)11) that 'in the long-term, the 'Next Steps' process should consider cross-cutting issues, such as climate change'. Also in 2012, the Secretary reported on the 'Salmon Summit' held in 2011. The Report of the 2012 Annual Meeting, CNL(12)39, page 100, stated:

'... over the last forty years, increased mortality at sea, linked to a warming climate, has resulted in a dramatic decline in the abundance of Atlantic salmon. Since management options in the ocean are limited, the report had concluded that the goal should be to maximise the number of healthy wild salmon that go to sea by focusing actions on impact factors in fresh, estuarine and coastal waters.'

Two key publications from the 'Salmon Summit' are available on the International Atlantic Salmon Research Board (the Board) website. Some of the scientific findings were published in a symposium issue of the ICES Journal of Marine Science (Vol. 69 (9)). A second report, 'Atlantic salmon at sea: Findings from recent research and their implications for management', focused on the management implications and applications of the research presented at the Salmon Summit.

In 2019, a two-day Symposium entitled 'Managing the Atlantic Salmon in a Rapidly Changing Environment – Management Challenges and Possible Responses' CNL(19)16 was hosted by Norway. This 'Tromsø Symposium' focused on the challenges facing Atlantic salmon and possible responses. It included presentations on climate change and the Tromsø Symposium Steering Committee made a recommendation that:

'To remain relevant in a period of rapid environmental and social change NASCO needs a renewed strategy to respond to the challenges facing wild Atlantic salmon. To begin this process NASCO should specifically identify strategic activities to deal with climate change and its cascading effects on salmon and salmon habitat, possibly by updating its 2005 'Strategic Approach for NASCO's 'Next Steps'.'

Climate Change and its Cascading Effects on Salmon and Salmon Habitat

In direct response to a question posed by NASCO in 2016, CNL(16)12, ICES held a workshop to quantify possible future impacts of climate change on salmon stock dynamics. The full workshop report was published in March 2017, and the findings were presented to the Council as part of the ICES Advice in June 2017, CNL(17)55. The report provides an excellent climate change overview, an overview of environmental and biological drivers that impact Atlantic salmon stock dynamics, a discussion of possible projections of climate change effects on these drivers and a comprehensive literature review of papers exploring climate change effects on Atlantic salmon.

However, the science of climate change is rapidly evolving. Since the 2016 ICES workshop and the Tromsø Symposium in June 2019, the Intergovernmental Panel on Climate Change (IPCC) has published several reports assessing the science related to climate change. One of its conclusions of the Sixth Assessment Cycle, published in 2021, is that the scale of recent changes across the climate system is unprecedented over many centuries to many thousands of years[2]. In this era of undoubted anthropogenic impact on the planet, with an already challenged environment for wild Atlantic salmon in both their freshwater and marine life stages, the need to update our knowledge base and engage in discussions on the most recent scientific information available has become imperative.

Objectives of the Theme-based Special Session

The overarching goal for the TBSS was to exchange information on the current and future impacts of climate change on salmon productivity in the North Atlantic and on management measures being implemented by NASCO Parties / jurisdictions, to identify best-practices and inform the development of a strategic approach by NASCO.

The TBSS addressed this overarching goal through the three following detailed objectives, each forming their own session within the TBSS.

1. Summarise the current and predicted impacts of climate change on Atlantic salmon productivity across North Atlantic freshwater and marine environments.

   Experts were invited to present information on:

   - a summary of existing and forecasted climate change across the north Atlantic relevant to salmon freshwater and marine ecology;
   - the current and predicted ecological impacts of climate change on salmon productivity in the North Atlantic, in freshwater habitats;
   - the current and predicted ecological impacts of climate change on salmon productivity in the North Atlantic, in marine habitats;
   - the role of freshwater and marine productivity in defining overall population productivity; and
   - anthropogenic stressors interacting with climate change.

[2] Ibid [1]

2a. Provide an overview of climate adaptive management actions undertaken by Parties / jurisdictions to mitigate the negative impacts of climate change, with an assessment of the effectiveness of these actions and lessons learned.

Parties / jurisdictions were invited to:

- describe the climate adaptive management measures that are being enacted, or plan to be enacted, within their relevant Party / jurisdiction;
- provide an assessment of the effectiveness of adopted management measures in mitigating the negative impacts of climate change on salmon productivity; and
- identify knowledge gaps and other factors that hinder progress.

2b. Provide an overview of climate adaptive management actions undertaken by other countries to mitigate the negative impacts of climate change, with an assessment of the effectiveness of these actions and lessons learned.

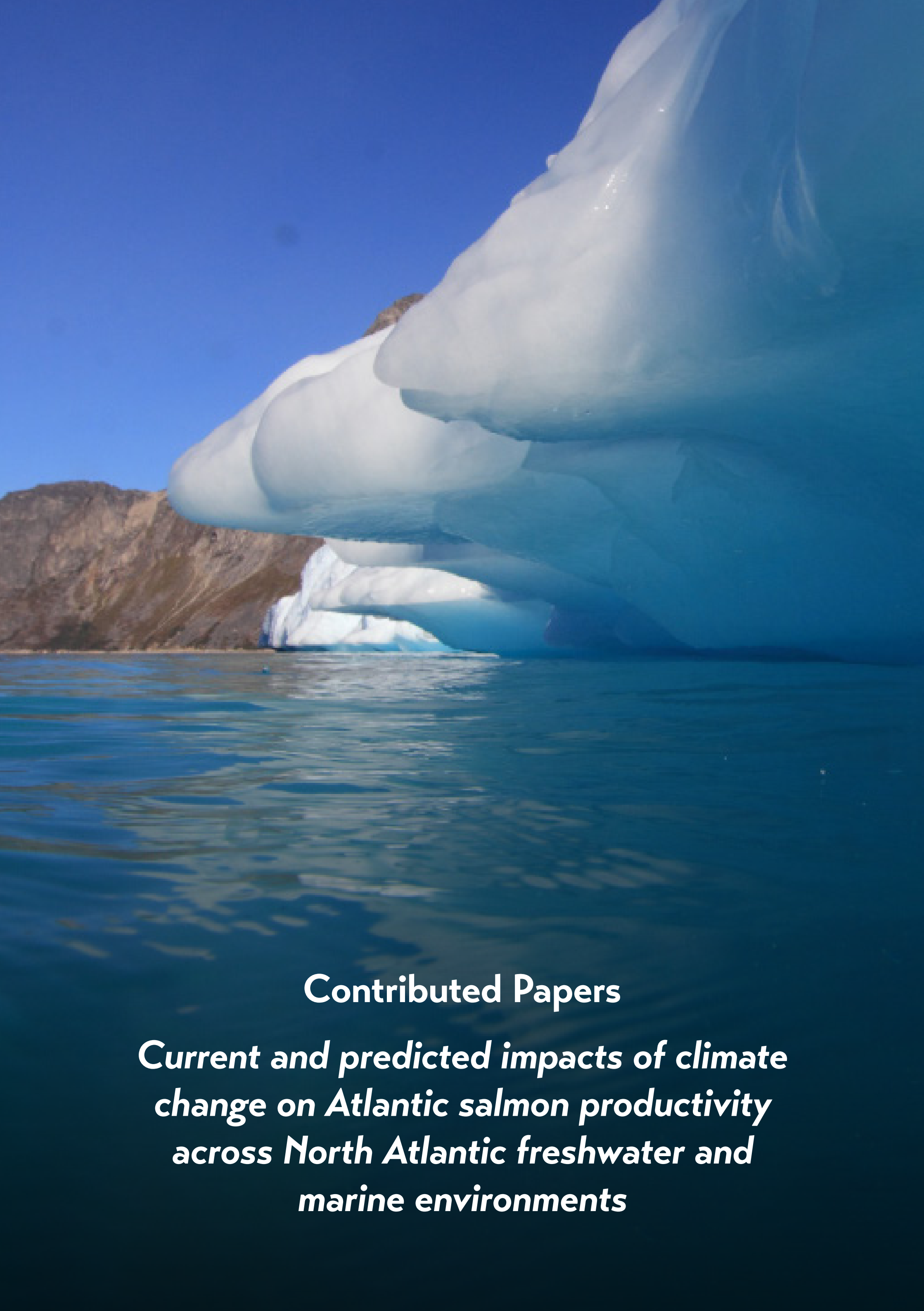
Other countries were invited to:

- describe the climate adaptive management measures that are being enacted, or plan to be enacted, within their country;
- provide an assessment of the effectiveness of adopted management measures in mitigating the negative impacts of climate change on salmon productivity; and
- identify knowledge gaps and other factors that hinder progress.

3. Review the effectiveness of management actions, the challenges and knowledge gaps that are hindering climate adaptive management efforts across jurisdictions, to result in a set of tangible recommendations to NASCO.

Steering Committee

The Steering Committee was formed in September 2022 and met periodically to develop the programme for the TBSS (CNL(23)19) and to draft tangible recommendations to present to NASCO at the 40th Annual Meeting of NASCO in Moncton, Canada on 6 June 2023.



Contributed Papers

Current and predicted impacts of climate change on Atlantic salmon productivity across North Atlantic freshwater and marine environments

Photo: Kai Benson Photography

Overview

The first part of the TBSS brought scientific experts in the field of climate change and salmon ecology to present an overview of expected climate change impacts to Atlantic salmon habitats, to describe evidence-based salmon impacts that are forecasted to occur within both freshwater and marine environments and to set out how these impacts may influence the productivity of Atlantic salmon across the species range. The relative influence that freshwater and marine productivity has in shaping the overall population productivity was also provided, alongside other anthropogenic stressors that may interact with the climate change stressors to further affect salmon populations.

The invited scientific experts were chosen by the Steering Committee based on their status in their field of expertise and their contribution to peer reviewed scientific literature. The following five presentations were delivered in Session One, with all the invited speakers providing a paper to NASCO prior to the TBSS. At the end of the presentations there was a question and answer session (Q&A), the details of which are set out at the end of this section.

- Øystein Skagseth presented a summary of existing and forecasted climate change across the North Atlantic relevant to salmon marine ecology;
- Timothy Sheehan on behalf of Kathy Mills presented on the current and predicted ecological impacts of climate change to salmon productivity in the North Atlantic, in marine habitats;
- André St-Hilaire presented on the current and predicted ecological impacts of climate change to Atlantic salmon freshwater productivity in the North Atlantic;
- Torbjørn Forseth presented on the anthropogenic stressors interacting with climate change; and
- Marie Nevoux presented on the role of freshwater and marine productivity in defining the overall outcome for an Atlantic salmon population.

CNL(23)48

Summary of existing and forecasted climate change across the north Atlantic relevant to salmon marine ecology

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North Atlantic salmon populations have generally shown a decreasing trend since the 1980s. This coherent large-scale decline both in productivity and abundance across Atlantic salmon stocks points toward changes in the marine phase of salmon as a governing factor. Coincident with the decline in salmon, the North Atlantic has become warmer since the 1980s, there have been marked changes in the circulation and associated changes in hydrography, nutrients, primary production. Temperature affects growth, survival and maturation of salmon during the marine phase (Beaugrand and Reid 2003; Friedland *et al.* 2005; Todd *et al.* 2008). The focus of this presentation is to review observed and projected climate change scenarios for the 21st century, with a focus on habitat changes in the North Atlantic of relevance for salmon. The more specific questions related to the biology effect related to salmon will be covered in accompanying presentations.

The North Atlantic plays a key role in redistribution of global heat. There is a much larger transport of heat to the Arctic via the North Atlantic compared to the Pacific. This explains the northward slanted isotherms toward northern Europe. It also explains why the Atlantic salmon has a much shorter latitudinal range in the western (US Canadian) compared to eastern north Atlantic. On the western side it spans latitudes of about 40-50 °N (1000 km) from the US to Canada while on the European side it spans latitudes from about 45-70 °N (2500 km).

The North Atlantic climate is observed to vary over a broad range of time scales. The longest period resolved by instrumental records is the Atlantic Multidecadal Oscillation (AMO) with period of order 60-70 years (e.g. Mann *et al.* 2020). If this is an intrinsic period of the North Atlantic climate system, e.g. related to the Atlantic Overturning Circulation, or if is simply forced by radiation change due to variability in volcanic forcing is under debate (Mann *et al.* 2020; Muller-Plath 2020). However, regardless of mechanism, there is substantial evidence of ecosystem response generally following the AMO phasing (Drinkwater *et al.* 2013).

One main characteristic of the North Atlantic climate system is the opposite climate variability between the Greenland Labrador region and the northwestern Europe (van Loon and Rogers 1978) with cited evidence of its existence dating back to the 18th century. Basically, this is connected to the local effect of the North Atlantic Oscillation (NAO) (Walker and Bliss 1932). The positive / negative phases of the NAO are associated with increased / decreased ocean heat loss over the Labrador Sea, while this relation is opposite for the Barents Sea. However, from the mid- 1990s, air and sea temperatures in both regions generally have been in phase, showing strong warming and reduced ice coverage. The cause of this change is related to changes in the spatial structure of the atmospheric pressure patterns, resulting in a general reduction in the importance of NAO forcing over the North Atlantic (Drinkwater *et al.* 2013).

Since the mid-1990s some remarkable changes have occurred in the North Atlantic. First, as a manifestation of a warming climate the general cooling of the Atlantic Water flowing northward to the Arctic has decreased, i.e. reduced ocean to air heat loss (Mork *et al.* 2014, 2019). The subpolar gyre, a large water mass bound by the Labrador current on the north and west and the Gulf Stream in the south and east, transitioned from a strong state prior to 1995, to a subsequent weaker state with reduced amount of relative cold / fresh subpolar water mixed into the North Atlantic Current (Hátún *et al.* 2005) and associated ecosystem response across many trophic levels (Hátún *et al.* 2009). Then during 2012 to 2016, the eastern subpolar North Atlantic underwent extreme freshening in response to anomalous winter wind patterns driving major changes in ocean circulation, including slowing of the North Atlantic Current and diversion of Arctic freshwater from the western boundary into the eastern basins (Holiday *et al.* 2020), a signal also evident in the Nordic Seas with an advective delay of some few years (Mork *et al.* 2019) that altered the water mass composition in the Norwegian Sea (Skagseth *et al.* 2022).

Since the 1980s observations show a general 1 °C warming in the upper ocean. However, a marked exception from this is in the subpolar North Atlantic that in fact has experienced slight cooling, often termed the North Atlantic warming hole or cold blob (Drijhout *et al.* 2012). The North Atlantic warming hole is associated with a decline of the Atlantic Meridional Overturning Circulation (AMOC). The warming hole is situated south of deep convection sites, indicating that it involves an adjustment of the gyre circulation. The warming hole is prominent in historical runs, where the response of the AMOC to global mean temperature is weak. In the more strongly forced scenario runs, the warming hole over the subpolar gyre becomes weaker, while cooling over the Nordic seas increases, consistent with previous findings that deep convection in the Labrador and Irminger Seas is more vulnerable to changes in external forcing than convection in the Nordic seas, which only reacts after a threshold is passed.

Figure 1. *The major ocean current systems in the North Atlantic.*

The main question here is how the wild salmon have responded to the North Atlantic climate variability that is observed to occur over a broad range of time scales. On the longest observed scales, the Atlantic Multidecadal Oscillation describes long-term fluctuations in annually autocorrelated sea surface temperatures with a period of about 70-80 years, that seems to have a positive correlation across trophic levels (Beaugrand and Reid 2003). Condron *et al.* (2005) suggested a shift in the AMO in the early 1990s may have deteriorated marine growing conditions for salmon and predicted that this could persist until the mid-2020s. The exact pattern in variation of the AMO appears to exert different effects on European and North American salmon stocks (Friedland *et al.* 2014).

For the North American salmon, there was a decline in abundance after 1990, and productivity declined between 1987-1996 (Mills *et al.* 2013). This period was extreme in terms of a positive NAO condition and severe condition on the northwest Atlantic shelves, but with a subsequent record drop to negative NAO conditions in 1996. Changes in salmon may be initiated by extreme changes in the environment. Further, the warming since about 2000 may have restricted southern spawning. The lack of recovery for salmon when environmental conditions reverted to 1980s-like conditions points toward ecosystem changes that prohibit recovery. In Labrador Sea after 2000 there have been increases in phytoplankton production (Behrenfeld *et al.* 2006). However, these have led to an increase in small zooplankton, while lipid -rich zooplankton and capelin have continued to decline compared to pre-1990 estimates (DFO 2019). This points to the importance of extremes in climate conditions that change the trophic interactions that prevent rebound of salmon despite climate condition returning to more normal conditions.

For the European salmon there is substantial evidence that temperature governs growth, survival and maturation of salmon during the marine phase (Beaugrand and Reid 2003; Friedland *et al.* 2005; Todd *et al.* 2008). From 1960 to 2009 pronounced declines have been noted for zooplankton (total copepods, Cal. Fin.) and euphausiids and salmon catches along with increasing trends in SST, AMO, NHT and phytoplankton (Beaugrand and Reid 2003, 2012). These changes occur as coincident progressive steps in both the environment and the biology (Beaugrand and Reid 2012). For Norwegian salmon stocks Vollset *et al.* (2022) reported an unprecedented collapse in growth about 2005 and suggest that there are additional explanatory factors beyond physiological limitations imposed by temperature. The simultaneous changes to temperature, zooplankton and marine growth of Atlantic salmon and subsequent decrease in size of mackerel occurred after what seemingly was a sudden reduction in the transport of Arctic water into the Norwegian Sea. This observation may suggest that the simultaneous occurrences of shifts in physical and biological measurements are driven by a bottom-up process associated with abiotic environmental changes or at least that these changes were set in motion by a shift in distribution of Arctic water in the Norwegian Sea (Skagseth *et al.* 2022). The zooplankton density and nutrients (Skagseth *et al.* 2022) is higher in Arctic water than in Atlantic water, so conveyance of food may also have declined after 2005 (Toresen *et al.* 2019; Utne *et al.* 2022). The reduced transport of Arctic water with high abundance of microzooplankton into the Norwegian Sea is therefore a plausible explanation for the shifts in post smolt growth and ecological regime (Utne *et al.* 2022). In farm-intensive areas, mortality of wild Atlantic salmon due to salmon lice may be considerable, and for survivors, the marine growth may be affected (Vollset *et al.* 2019). However, the decline in growth and decline in one-sea-winter fish that occurred in 2005 is not mainly driven by impacts of fish farms.

Given the ~post 2000s decline in salmon that has coincided with a warmer North Atlantic the question of how climate will evolve and what will be the expected effect on salmon is highly relevant. In a comprehensive modelling study Alexander *et al.* (2018) assessed changes in the mean, variability and extreme sea surface temperatures (SSTs) using the observed greenhouse gas concentrations for 1976-2005 and the RCP8.5 ‘business as usual’ scenario for greenhouse gases through the remainder of the 21st century. They found that the annual mean trend over North Atlantic was in the range from 0.05 to 0.5 °C decade^{-1}. Forecasted SST changes by the end of the 21st century are primarily due to a positive shift in the mean with only modest changes in the variability for shelves across the North Atlantic. The SST trends are generally stronger in summer than in winter, as greenhouse gas heating integrates over a much shallower climatological mixed layer depth in summer than in winter, which amplifies the effect of greenhouse warming. However, a pronounced feature of these scenario runs is the subpolar North Atlantic where the trend was generally small, and even negative for March.

A forecasted general warming of the North Atlantic in the 21st century suggests that southern stocks across the Atlantic will decline. This would be especially true if the global general warming and extremes are even stronger over land than ocean, which may result in increased migration to northward shifting marine feeding areas. At the same time, it is very likely that a generally warmer climate could provide a thermal regime allowing for salmon to occupy more northern rivers. The warming of the upper ocean is likely to increase the stratification and reduce the mixed layer depth and phytoplankton production may increase, but again a warmer ocean may favor smaller zooplankton that again may not be beneficial as prey for fish including salmon. However, while an overall warming trend is expected, the subpolar North Atlantic is an area of large natural variability with associated changes in circulation, water masses, nutrients and biota, that is likely to affect salmon in non-linear ways. Thus, to predict the marine condition for salmon growth and survival is a difficult task, especially given the spatial variability in how these conditions may develop across the North Atlantic. However, recent high temperatures are considered anomalous within the context of 1000s of years, and this warming will continue. The Atlantic salmon will need to adapt to this warming climate, and thus changes of occupation area are to be expected in both the freshwater and marine phases.

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Current and predicted ecological impacts of climate change to salmon productivity in the North Atlantic, in marine habitats

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Introduction

After spending their early life stages in freshwater habitats, Atlantic salmon (*Salmo salar*) migrate to the ocean to feed, grow and mature. Salmon move into the ocean as smolts and mature into adults over a 1- to 4-year period. In the Northwest Atlantic, salmon leave rivers in the Northeast U.S. and Canada and migrate to marine feedings areas in the southern Labrador Sea (ICES 2021). After overwintering in the Labrador Sea, individual salmon will either continue their migration to the coast of Greenland to feed for another summer or will initiate their return migration to natal rivers to spawn. Individuals that feed off the coast of Greenland are believed to overwinter in the Labrador Sea the following year with new migrant salmon from the subsequent year's cohort. In the Northeast Atlantic, juvenile salmon from rivers as far south as Portugal, north to Norway and east to Russia follow a similar pattern after emigration by converging across a broad swath of the Northeast Atlantic, particularly within the Norwegian Sea (ICES 2021). As these post-smolts grow and feed during their first summer and overwinter within these areas, decisions are made to mature and return to natal rivers to spawn as one-sea-winter spawners or to remain at sea for another year or more, eventually becoming multi-sea-winter spawners. These multi-sea-winter spawners will continue their migration to distant summer feeding areas off the west and east coast of Greenland and may overwinter in similar areas with the new migrant salmon from the subsequent year's cohort.

Both North American and European origin salmon have been shown to undergo trans-Atlantic migrations. North American origin salmon have been detected in relatively low numbers within the Norwegian Sea (Gilbey *et al.* 2017), and European origin salmon have been detected along the west and east coasts of Greenland (ICES 2021, 2022) and in the southern Labrador Sea (Bradbury *et al.* 2021). In the Labrador Sea and along the west coast of Greenland, southern European origin salmon are more prevalent than those from northern Europe, whereas east of Greenland potential multi-sea-winter salmon from northern Europe have a more easterly distribution than those from southern Europe (Reddin *et al.* 2012). These stock-specific patterns of marine migration are beginning to emerge more clearly given recent genetic studies (Bradbury *et al.* 2021; Gilbey *et al.* 2021; O'Sullivan *et al.* 2022), stable isotope studies (MacKenzie *et al.* 2011; Almodóvar *et al.* 2020) and tagging studies involving post-spawn migrants (Strøm *et al.* 2017; Rikardsen *et al.* 2021).

In all these marine habitats, physical and ecological conditions affect Atlantic salmon productivity. Since the late 1980's, marine survival rates have declined and remained depressed for many of the monitored populations across both North America and Europe (Olmos *et al.* 2019; ICES 2021) and the coherence of these declines across widespread geographies implicates marine ecosystem conditions as a key driver (Beaugrand and Reid 2003, 2012; Mills *et al.* 2013; Olmos *et al.* 2019; ICES 2021). Temperature, stratification and ocean currents influence the environmental and ecological conditions experienced by Atlantic salmon, and climate-driven alterations have and will continue to directly and indirectly affect the productivity of Atlantic salmon populations across the species' range.

This paper provides an overview of the key habitat features that influence Atlantic salmon during their marine life stages. It draws upon prior studies to elaborate the direct and indirect pathways by which climate change may affect Atlantic salmon populations. Finally, it synthesizes projected changes in ocean conditions and hypothesizes the potential impacts of climate variability and change on Atlantic salmon productivity.

Habitat features that influence Atlantic salmon marine life stages

Temperature, stratification and ocean currents represent key physical variables determining the suitability of Atlantic salmon marine habitats. These variables also influence numerous characteristics of the broader marine ecosystems within which Atlantic salmon are embedded.

Temperature

Ocean temperatures constrain habitat areas Atlantic salmon and other species can occupy, based on the thermal limits, tolerances and preferences of the species. Lower critical temperatures (i.e., the limit of temperatures that can be tolerated) for Atlantic salmon range from 0-7 °C, while upper critical temperatures span 22-33 °C (Elliott and Hurley 1997). As migratory species, individual Atlantic salmon may experience a wide range of temperatures, particularly during the riverine-marine transition and over the north-south latitudinal gradient they transit. Despite being able to survive a broad temperature range in laboratory-based thermal tolerance tests, a narrower range of preferred temperature typically constrains their spatial and temporal patterns in the ocean. Atlantic salmon are most commonly found in areas with sea surface temperatures between 3 to 8 °C (Reddin and Shearer 1987) with more recent studies providing more specificity (e.g., 5.0-13.4 °C (Sheehan *et al.* 2012), 3.9-9.7°C (Minke-Martin *et al.* 2015), 1.6-8.4 °C (Strøm *et al.* 2020)). In addition to absolute temperatures, the seasonal temperature cycle also affects spatiotemporal availability of suitable thermal habitat for salmon and may provide important cues for life history events such as migration to and from rivers or to seasonally used ocean areas (Henderson *et al.* in press).

For ectotherms like Atlantic salmon, temperature also exerts a strong direct influence on metabolism. Metabolism rises as temperature increases, resulting in higher energy costs (Jonsson and Jonsson 2009). These costs can be multiplied during active life phases, such as migration windows when Atlantic salmon must exert energy for swimming. In general, whether these rising energetic demands can be satisfied depends on the abundance and quality of prey available to Atlantic salmon (Renkawitz *et al.* 2015), which also may be indirectly affected by temperature. Similarly, temperature influences the spatial and temporal distributions of Atlantic salmon predators, which may alter encounter frequency and modify natural mortality rates (Friedland *et al.* 2012). As such, temperature-related effects on species across the marine ecosystem can disconnect or concentrate interactions between salmon and other species (e.g. predators, prey) that ultimately affect vital rates such as growth and mortality.

Stratification

Rising sea surface temperature and declining salinity strengthen ocean stratification, which in turn may affect primary productivity and zooplankton composition in ways that influence trophic relationships across the ecosystem (MERCINA Working Group 2012). In the North Atlantic habitat areas occupied by Atlantic salmon, temperature and salinity changes have historically been driven by changes in ocean circulation that modulate the influence of ocean currents with different salinity properties. For example, the relative balance of Labrador Sea water (colder, relatively less saline) versus Gulf Stream water (warmer, relatively more saline) entering Northwest Atlantic shelf ecosystems affects both salinity and temperature, thereby determining the strength of stratification (MERCINA Working Group 2012). In general, changes in the Gulf Stream and Arctic circulation affect temperature, salinity and stratification across much of the North Atlantic Ocean used by Atlantic salmon (Meyer-Gutbrod *et al.* 2021; Vollsett *et al.* 2022), which creates cascading impacts that can positively or negatively affect Atlantic salmon productivity and abundance (Mills *et al.* 2013).

Ocean currents

As described above, large-scale ocean circulation patterns associated with major current systems influence ecosystem conditions and dynamics in the North Atlantic region. These broad circulation patterns and other environmental conditions (e.g., wind, river discharge) also affect current strength at local scales within the North Atlantic. The strength of local currents is particularly important for Atlantic salmon during their ocean-going migration as post-smolts, when altered currents may impact the efficiency of migration by increasing or decreasing their swimming time and distance traveled (Friedland *et al.* 2012; Mork *et al.* 2012; Byron and Burke 2014). As adults, Atlantic salmon are strong swimmers that are unlikely to be significantly deflected from their migration route, although swimming against stronger currents imposes a higher energetic demand. The altered metabolic cost of migration for both post-smolt and adults may divert energy from growth and may be compounded by conditions such as warmer temperatures, foraging quality and predation risk (Friedland *et al.* 2012; Byron and Burke 2014), ultimately influencing both growth and survival.

Ecosystem changes

The above descriptions of how physical habitat variables affect Atlantic salmon during their time at sea introduce some indirect mechanisms through which these variables alter ecosystem conditions. Yet it is valuable to highlight that these underlying physical variables exert a strong influence on the development of the entire marine ecosystem. Their variability affects the magnitude and timing of phytoplankton blooms, composition of the zooplankton community, abundance and quality of prey fish and the spatiotemporal distribution of predators, all of which may indirectly influence population dynamics such as growth, maturity, fecundity and survival of Atlantic salmon during their marine life stages.

Impacts of ecosystem change on Atlantic salmon

A number of studies from the Northwest and Northeast Atlantic have demonstrated relationships between changing ecosystem conditions and Atlantic salmon population characteristics and dynamics. Direct effects of temperature have been associated with spatial distribution and run timing of Atlantic salmon smolts and adults. Warming and broader ecosystem changes have been associated with changes in growth, productivity and abundance of Atlantic salmon populations.

Temperature range and spatial distribution

As noted earlier, marine spatial and temporal patterns of Atlantic salmon are generally constrained by a relatively narrow range of preferred temperatures. Salmon have evolved to depend on the ecosystem dynamics that are represented within this range, and alterations of these spatial and temporal patterns may have consequences for Atlantic salmon productivity. Generally speaking, it is hypothesized that salmon seek a preferred temperature range and that their marine distribution may shift both inter-annually and over the long-term in response to short and longer term warming trends (Strøm *et al.* 2020).

A recent large-scale tagging study on Atlantic salmon has helped define the marine migration patterns of post-spawned adults from across Europe and Iceland (Rikardsen *et al.* 2021). Salmon from different populations utilized different migration routes and areas, with differing temperature profiles, but they consistently migrated to areas of high productivity located between North Atlantic and cold polar water frontal areas. Increased diving activity indicated these areas to be important feeding areas. If the locations of these boundary areas change over time, it is unclear how populations will respond in terms of migration routes and timing. If the location of these areas moves northward because of ocean warming, southern populations may be especially challenged given increased migration distance, time and energy demands. Although Rikardsen *et al.* (2021) investigated post-spawned adults, the dynamics seen may also be indicative of dynamics for early marine phase Atlantic salmon.

Run timing

The timing of emigration of Atlantic salmon smolts and immigration of adults is shifting, and temperature has been identified as an influential factor. Smolts leaving rivers in the Northwest and Northeast Atlantic have migrated seaward 2.5 days earlier per decade, on average (Otero *et al.* 2014). However, smolt migration timing is variable across rivers, with smolts from southern rivers migrating earlier than northern ones (Hvidsten *et al.* 1998) and Northeast Atlantic populations migrating earlier than Northwest Atlantic populations at analogous latitudes (Otero *et al.* 2014). Differential migration timing has been associated with freshwater and sea surface temperatures; although photoperiod also cues smoltification and migration, river temperature enables salmon to refine the timing of ocean entry to encounter optimal ecosystem conditions (Otero *et al.* 2014). Recent studies have further investigated the complex relationship of these and other drivers of smolt emigration (Vollset, *et al.* 2021; Simmons *et al.* 2021; Frechette *et al.* 2023). As the seasonality of annual temperature cycles shifts, the influence of photoperiod on migration timing may create disconnects between salmon smolts and their prey or may intensify interactions with their predators (Friedland *et al.* 2012). Further, differential warming between freshwater and marine environments could result in cues that cause smolts to enter the ocean at unfavorable times or under unideal conditions.

Return migration timing of adult Atlantic salmon has been changing in many rivers in which this phenomenon has been studied. Analysis of long-term recreational catch data have suggested that the timing of adult returns across France has been delayed by 20-40 days (Bal *et al.* 2017), and a study in Scotland indicates stable median adult return dates in some rivers but delayed returns in others (Todd *et al.* 2012). However, in other locations, advances in adult return dates have been observed. A study of Atlantic salmon adults observed in monitoring stations on 28 rivers across France estimated that return dates have advanced 2.9 days per decade (Legrand *et al.* 2021). In the Burrishoole catchment (Ireland), 50 % of returning Atlantic salmon are arriving 1-2 months earlier than in the 1970s: a rate of 0.75 days earlier per year (de Eyto *et al.* 2022). In the Penobscot River (Maine, USA), the median date of adult Atlantic salmon migration has advanced 0.7 days per year from 1978-2001 and 1.3 days per year from 1986-2001 (Huntington *et al.* 2003; Juanes *et al.* 2004; Staudinger *et al.* 2019). These advances in return migration date have been concentrated at the end of the run, with the 75th and 90th percentiles of the run experiencing the most rapid advances (Mills et al. 2024). In both the Burrishoole and

Penobscot systems, limited change has been noted for the start of the run, but advancement of the end has resulted in a contraction of the total length of the run (de Eyto *et al.* 2022; Mills et al. 2024). This shorter return period reduces the potential for buffering unfavorable conditions that could be gained if the returning population is spread out over a longer time period. However, if stress is induced by the duration of exposure to unfavorable ocean conditions, a tighter and earlier return period facilitates escapement from these conditions. The different return timing responses and how they are distributed over the course of the run may indicate multiple drivers of return migration timing, which may be acting at basin and local scales.

Growth

Many studies have examined changes in growth of Atlantic salmon based on measures of circuli from salmon scales, with an interest in also understanding how changes in growth are related to marine survival rates and to environmental conditions, particularly temperature. Generally, these studies have focused on the post-smolt stage (through the end of the first calendar year at sea) and have found contrasting results for Northeast and Northwest Atlantic salmon populations. In the Northeast Atlantic, the influence of post-smolt growth on subsequent survival has been detected in some populations (Peyronnet *et al.* 2007; Friedland *et al.* 2009a), whereas no similar relationship has been found for Northwest Atlantic populations (Friedland *et al.* 2009b; Hogan and Friedland 2010; Izzo and Zydlewski 2017).

Correlations between temperature and growth are nuanced. The optimum temperature for growth of post-smolts in the ocean has been estimated to be 13 °C based on experimental tests (Handeland *et al.* 2003) and 14.8 °C based on bio-energetic modelling (Smith *et al.* 2009). However, temperature does not act in isolation to determine growth; food resources, particularly plankton and prey fish, are also necessary to support growth (Friedland *et al.* 2009b; Vollset *et al.* 2022). For some populations at the northern extent of the range of Atlantic salmon, warmer sea surface temperatures have been associated with faster growth (Jensen *et al.* 2011). However, for most populations, rising sea surface temperatures have been associated with declines in Atlantic salmon growth (McCarthy *et al.* 2008; Todd *et al.* 2008; Friedland *et al.* 2009b). Most studies have considered growth during the post-smolt life stage, but a recent study found significant declines in growth during the second winter at sea for MSW Atlantic salmon, with the most substantial declines occurring during the warmest period of the time series (Barajas *et al.* 2022). In contrast, marine growth from a French population has demonstrated declines in growth over the first summer only, but also provided evidence on the complex relationship between sex, marine growth and maturation (Tréhin *et al.* 2021). This relationship between growth, survival and maturation is complicated and deserves further attention given its interconnectedness in determining overall population productivity (ICES 2023).

Recent studies provided new insights into relationships between ecosystem conditions, growth and marine survival of Atlantic salmon, highlighting complex non-stationary relationships. Vollset *et al.* (2022) studied salmon returning to rivers across Norway and found substantial, sudden declines in early marine growth and increases in the proportion of MSW salmon (i.e. later maturity) after 2004. These changes coincided with broader oceanographic and ecosystem changes, including an increase in spring sea surface temperature, reductions in zooplankton biomass and declines in prey fish abundance, all of which reflect a regime shift in the Northeast Atlantic ecosystem that impacted Atlantic salmon. In addition, Tillotson *et al.* (2021) examined Atlantic salmon from multiple North American stocks feeding off West Greenland and found that while marine growth has generally increased, a strong non-stationary relationship between growth and survival emerged. Growth was positively related to marine survival prior to the 1990s, but the relationship broke down after 1990 when a regime shift affected multiple levels of the North Atlantic ecosystem, indicating that mechanisms controlling marine survival changed. These studies both show direct, indirect and interacting climate influences on Atlantic salmon growth and survival, but these relationships need to be examined in an ongoing manner as ocean ecosystem regimes change.

Productivity and abundance

Atlantic salmon have experienced population declines across their North American and European range, with particularly strong declines in post-smolt survival, productivity and abundance observed in the early 1990s (Beaugrand and Reid 2003, 2012; Mills *et al.* 2013; Olmos *et al.* 2019, 2020). These declines have been coherent across North American and European regions (Olmos *et al.* 2019, 2020), but the greatest declines have been experienced by populations at the southern extent of the range (ICES 2021). Moreover, declines have been more severe for fish that spend more time in the marine environment (i.e. multi-sea-winter fish), including those that migrate longer distances.

These multi-population studies have identified relationships between population declines and environmental conditions such as sea surface temperature and changing dynamics of ocean currents (Beaugrand and Reid 2012; Mills *et al.* 2013; Olmos *et al.* 2020; Vollset *et al.* 2022). However, the concurrent broader ecosystem conditions may exert stronger influences on Atlantic salmon populations via indirect mechanisms acting through bottom-up or top-down processes. A recent bioenergetics modelling study concluded that increases in ocean temperatures will result in significant indirect impacts (e.g. prey quality and abundance) to individual Atlantic salmon productivity compared to the direct impacts of temperature on physiological performance (Strøm *et al.* 2023). The authors suggest their conclusions may be applicable to many northern Atlantic salmon populations, but possibly not southerly populations given that they are already experiencing warmer temperatures than their northern conspecifics.

Bottom-up trophic mechanisms have received the greatest attention in existing studies. A major trophic shift in the 1990s on both sides of the North Atlantic. This shift resulted in changes in phytoplankton and zooplankton communities (Pershing *et al.* 2005; Beaugrand and Reid 2003) and reductions in the abundance and energetic quality of prey (Mills *et al.* 2013; Renkawitz *et al.* 2015), which have contributed to changes in productivity and abundance of Atlantic salmon populations (Beaugrand and Reid 2003, 2012; Mills *et al.* 2013). In addition, shifts in the distribution and phenology of predators may enhance their overlap with and mortality of Atlantic salmon, particularly during certain critical life stages such as estuarine and coastal migrations (Friedland *et al.* 2012).

Projected climate-driven changes and impacts to Atlantic salmon

Projected climate-driven changes in physical ocean conditions

Climate projections indicate that physical features of the North Atlantic region inhabited by Atlantic salmon will change over the coming decades, and these physical changes are expected to drive ecological changes in the region. The magnitude of change will be influenced by greenhouse gas emission trajectories, and results presented below contrast two extreme scenarios using the most recent Intergovernmental Panel on Climate Change's (IPCC) Coupled Model Intercomparison Project 6 (CMIP6) model ensemble (Eyring *et al.* 2016). The SSP1-2.6 scenario is based on substantial global CO_2 emission cuts that achieve net-zero emissions around 2070, with temperatures stabilizing around 1.8 °C warmer at the end of the century. In contrast, the SSP5-8.5 scenario assumes a future with continued rapid economic growth and CO_2 levels doubling by 2050, resulting in a 4.4 °C increase in global temperature by 2100 (IPCC 2021, Table SPM.1). Oceanographic responses under these scenarios begin to diverge by mid-century (2040-2069), but the differences are most apparent at the end of the century (2070-2099).

Sea surface temperature is projected to increase over much of the North Atlantic under both scenarios, with the strongest warming expected south of Newfoundland to the Gulf of Maine in the Northwest Atlantic and in the Norwegian Sea in the Northeast Atlantic. In these areas, sea surface temperatures are projected to warm by more than 1.6 °C by mid-century and 2.0 °C by end-of-century under the SSP1-2.6 scenario and by up to 2.5 °C by mid-century and 4.8 °C by end-of-century under the SSP5-8.5 scenario (Figure 1). However, Arctic and Greenland ice melt and other factors are expected to contribute to weakening of the Atlantic Meridional Overturning Circulation (AMOC, the global ocean conveyer belt that brings warm water north and cold water south), creating a 'warming hole' south of Greenland, one of the only places in the ocean that is projected to *cool* in future decades under certain scenarios (Bakker *et al.* 2016; Ceasar *et al.* 2018; Keil *et al.* 2020). Cooling is projected to be as great as 0.6 °C under the SSP1-2.6 scenario at the end of the century. Under the SSP5-8.5 scenario, this area is projected to warm modestly (up to 0.8 °C by the end of the century), yet far less than surrounding portions of the North Atlantic.

Salinity is projected to decline across the North Atlantic region (Figure 2). Under both the SSP1-2.6 and SSP5-8.5 scenarios, sea surface salinity is projected to be 0.5-0.6 practical salinity units (psu) fresher in the Labrador Sea, east of Newfoundland and in the North Sea at mid-century. By end-of-century the area experiencing the strongest freshening will expand to cover more of the North Atlantic, and salinity is projected to decline by 0.5-0.7 psu under the SSP1-2.6 scenario and by 1.4-1.8 psu under the SSP5-8.5 scenario.

Further, shallower mixed layer depths are projected across much of the North Atlantic (Figure 3). Shallowing of the mixed layer reflects enhanced water column stability (i.e. stratification) that is influenced both by warming of the surface waters and reduced salinity. Mixed layer depths are projected to shoal by 110 m across much of the North Atlantic, from the southern part of the Labrador Sea to Ireland, at mid-century under both scenarios. At end-of-century, the same areas will experience the greatest shallowing of mixed layer depth, with a projected shoaling of as much as 120 m under SSP1-2.6 and 200 m under SSP5-8.5.

Implications for Atlantic salmon populations

Climate change will push ocean conditions in the North Atlantic beyond bounds that have been experienced during the observational record for Atlantic salmon. Ocean temperatures are projected to rise substantially in certain areas, including the Gulf of Maine, Gulf of St. Lawrence, Scotian Shelf and southern Newfoundland Shelf, Iceland Sea and Norwegian Sea. Many of these areas are primary Atlantic salmon marine habitat and these increased temperatures, combined with potential ecosystem changes that affect Atlantic salmon feeding success and predation rates, may significantly impact the marine productivity of this species. These impacts may particularly threaten the survival of populations at the southern extent of the range, as these stocks will not only experience the highest-magnitude temperature increases, but also have the largest migration distances to reach marine feeding areas.

In addition to increasing temperatures, Atlantic salmon will experience stronger temperature gradients and changing seasonality, which may affect their migrations from southern areas of the Northwest Atlantic to the Labrador Sea and from Europe to the Norwegian Sea. In particular, in the mid-North Atlantic, the cooling (SSP1-2.6) and less dramatic warming (SSP5-8.5) effects associated with a slowdown of the AMOC will disrupt temperature gradients across much of the area south of Greenland and Iceland. This disrupted temperature gradient may interfere with migration cues and the ability of salmon to effectively navigate through feeding, overwintering and other habitats in the ocean. Changing seasonality of spring warming and fall cooling will also shift migration cues, creating the potential for mismatch between the needs of salmon and the ecosystem conditions they encounter.

Further, shifting seasonality will alter the length of the summer feeding and overwintering periods, which will have energetic implications for Atlantic salmon. This varied temperature gradient will likely create a complex mosaic in which contemporary direct and indirect drivers of salmon productivity are changing in vastly different directions and magnitudes across the spatial marine range of the species. The impact of these varied changing conditions could range from strongly negative, to neutral to strongly positive. Collectively, this will create a future salmon marine ecosystem that is difficult to predict and even more difficult to forecast the impact it may have on the productivity of Atlantic salmon populations across the species' entire range. These scientific limitations will require managing salmon populations within a context of greater uncertainty.

Although temperature, salinity and stratification are key physical properties that will be affected by climate change, it is critical to recognize that most of the impacts to Atlantic salmon will not be attributable to one variable acting directly or in isolation of other variables. The interactive effects of multiple changes and their indirect effects through the ecosystem will exert the greatest effects on Atlantic salmon. Physical changes that alter primary productivity, zooplankton composition, prey fish and predators will all affect Atlantic salmon. Bottom-up effects may accrue through changes in species overlap and interactions, or they may emerge through changes in energy pathways and energy density. As such, future success of Atlantic salmon in terms of growth, productivity and survival may not be determined only by changes in prey composition but also by changes in the quality of the prey items in terms of energetic value (Renkawitz *et al.* 2015). Top-down effects may emerge as predators of Atlantic salmon shift their spatiotemporal distributions and experience different encounter rates (Friedland *et al.* 2012). In addition, changing overlap between Atlantic salmon and fishing fleets could occur if fleets shift their locations as their target species move.

The Atlantic salmon marine environment is extremely complex and is changing at a rapid pace, which is projected to continue with climate change. The expected changes are varied within regions of the North Atlantic used by Atlantic salmon, and the magnitude of these changes is not yet known given uncertainty in future global greenhouse gas emissions and interconnectedness of the ecosystem. However, even with this uncertainty, rising temperatures, changing stratification, shifts in ocean currents and other climate-related changes will act directly and indirectly on Atlantic salmon to:

1. Shift spatial distributions, which may:

   a. Increase risk of extirpation, as southern portions of range may exceed bioenergetic thresholds or tolerance limits;

   b. Increase potential for northerly range expansion and enhanced productivity of stocks within the northern portion of the range; and

   c. Shift locations of preferred habitats.

2. Shift temporal distributions, which may:
    a. Alter smolt migration timing, resulting in different ecosystem conditions at sea-entry (potential predator-prey mismatch);
    b. Alter dates of return from sea, with evidence of both earlier and later returns emerging from studies in different systems; and
    c. Shift the timing of transition between various marine phases (e.g. overwintering, summer feeding).
3. Alter growth, maturation and survival schedules:
    a. Increase or reduce metabolic demand due to changes in temperature, currents and other conditions, which would affect the quantity and quality of prey salmon need to satisfy their energetic requirements;
    b. Influence growth of Atlantic salmon during all marine phases, with changes during post-smolt and late marine phases being most tightly associated with marine survival (based on prior studies); and
    c. Alter maturation decisions, creating the potential for slower maturation with lower marine growth or earlier maturation with faster growth.

Prior studies of how warming and other ecosystem changes have affected Atlantic salmon populations lead us to expect mostly negative effects of continued climate change. However, it is possible that some effects may be positive, particularly the potential for the northward expansion of favorable habitats. In addition, if warming causes alternative high-energy prey species to increasingly overlap in distribution with Atlantic salmon, positive indirect effects of warming could be realized (Strøm *et al.* 2023). However, multiple sources of uncertainty associated with future climate scenarios, magnitude of physical and ecosystem changes and how those will affect Atlantic salmon across their mosaic of ocean habitats and life stages limit our ability to confidently project the future of Atlantic salmon under climate change.

Further, just as variables associated with climate change do not act alone, neither does climate change operate as a singular stressor. Climate-related challenges facing Atlantic salmon during their marine life stage cannot be separated from, and in fact will likely be compounded by, climate impacts during their freshwater life stages and by a large suite of anthropogenic stressors, such as habitat degradation, pollutant loads and fishery interactions. Reducing these other stressors can enhance the resilience of Atlantic salmon to climate impacts, giving them the greatest opportunity to withstand negative impacts of changes in the marine ecosystem during their time at sea.

Uncertainties and research needs

Conserving Atlantic salmon populations as climate change progresses requires managing in the context of uncertainty. Understanding how climate change impacts Atlantic salmon and elucidating mechanisms influencing these impacts necessitates knowing how Atlantic salmon use the marine environment. As salmon populations have declined, the ability to observe individuals in large-scale surveys has been reduced, making it harder to know if and how their spatiotemporal distribution in the ocean is changing. Leveraging newer techniques, such as tagging and genetic identification over larger numbers of individuals, at higher temporal frequency and at larger spatial extents of observation will facilitate a better understanding of the spatiotemporal distribution of salmon and the physical and ecosystem conditions they encounter through their marine life stages.

In addition, many uncertainties exist related to the ecosystem-scale effects of projected physical changes. The direct, indirect and cascading effects of physical changes on marine ecosystems and species of interest are challenging to predict in most ecosystems. This challenge is especially unique in the North Atlantic, where general ocean warming patterns around the edges of the basin are distinct from projected trends of reduced warming (and even cooling under certain scenarios) in the middle of the basin due to changes in the AMOC. These unique features in the area south of Greenland and Iceland may preserve habitats suitable for *Calanus* and other cold-water lower trophic level species, and this area represents one of few places of the ocean where fish biomass is projected to increase under future climate scenarios (Cooley *et al.* 2022, Figure 3.21). These divergent projections for North Atlantic regions pose unique considerations for Atlantic salmon, given their use of multiple habitat areas across the basin. In addition, critical tipping points associated with melting of the Greenland ice sheet and slowdown of the AMOC are not well characterized, both of which would exert major impacts on the North Atlantic ecosystem and, hence, Atlantic salmon populations.

Research programs directed at resolving these uncertainties can be built collaboratively with institutions that represent broad expertise across the North Atlantic, enhancing the potential for Atlantic salmon-focused studies to leverage other larger efforts. While enhancing understanding of these uncertainties is possible, it will not be possible to pursue conservation and management efforts in the absence of uncertainty. As such, managing for resilience through efforts to reduce other stressors affecting Atlantic salmon populations will be an important element of conservation efforts in the context of climate change.

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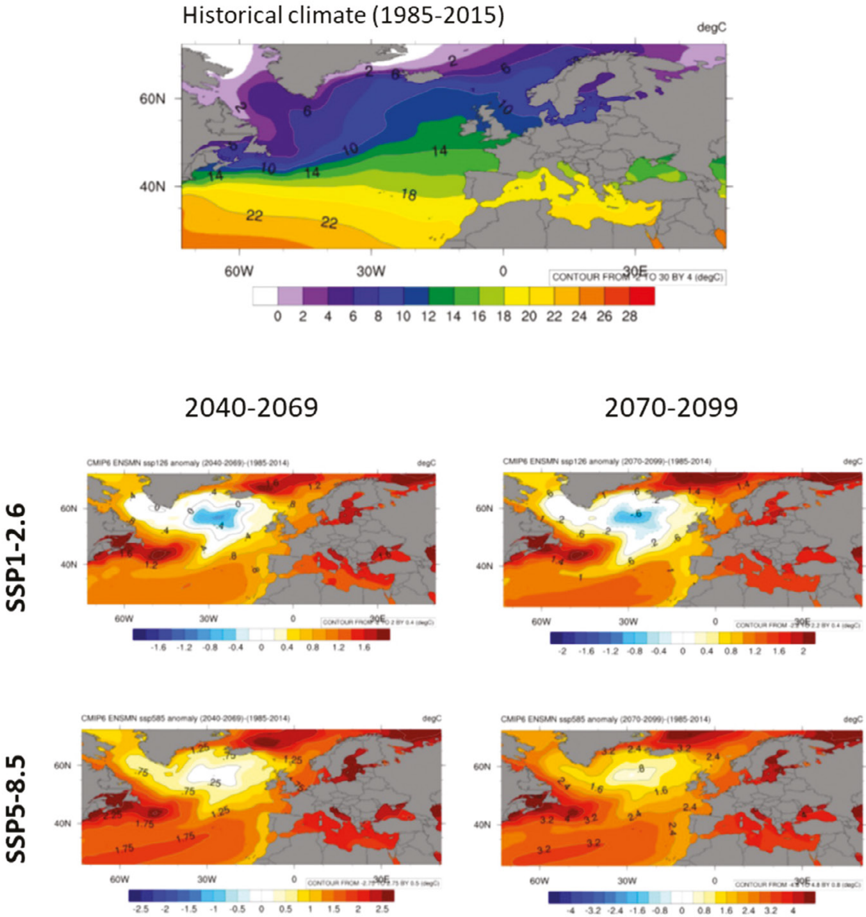

__Figure 1.__ Historical (1985-2014) sea surface temperatures (°C) across the North Atlantic are shown in the top panel. The bottom panel shows projected changes in sea surface temperature for a mid-century period (2040-2069; left column) and an end-of-century period (2070-2099; right column) for two scenarios: SSP1-2.6 (top row) and SSP5-8.5 (bottom row).

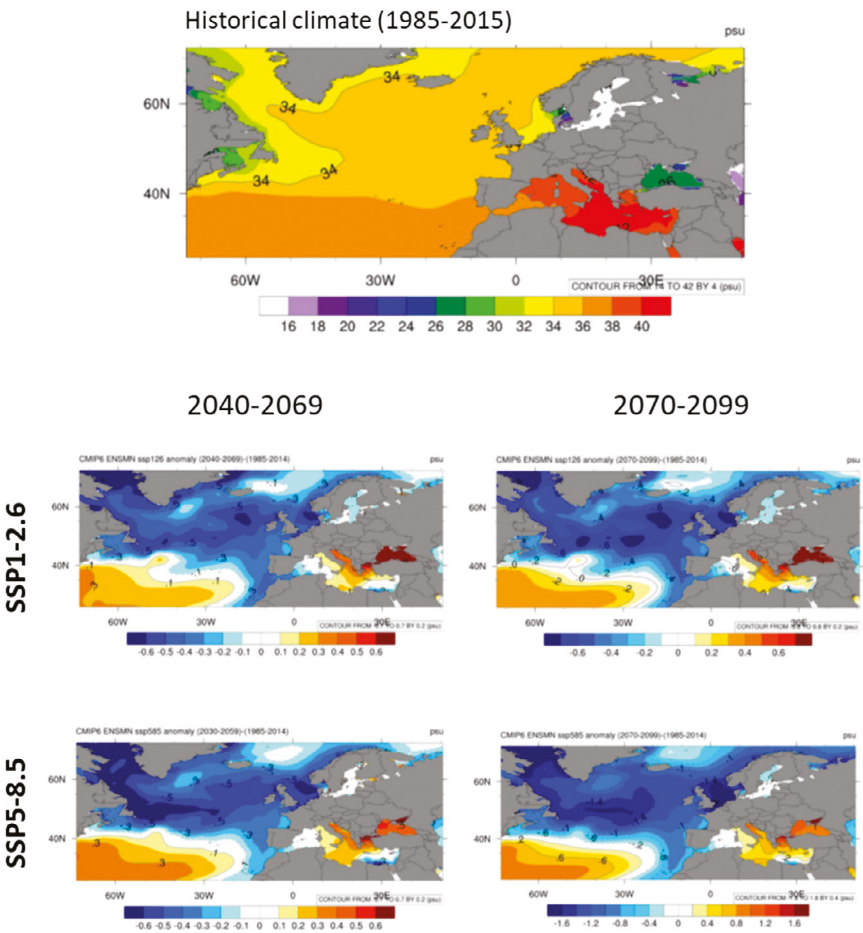

__Figure 2.__ Historical (1985-2014) salinity (practical salinity units, psu) across the North Atlantic are shown in the top panel. The bottom panel shows projected changes in salinity for a mid-century period (2040-2069; left column) and an end-of-century period (2070-2099; right column) for two scenarios: SSP1-2.6 (top row) and SSP5-8.5 (bottom row).

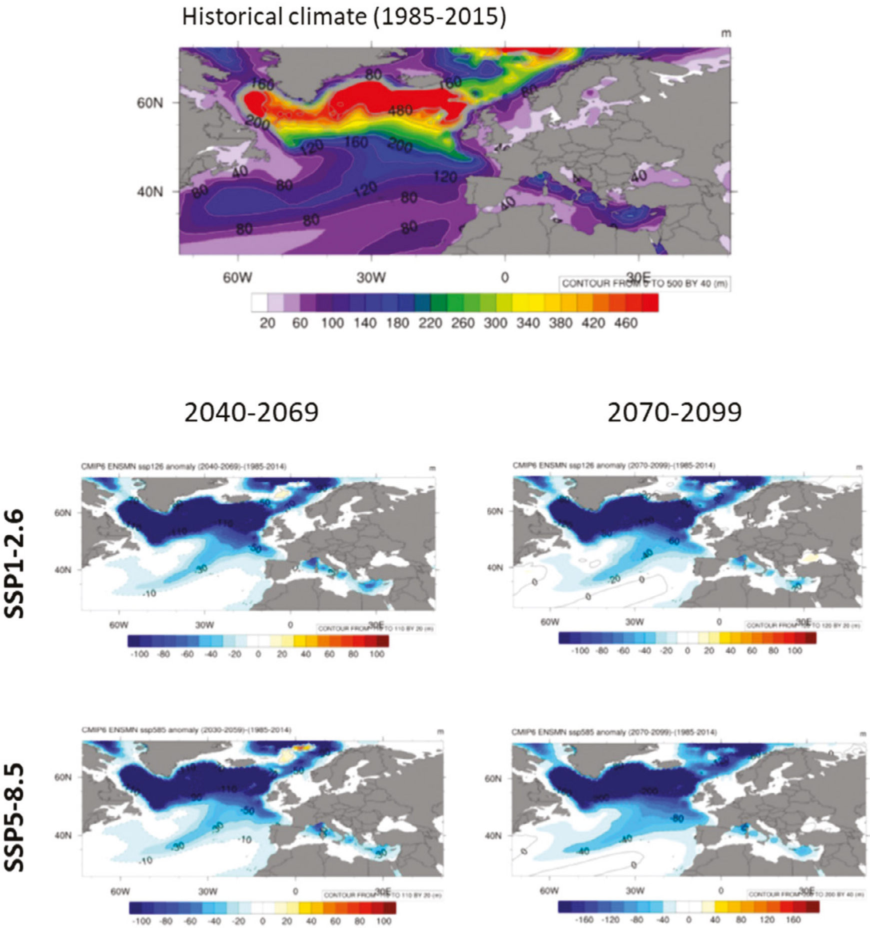

Figure 3. *Historical (1985-2014) mixed layer depth (m) across the North Atlantic are shown in the top panel. The bottom panel shows projected changes in mixed layer depth for a mid-century period (2040-2069; left column) and an end-of-century period (2070-2099; right column) for two scenarios: SSP1-2.6 (top row) and SSP5-8.5 (bottom row).*

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Current and predicted ecological impacts of climate change to Atlantic salmon freshwater productivity in the North Atlantic

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Introduction

Context

Atlantic salmon (*Salmo salar*) reproduce in freshwater habitats on both coasts of the Atlantic Ocean (MacCrimmon and Gots 1979). The species' historic native distribution ranges from the Housatonic River in Connecticut, USA, to Ungava Bay in the Nunavik region of Quebec, Canada in North America and from northern Portugal and Spain to Scandinavia, Finland and Russia in Europe. The species is also present in Greenland and in the North Atlantic islands (Iceland). Freshwater habitat is of crucial importance for Atlantic salmon to complete several life functions including reproduction, juvenile rearing and smoltification (Klemetsen *et al.* 2003; Thorstad *et al.* 2012). In addition, successful smolt migration to the sea is thought to be dependent on freshwater habitat quantity and quality. Two key environmental variables affecting freshwater habitat quantity and quality for Atlantic salmon are river discharge and water temperature (Armstrong *et al.* 2003; Jonsson and Jonsson 2009). Discharge, which depends in part on precipitation, evaporation, land use, soil types and local geology, influences the surface area of available habitat, juvenile feeding rates, the speed of upstream and downstream migrations as well as spawning success (Jonsson and Jonsson 2009). Water temperature, which is governed by incoming solar shortwave radiation, net longwave radiation, evaporation, convection and local advection of surface runoff, interflow and groundwater, is the principal controlling factor of metabolism in ectotherms through effects on rates of biochemical reactions and thus, on physiological and behavioural performance (Fry 1947, 1971; Claireaux and Lefrançois 2007). Thermal tolerance of Atlantic salmon varies with life stage, with incubating eggs/emerging alevin and spawning adults having the narrowest tolerance (0.5-16 °C and 4-12 °C respectively; Gillis *et al.* (2023)), while the optimal range for parr growth is between 16-18 °C (Breau *et al.* 2007; Elliott and Elliott 2010). Throughout the range of Atlantic salmon, climate change is expected to alter the future flow and thermal regimes of salmon rivers (Sundt-Hansen *et al.* 2018) and subsequently impact Atlantic salmon productivity.

Objective

The objective of this paper is to provide a brief overview of the changes to river discharge and water temperature likely to occur in the freshwater habitat due to climate change and of their potential effects on Atlantic salmon life functions and productivity.

Trends and scenarios of key abiotic variables

Discharge

Seasonal patterns of freshwater discharge have been studied in many subregions. Hodgkins *et al.* (2003) investigated trends in 23 unregulated rivers in New England, USA with over fifty years of historical flow data and found that the timing of the spring flood occurred increasingly earlier with time in 11 rivers with nival regime (spring flood produced by snowmelt). Zhang *et al.* (2001) investigated trends in flow characteristics in Canadian Rivers in Quebec and the Atlantic provinces, where Atlantic salmon populations are present. Most hydrometric stations had negative trends for mean annual discharge (MAD), mostly caused by a decrease in summer discharge. However, most stations in the same region showed an increase in annual minimum flows, mainly associated with a possible increase in winter discharge. Stahl *et al.* (2010) investigated trends in stream flows of European rivers and found that over 50 % of the time series (1962-2004) showed increasing discharge in the winter months and 60 % showed an increasing trend in June. This percentage decreases to 34 % in July and 47 % in August. Trends in annual discharge for the same period were found to be negative in Northern Spain and Southern France, while past river flows have increased in winter over the last 40 years but no significant summertime trends were found in the U.K. (Watts *et al.* 2015). For Northern Europe, there was no definite spatial pattern in trends, with some stations showing slightly negative trends, while others slightly positive trends in the winter. Summer discharge trends are negative for most stations located in the southern limit of Atlantic salmon distribution in Europe, including southern parts of the U.K., especially in August and September.

More generally, The Intergovernmental Panel on Climate Change's (IPCC) trend analyses on drought have been qualified as uncertain for Eastern North America, Greenland, positive for Western and Eastern Europe, but possibly negative for Northern Europe, though highly uncertain. For floods, trends are uncertain in Eastern North America, somewhat positive in Greenland (medium uncertainty), possibly negative in Northern Europe and uncertain in Russia (https://interactive-atlas.ipcc.ch/regional-synthesis).

Future discharge scenarios can be obtained by coupling hydrological models to climate models. The seminal work of van Vliet *et al.* (2013) provides a global overview of discharge scenarios for the 2071-2100 horizon under two different greenhouse gas emission scenarios. At the coarse scale of their model, little change in MAD is expected in North American and North European rivers in which Atlantic salmon occur, while slight increases in MAD are predicted for Northern Spain and Southern France. What may be more important is the predicted increase in MAD variability, i.e. indicating that more extremes are to be expected, especially in regions where a slight mean increase is expected. By categorising the discharge values as low, medium and high flow scenarios, the models indicated that low flows are likely to decrease in most Atlantic salmon rivers, except for the northernmost regions. Increased seasonality (i.e. higher peak flows and lower low flows) is projected for most of New England, Atlantic Canada and Eastern Quebec, as well as for Northern France, the U.K., Denmark and southern Sweden. Increased winter flows are also expected in many sub-regions, including the U.K. (Kay, 2021). It should be noted that van Vliet *et al.* (2013) modelled relatively few stations in Eastern Canada and New England and therefore, projections from this study should be considered more uncertain for these sub-regions.

Temperature

According to the IPCC, trends for extreme heat events (defined by the IPCC as the maximum daily temperatures that were exceeded on average once during the previous 10-year period) are uncertain for Eastern North America, but positive elsewhere (https://interactive-atlas.ipcc.ch/regional-synthesis). River temperature trends have been examined in different subregions of Atlantic salmon distribution. In general, trends are positive, especially for extreme (maximum and minimum) temperatures towards the southern limits of the Atlantic salmon's range, with some local exceptions. Reasons for local exceptions include local climate variability, anthropogenic mitigation and poor statistical power for trend detection related to sample size.

One of the most extensive works on temperature trend analyses in Atlantic salmon rivers was completed by one of the co-authors (Daigle) in Québec (Canada) rivers. The trend analysis was performed on 34 time series from 24 different Atlantic salmon rivers, with lengths varying from 21 to 44 years. Positive trends were identified for >75 % of time series between June and October, with between 3-26 % of trends statistically significant, depending on the method. The significant increases vary between 0.7-0.9 °C per decade. Shifts were also detected in the thermal regimes shape and seasonality (Daigle *et al.* 2019): annual maxima were found to be reached later in the season in 70 % of the time series (median of 1.2 day / decade), and to increase (median of 0.6 °C / decade) in all time series for which statistically significant trends were detected (40 % of the cases).

Kelleher *et al.* (2021) investigated temperature trends in U.S. rivers. For the Northeast region, they found positive summer trends for 13 out of 20 stations.

Positive trends were also found for nearly all 20 stations in the winter months. Orr *et al.* (2020) analysed trends in rivers of England and Wales and found an average increase in mean temperature of 0.3 °C / decade between 1900-2006, while Pohle *et al.* (2019) estimated a similar annual temperature increase 0.2 °C / decade for Northeast Scotland (River Spey) between 1912-2016. Mean river temperature in English rivers cooled by −0.4 °C / decade between 2000-2018, but summer temperature increased by +0.6 – +1.1 °C / decade in central/northern parts of the country, according to Wilby and Johnson. (2020). Historical mean temperature increases of ~1 °C / decade have been measured across a range of coastal salmonid-bearing streams in France over a 20-year period (Bal *et al.* 2014). Moatar and Gailhard (2006) suggested that the Loire River, France only warmed by ~0.8 °C between 1881-1976, whereas the post 1980s temperature increased at a much faster rate. In France, future increases in mean river temperature are projected to be between 1.2-2.0 °C by 2045-2065, in relation to a 1961-1991 baseline period (Ministère de l'écologie, du développement durable et de l'énergie, 2012).

Dmitrieva and Buchik (2021) examined the temperature time series of the Don River in Russia and found mixed results over 70 years, i.e. some positive and some negative trends. Lammers *et al.* (2007) studied river temperature trends in the Russian Pan Arctic region for datasets with a mean length of 40 years and found significant positive trends in the maximum decadal values. Other Pan Arctic work includes the study of Park *et al.* (2017) who used synthetic temperature time series generated by the CHANGE model. Their modelling exercise suggested an average increase of 0.16 °C / decade.

A similar approach to the one used for flow forecasting was used by van Vliet *et al.* (2013) to produce global river temperature scenarios from climate model outputs. Their most optimistic scenario indicated that an increase in mean river temperature would be < 1 °C between the reference period and the end of the century in regions such as northern Quebec and Labrador, as well as most of the coast of Greenland and most of the U.K. Other subregions would have larger temperature increases (1-2 °C) under the more optimistic scenario. However, the more pessimistic scenario (arguably more realistic) predicts increases ≥ 2 °C for most of the distribution area of Atlantic salmon. A number of more geographically focused studies have also been completed in the last two decades, including that of Hrachowitz *et al.* (2010) who investigated temperature changes in the Dee River drainage basin in Scotland associated with two air temperature future scenarios: assuming an increase in air temperature of 2.5 and 4 °C, respectively. At this scale, they were able to identify temperature sensitive zones in the river system.

Some regions, such as Scotland, have a relatively dense river temperature monitoring network and salmon rivers are well-covered (SRTMN, designed for modelling river temperatures across Scotland; Jackson *et al.* 2016). Other regions, such as Eastern Canada are currently constructing a network (RivTemp; www.rivtemp.ca). England and Wales are much more poorly covered by existing temperature records, with the English Environment Agency's surface water temperature archive only providing sporadic longer-term data amongst predominantly spot temperature records. France has some long-term temperature time series, but not in all salmon rivers. Spot or instantaneous records exist in most jurisdictions and recent work (Daigle *et al.* 2022) has shown the usefulness of such data, as well as those gathered by remote sensing. For the latter, progress has been made in North America (e.g. Fakhari *et al.* 2022) and this effort should be expanded throughout the region of interest.

Arevalo *et al.* (2020) investigated bivariate trends (combination of low flows and high temperatures) in six major French rivers and found that all rivers suffered from increased temperatures from spring to fall and most (5 out of 6) were characterized by a negative trend in summer-fall discharge between the latter part of the 20th century and the first 15 years of the 21st century. Bivariate extreme analysis tools such as copulas have been extensively used in hydrology to characterize and model floods (e.g. Latif and Mustafa. 2020). Some work is underway to develop both parametric and non-parametric copula to jointly estimate return periods of events with high river temperatures and low flows (Latif *et al.* 2023). These tools offer the advantage of estimating joint or conditional probabilities of exceedances of two extremes that can have compounding impacts on Atlantic salmon: stressful temperatures and low habitat availability.

Effects of changing environmental conditions on Atlantic salmon life stages

Atlantic salmon populations are adapted to the environmental conditions of their local river (Dionne *et al.* 2008; Jonsson and Jonsson 2009). Subsequently, the present and projected cumulative changes in environmental conditions in native rivers pose considerable adaptive challenges on Atlantic salmon populations by directly affecting the life functions, fitness and survival, particularly in the southern range of the distribution. Here, we focus in particular on the effects of river discharge and water temperature on the different life stages and on indirect consequences on Atlantic salmon productivity (Table 1).

Egg incubation and alevin emergence

Fluctuating temperatures during winter months leading to freeze and thaw events are likely to affect the discharge and water temperature during the sensitive egg incubation period (Bergeron and Enders 2013). Embryo development is temperature-dependent and emergence is timed with optimal environment conditions for alevin survival (Elliott 1987). In general, high discharges during the winter risk disturbing the substrate in which the eggs are incubating and potentially leading to lower survival rates (Levasseur *et al.* 2006). Increased winter temperature will lead to higher metabolic rates and consequently an accelerated development of eggs and early alevin emergence (Elliott 1987; Rahmati 2023). For example, under the IPCC's Representative concentration pathways (RCP) 8.5 climate change scenario (aka 'business as usual'), the number of days of egg incubation may be significantly reduced by more than 20 days in the Tobique River (N.B., Canada; Rahmati 2023). Gregory *et al.* (2020) also indicated recruitment was reduced when spawning temperatures are warmer and flood frequency increases during the pre-emergence and emergence periods.

Fry and parr rearing

In juvenile Atlantic salmon, growth rate correlates positively with survival rate (Nislow *et al.* 2004), and thus productivity. Juvenile Atlantic salmon typically defend territories, from which they feed on drifting invertebrate prey (Steingrimsson and Grant 2008). Climate change can influence the phenology and distribution of organisms which may cause mismatch in trophic linkages, such as synchrony in invertebrate prey availability and fry emergence (Larsen *et al.* 2016; Winder and Schindler 2004). Temperature and discharge are therefore important drivers of juvenile productivity, as they affect growth through cascading changes on foraging behavior and physiology.

Discharge is a key driver of productivity through effects on growth, survival and movement costs. Generally, lower discharge and subsequently lower velocities correlate with lower invertebrate drift concentration (Rashidabadi *et al.* 2022) and can lead to benthic feeding (Nislow *et al.* 1998), ultimately reducing energy acquisition. Higher flows can correlate with higher food availability through invertebrate prey displacement (see Naman *et al.* 2016 for a review), but fish may also exhibit reduced foraging efficiency via increased swimming cost and lower catchability of invertebrate drift (Hill and Grossman 1993).

Atlantic salmon growth follows a bell-shaped curve across temperatures, with optimal growth occurring near 16-18 °C (Forseth *et al.* 2001). Colder (6-16 °C) temperatures result in slower growth through reduced digestion speed, whereas warmer temperatures (18-27 °C) result in reduced foraging efficiency as well as reduced conversion of energy intake into growth (i.e. growth efficiency) through increases in metabolism (Elliott and Elliott 2010), ultimately leading to reduced growth and greater starvation risks. When applying the functional model for growth of juvenile Atlantic salmon developed by Elliott and Hurley (1997) to climate change scenarios, it is expected that salmon growth rates would generally improve in United Kingdom rivers in a low emission scenario but would decrease in a high emission scenario (Davidson *et al.* 2006).

Juvenile Atlantic salmon can, to some extent, regulate temperatures by actively seeking thermal refuges (Wilbur *et al.* 2020) in a process known as 'behavioural thermoregulation'. Applying different future climate scenarios to five Quebec rivers predicted that most tributaries would likely remain sufficiently cool to be used as refuges by the end of the century, while most river main stems would be characterized by a significant increase in the number of thermally stressful events for the parr life stage (Jeong *et al.* 2013; Daigle *et al.* 2015). However, most climate change scenario studies focus on summer temperature, but changes in winter temperature may also affect juvenile life stages of Atlantic salmon.

Smolt downstream migration

Anadromous salmonids undergo smoltification to adapt to outmigration and life in saltwater. Abiotic variables such as water temperature and photoperiod regulate smolting process by rate of development (McCormick *et al.* 2002). With increasingly earlier spring temperatures due to climate change, the onset of smolt migration is predicted to occur earlier. Smolts use higher spring discharges for their downstream migration. Changes in discharge, due, for example, to reduced snowpack, may consequently affect and potentially reduce downstream migration rates when smolts are actively searching for high velocity fields (Svendsen *et al.* 2007). Advanced or delayed arrival at sea may lead to a mismatch with optimal ocean survival conditions (i.e., food availability, predator presence, ocean current; Satterthwaite *et al.* 2014).

Adult upstream migration

Atlantic salmon returning to their native rivers are likely to encounter decreased discharge and increased temperature associated with climate change. River entry and, to some extent, upstream movement rates are dependent on discharge (Banks 1969; Thorstad *et al.* 2021), which could potentially lead to a delay in upstream movement with climate change (Solomon *et al.* 1999). Some plasticity in movement behaviour to suboptimal discharge conditions has been observed (Tetzlaff *et al.* 2005). Temperature is also affecting the river entry and upstream migration of adult Atlantic salmon to the spawning grounds in complex ways. High river temperature has been associated with delayed river entry in Southwest England (Solomon and Sambrook 2004). In contrast, the timing of the migration of adult Atlantic salmon is occurring increasingly earlier in Newfoundland and Labrador rivers, with some variability among rivers (Dempson *et al.* 2017). While adult Atlantic salmon are also known to behaviourally thermoregulate in cool water refuges (e.g., Frechette *et al.* 2018), extreme temperatures that approach sub-lethal or lethal limits will decrease spawning success, fitness and survival.

Spawning

Exposure of adult female to high temperature (e.g. >22 °C) during egg maturation may lead to lower egg quality and survival (King *et al.* 2003). Aside from these direct effects of temperature on egg development, carry over effects of temperature over the salmon life cycle could influence salmon recruitment. Hedger *et al.* (2013) reported that increased temperatures under future climate regimes will likely result in faster parr growth, earlier smolting and elevated smolt production in more western and northern rivers. This may lead to an increase in egg deposition, in turn producing a possible increase in recruitment, depending on adult returns. Conversely, in southern locations, density-dependent mortality of parr may be caused by lower flows in the summer (less habitat) and thus reduce future smolt production in comparison to the more northern rivers. It can be inferred, therefore, that climate change may have both positive and negative effects on anadromous fish abundance within the subarctic-arctic rivers according to geographical region. Studies have indicated that the potential of establishment of Atlantic salmon in the Arctic increases with increased water temperature and overlap between Atlantic salmon and Arctic char habitat may lead to interspecific competition (Bilous and Dunmall 2020).

Indirect and cumulative effects

In addition to the direct impact on productivity, indirect and cumulative effects are also likely to affect Atlantic salmon productivity. Indirect effects that may be caused by climate changes include for example changes to prey availability, predator abundance, aquatic invasive species presence as well as density-dependent effects. Additional indirect effects may also include an increased prevalence of parasites (e.g. myxozoan parasites causing proliferative kidney disease; PKD) and vulnerability of Atlantic salmon to infections with higher temperature and altered flows in natural habitats (Sterud *et al.* 2007; Forseth *et al.* 2017). Higher temperatures may also impact the concentrations and uptake of organophosphates (Laetz *et al.* 2014).

Table 1. *Present and predicted effects of climate change on Atlantic salmon by life stage and life function.*

Life stage	Life function	Key period	Present	Predicted	Key references
Egg	Incubation	Winter	Negatively correlated with precipitation (proxy for discharge)		Gallagher *et al.* 2022.
Egg	Incubation	Winter		Increasing number of freeze and thaw events leading to reduced egg survival	Levasseur *et al.* 2006. Bergeron and Enders 2013.
Egg	Incubation	Winter	Reduced incubation time with higher temperature	Reduced incubation time with higher temperature	Elliott 1987. Rahmati 2023.

Fry, Parr	Rearing	Summer	Discharge correlates with invertebrate drift concentration, feeding behaviour, foraging efficiency	Possible decreased growth rate if temperature exceeds optimal thermal range for growth	Hill and Grossman 1993. Nislow *et al.* 1998. Naman *et al.* 2016. Rashidabadi *et al.* 2022.
Fry, Parr	Rearing	Summer	Increased development rate with temperature Possible periods of no or little development	Possible increased development rate with temperature	Forseth *et al.* 2001. Jonsson and Jonsson 2009. Elliott and Elliott 2010.
Fry, Parr	Movement	Summer	Increased importance of thermal refuge	Increased importance of thermal refuge	Wilbur *et al.* 2020. Breau *et al.* 2007. Corey *et al.* 2020. Morgan and O'Sullivan 2022.
Smolt	Smoltification	Spring	Earlier smolt transition with earlier spring temperatures	Earlier migration with earlier spring temperatures	McCormick *et al.* 2002. Jonsson and Jonsson 2009. Russel *et al.* 2012.
Smolt	Movement	Spring	Higher spring discharges are correlated to successful downstream migration	Decreased spring freshets delayed migration and mismatch with optimal ocean survival conditions	Svendsen *et al.* 2007. Satterthwaite *et al.* 2014
Adult	Upstream migration	Summer/ fall	Earlier run timing	Increased frequency of extreme flows and misleading spawning cues	Thorstad *et al.* 2021. Dempson *et al.* 2017. O'Keefe *et al.* 2019.
Adult	Reproduction	Fall	Decrease in spawning success with increasing temperatures	Increased risk of unsuccessful spawning due to prevalence of parasites, pathogens and pollution	Sterud *et al.* 2007. Jonsson and Jonsson 2009. Laetz *et al.* 2014. Forseth *et al.* 2017.

Population	Abundance	n/a	General decrease in recruitment in Europe with increasing temperatures	Decrease at low latitudes / Increase at high latitudes Increase density-dependent parr mortality in southern regions Elevated smolt production in northern and western regions, decrease elsewhere	Friedland *et al.* 2009. Hedger *et al.* 2013.

Conclusions and recommendations

This brief overview confirms that the observed and predicted changes in river discharge and water temperature have and will continue to have serious impacts on all life stages of Atlantic salmon. The impacts will vary in severity latitudinally. Although coarse scale predictions such as those provided by the IPCC seem to provide a clear signal, our brief overview of local trend analyses and local (downscaled) scenarios of discharge and temperature show more variability. Some of this variability is imputable to relative data scarcity and model uncertainty. However, modelling remains the main tool by which inference on future habitat conditions can be made. In addition, while current modelling efforts are mostly targeted towards providing long term discharge and temperature scenarios, short term forecasts will become increasingly useful for fisheries management. While operational flow forecasting models have been developed (mostly for dam management and flood control) in recent decades, much fewer river temperature forecast models are operational. Models that can investigate the joint impacts of climate change and other anthropogenic impacts such as deforestation, dams and agriculture should be developed and/or implemented across the Atlantic salmon range. The relative paucity of data and available forecasts have been identified as bottlenecks for future Atlantic salmon management efforts (Bull *et al.* 2022).

One key recommendation is to expand and perpetuate river temperature monitoring across the Atlantic salmon's range. The reason for a spatially denser monitoring network is to not limit trend detection. Other characteristics of the thermal regime (extremes, variability, etc.) need to be fully characterized, and model development (and calibration) requires *in situ* measurements. Effective river monitoring could help the management of Atlantic salmon populations through initiatives such as implementation of in-season closure of recreational fisheries when water temperature exceeds a determined threshold (Breau 2013) and better predict current and future spatial distribution of Atlantic salmon.

Finally, protection of thermal refuges is a key management strategy to mitigate effects of increases in water temperatures in salmon rivers. While the long-term impacts of these refuges on individual fitness and population productivity remain to be assessed, their use for behavioural thermoregulation have been demonstrated for Atlantic salmon of all life stages (Breau *et al.* 2007; Frechette *et al.* 2018; Corey *et al.* 2020; Morgan and O'Sullivan 2022). It is thus imperative to identify, protect and, if necessary, restore important thermal refuges in warming salmon rivers. Future research should investigate the bioenergetic benefits of thermal refuge use by Atlantic salmon of all life stages and the variability of thermal onset of movement to thermal refuges among and within populations.

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Anthropogenic stressors interacting with climate change

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The most important pressures

Atlantic salmon are exposed to several anthropogenic stressors that may directly or indirectly interact with climate change effects in both the freshwater and marine environments. While the pressures are well known there are currently no compiled overview of their relative importance throughout the Atlantic salmon distribution area. In Norway, the Norwegian Scientific Advisory Committee for Atlantic Salmon annually assesses and ranks the major threats to the 448 salmon stocks of Norway. The assessment is a two-dimensional classification system (Forseth *et al.* 2017), with the effect axis describing the effect of each stressor on the stocks, ranging from factors that cause loss in adult returns, to factors that cause such a high loss that threaten stock viability and genetic integrity. The development axis describes the likelihood for further reductions in stock size or loss of additional stocks in the future. In the most recent assessment, stressors related to salmonid farming (escaped farmed salmon, salmon lice and other infections related to farming) ranked highest, followed by climate change and habitat alteration (Figure 1). Pink salmon is a new and emerging threat, but the confidence of our assessment is low.

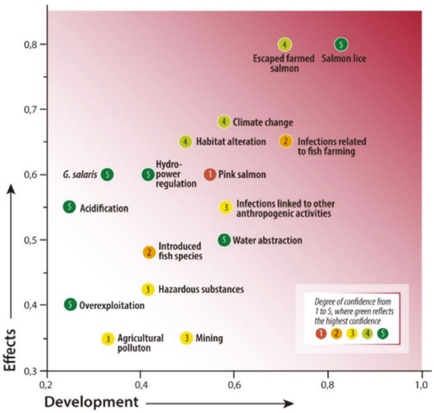

Figure 1. *Ranking of 16 stressors considered in 2021, according to their effects on wild Atlantic salmon stocks, and the likelihood of a further negative development. Confidence for the assessment of effect by each stressor is indicated by the colour of the markers, where green indicates the highest confidence level and red the lowest (figure from Vitenskapelig råd for lakseforvaltning 2022).*

Some of the stressors to Norwegian stocks are found all over the Atlantic salmon distribution area and may rank similarly, other stressors related to fish farming rank particularly high in Norway due to the size of the industry and the introduced and aggressive *Gyrodactylus salaris* parasite is a stressor mainly found in Norway. Using a modified version of the Norwegian system (Gillson *et al.* 2022) assessed the major marine threats to English stocks, and climate change, predation, water quality and bycatch were ranked most severe. Recently, Marine Scotland and Fisheries Management Scotland (2023) presented a similar assessment for Scotland, involving a total of 27 pressures grouped into 12 pressure themes. In contrast to the Norwegian and English assessment, the distinction between natural and anthropogenic stressors appeared less clear. Predation by birds and seals and upstream barriers were considered the most severe contemporary and expanding pressures acting on wild salmon in Scotland, and climate change and introduced species as emerging threats. Further, based on assessment by experts from 23 regions / countries 15 stressors to Atlantic salmon were recently ranked by assigning to groups of zero, minor, moderate, or major impacts (Lennox *et al.* 2021). Barriers and hydropower were strong pressures in many regions / countries, followed by terrestrial nutrients / sediment, climate change and channel / substrate modifications. Acidification was regionally important in Norway and Canada. Being the main producers of farmed Atlantic salmon within the species' natural range Norway, Canada and Scotland were the regions that scored high on impacts from escaped farmed salmon and pathogens from salmonid aquaculture.

Interactions between anthropogenic stressors and climate change

Based on the above assessments of the most important anthropogenic stressors for Atlantic salmon I discuss the major stressors that may directly or indirectly interact with climate change effects.

Salmon lice and infections related to fish farming

Salmon lice *Lepeophtheirus salmonis* is a natural marine parasite on Atlantic salmon that has proliferated after the establishment of the salmon farming industry and is ranked as a major threat to salmon stocks in Norway and parts of Scotland. The reproduction of salmon lice is strongly influenced by water temperature (Johnson and Albright 1991) and increased temperatures are expected to challenge the measures in the farming industry to control lice levels in the farms and increase the infestation pressure on wild salmonids (Sandvik *et al.* 2021). Moreover, in Norway thermal conditions along the coast protects against strong infestation in northern parts, and warming due to climate change is expected to gradually increase the area heavily affected by sea lice related salmon smolt mortality (Sandvik *et al.* 2021). Increasing challenges of controlling salmon lice levels in the farms in western Norway may also stimulate growth of the industry in northern parts. Because smolt mortality due to salmon lice is strongly size dependent (e.g. Grimnes and

Jakobsen 1996; Samsing *et al.* 2016), increased parr growth due to elevated river temperatures that result in smaller smolts will make the fish more susceptible to lice infestations. Similarly, several other infective agents from fish farming may proliferate in warmer waters and the risk of disease outbreaks in salmon rivers may increase. A classic example in Norway is the furunculosis bacteria, introduced to Norway by the farming industry and established in several rivers, with severe mortality associated with low river flow and high temperatures.

Habitat alterations

Habitat alterations have strongly impacted salmon stocks throughout the distribution area for centuries, as we have strongly modified most of the rivers. Climate change may elevate effects of habitat alterations such as weir, where the dammed and slow flowing river sections may become more exposed to high temperatures, challenging Atlantic salmon tolerance levels, or increasing the risks of disease outbreaks. Probably more important, the predicted (and observed) increases in extreme weather due to climate change will increase societal pressures to implement new or enhanced flood protection measures. Traditional flood protection involves channelization or embankments, which without consideration of fish habitat may strongly and negatively affect salmon production.

Invasive species

An invasive species is a species which is not native to a particular area. To be considered an invasive species, the species must be able to adapt and be able to reproduce within the new environment and must cause some form of ecological or economic harm. Invasive species can enter new environments through purposeful or accidental introductions by human activities or through range expansion given a changing climate. One of the major biological effects of climate change is changes in the distribution range of different species. Some species distributions are limited by tolerance to low temperatures and may expand their distribution when temperatures increase in the Northern Atlantic Ocean and the rivers feeding into this ocean area. This may challenge Atlantic salmon, both in freshwater and at sea as new species can become competitors or predators on salmon. A current challenge is the establishment and spread of pink salmon in the Atlantic Ocean. After introduction in the White Sea there has been a southward expansion in Europe and an eastward expansion across the North Atlantic (ICES 2022). The abundance of pink salmon is predicted to increase with increasing temperature both in the rivers and at sea (Nielsen *et al.* 2013). Moreover, an ice-free Northeast Passage may open for further exchange of fish species between the Pacific and Atlantic Oceans, which has the potential to cause further impact from invasive species on native North Atlantic salmon populations.

Hydropower regulations

Hydropower regulations are important pressures in many rivers, but its interaction with climate change is ambiguous. On one hand, in many reservoir-based regulations one of the major challenges is reduced summer temperature due to releases of cold hypolimnion water into the river stretches where salmon live. Such river sections may benefit from higher temperatures. Moreover, reservoir-based hydropower may be used to mitigate low flow and high temperature events (Sundt-Hansen *et al.* 2018), predicted to be increasingly common in a changed climate. On the other hand, residual flow stretches (receiving water only from a reduced local watershed) may become more exposed to low flow and high temperatures and high temperature may be a challenge in river stretches with minimum flow stipulations. Because hydropower is renewable energy, the pressure for further hydropower development may increase as part of the energy transformation from fossil to renewable energy. Moreover, the increasing share of intermittent energy sources such as wind and solar power may increase the need for hydropower balancing of the electricity grid. This may challenge Atlantic salmon through hydropeaking with stranding of salmon juveniles and invertebrates (Harby and Noack 2013).

Migration barriers

Migration barriers are major challenges for Atlantic salmon, particularly in North America and central Europe (Lennox *et al.* 2021) being responsible for numerous stocks being lost or strongly reduced. While there is no direct link between climate change and barriers, (except when low flows impact barrier passage) reduced or restricted access to higher altitude tributaries and thermal refugia may become increasingly important for salmon (Dugsdale *et al.* 2016; Wilbur *et al.* 2020; Rubenstein *et al.* 2022), particularly in large watercourses in the southern distribution area. The availability of thermal refugia is important for both adults and juveniles and barriers may delay adult migration and hinder juvenile access to refugia.

Predators

Predation is a natural phenomenon affecting salmon stocks both in the freshwater and marine environments. However, sometimes the abundance and population level effects of predation may be affected by human activity and become an anthropogenic stressor. An example of a direct interaction between climate and predation is when ice cover is reduced or disappears allowing increased access by bird and mammal predators on juvenile salmon (Finstad and Forseth 2006). Other hydrological changes may also affect predation rates, but such effects are poorly documented.

Watershed runoff

More extreme precipitation events and floods predicted (and observed) in several coastal regions under climate change will influence watershed runoff of nutrients, fine sediments and different pollutants with potential large effects on productivity of salmon rivers. Effects ranges from mortality events due to toxic substances to long term deterioration of juvenile habitat.

Escaped farmed salmon

Genetic introgression of farmed salmon in wild stocks is a major problem in parts of the distribution area. While there are no evident direct interactions between escaped farmed salmon and climate change, the loss of local adaptations and genetic variability when several stocks are introgressed may challenge the adaptability of the salmon stocks to the environmental changes.

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The role of freshwater and marine productivity in defining the overall outcome for an Atlantic salmon population

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Introduction

Understanding the demographic and ecological processes shaping the response of populations to multiple stressors is a prerequisite for scientific assessment of populations and their sound science-based management. This approach is particularly critical in the context of rapidly changing ecosystems under climate change (Cooke *et al.* 2023), but it is highly challenging to implement in the case of migratory species like Atlantic salmon (*Salmo salar*). Indeed, the anadromous life cycle of Atlantic salmon makes the species particularly vulnerable to multiple stressors acting at different times throughout their life cycles and across a wide range of ecosystems (fresh water, estuarine and marine) and spatial scales (Bull *et al.* 2022). They also highlight a large diversity of life-history strategies (Erkinaro *et al.* 2018), which further complicates the understanding of interactions between individuals, populations and their environment.

The freshwater and the marine ecosystems are two distinct environments separated in space and in the timing of their use throughout the life cycle. Nevertheless, influences of environmental conditions accumulate throughout the life history of individuals, and carry-over effects can have long-lasting consequences across life stages. The life of salmon in the marine environment thus partly depends on its earlier life in fresh water. Similarly, the life of salmon returning to fresh water carry over the influence of its life at sea. However, the most visible changes may not always be the most impactful in terms of population dynamics and resilience.

Overall, understanding the processes that shape population productivity and resilience calls for an integrative approach to consider the cumulative influence of environmental conditions throughout the whole life cycle. Such an approach would consider both short term effects of stressors on specific life stages together with their propagation to future life stages through carry-over effects. In the longer term this also calls for a comprehensive understanding of evolutionary processes that shape the evolution of life histories and the potential adaptation of salmon to climate change.

Carry over effect of the environmental conditions experienced in fresh water on the marine life

Survival and growth of juveniles in fresh water is the first bottleneck of Atlantic salmon population dynamics and productivity, with both direct and carry-over effects on the marine phase. The early development of salmon in fresh water ends at the time of the migration of smolts to the sea. From an initial number of eggs spawned, density independent and density dependent processes, most of them being controlled by environmental conditions in the river, such as food resources, temperature and flow, influence the survival and growth of salmon parrs. Thus, growth conditions and survival in fresh water controls the number of smolts released at sea and hence the expected number of individuals to return to spawn after the marine sojourn.

In the southern edge of the freshwater distribution area, growth conditions during the first year can be high hence offering the opportunity for male parr to mature precociously (Baglinière and Maisse 1985; Thorpe 2007). Proportion of precocious male parr may even increase in the future under climate change, in response to increasing temperature in fresh water and reduced survival at sea (Caswell *et al.* 1984; Thorpe 2007). As a direct consequence, a non-negligible part of male individuals may complete their life cycle without migration to the sea. Although early maturation does not prevent later migration, it does result in higher mortality for parr (Buoro *et al.* 2010). Precocious maturation therefore has direct short-term consequences on population dynamics and productivity by substantially biasing the sex ratio, reducing the number of migrating smolts and hence the number of returning adults. Underlying genetic mechanisms and potential long term evolutionary consequence of precocious parr development are poorly known and deserve future research (Lepais *et al.* 2017).

Freshwater growth and genetic determinism partly drives the age at smoltification (Debes *et al.* 2020), and thus the smolts body size. The mean age of smolts in Europe follows a latitudinal gradient, ranging from 1.0 in southern France (Prouzet 1990) to 4.1 in northern Finland (Englund *et al.* 1999), as temperature and day length positively correlate with the productivity of the freshwater ecosystem and the length of the growing season (Metcalfe and Thorpe 1990). Comparatively, there is little difference in the mean body size of smolts between populations, suggesting that strong selection forces may be controlling this life history trait. Within populations, fast growing individuals are likely to smoltify at a young age (Buoro *et al.* 2010; Debes *et al.* 2020), while slow growers delay smoltification decision to take advantage of another year of growth and migrate to the sea with a larger body size (Russell *et al.* 2012). This heterogeneity in the size of smolts has significant implication for salmon life at sea, through survival and maturation. There is evidence that larger smolts are more likely to survive at sea than smaller ones (Russell *et al.* 2012; Gregory *et al.* 2018, 2019), as a larger size may confer better swimming performance for predator avoidance, lower vulnerability to gape-size limited predator and a more rapid shift to high energetic piscivorous diet. In addition, there is evidence of a correlation between freshwater and marine growth, although the direction of the reported effect differs between studies (Nicieza and Braña 1993; Salminen 1997; Jonsson and Jonsson 2007). Any change in the marine growth may potentially impact the survival, the age at maturation and thus the age composition of the returning adults.

Another factor controlling survival of smolts at sea, which is likely to be climate dependent, is the phenology of smolts migration. The migration phenology of smolts is globally driven by the photoperiod, but the local freshwater conditions dictate annual population-specific run timing (Otero *et al.* 2014). Spring flood events and temperature changes for instance contribute to the onset of seaward migration (McCormick *et al.* 1998; Simmons *et al.* 2021). The run timing dictates the specific condition of the environment faced by smolts upon sea entry, such as the availability of prey, thermal conditions and current-induced transport. It is a site-specific evolutionary adaptation to maximise the chance of entering the sea during the window of optimal conditions for growth and survival (Thorstad *et al.* 2012). As climate change has profound and varied effects on the phenology of species through the modification of the ontogeny and environmental clues triggering migration e.g. thermal and hydrological regimes (Todd *et al.* 2012; Otero *et al.* 2014), there is a risk of increasing mismatch between the smolt migration phenology and the optimal windows in coastal and marine ecosystems.

Overall, the smolt body size and their timing of migration will have an impact on survival and growth at sea (Jonsson *et al.* 2017). But all smolts are not equal in their ability to survive, grow and mature in the marine environment, and this heterogeneity is partly driven by the conditions encountered by parrs during their life in fresh water. Thus, freshwater productivity should not only be assessed by the number of smolts, but also by their *quality*, or phenotype and their underlying genotype.

Carry over effect of the environmental conditions experienced at sea on the life back in fresh water

The marine life of anadromous salmon ends with the return migration of maturing individuals to fresh water, up to several months before reproduction. The environments encountered during marine migration contribute to natural and fishery induced mortality and growth and maturation, that ultimately shape the abundance of returning individuals, as well as their phenotype (e.g. age, size, sex) and the underlying genotype (Debes *et al.* 2020; Mobley *et al.* 2021). From a population dynamics perspective, the main bottleneck is probably the number and the quality of eggs produced, rather than the number of spawners itself. The number of eggs spawned is determined by the number of returning adults, survival in fresh water until spawning and sex-specific fecundity. All these processes result from the interaction between individual characteristics derived from the migration in the marine environment, the timing of the transition from the sea to fresh water and the conditions experienced in the freshwater environment until reproduction.

The maturation decision takes place at sea and has profound repercussions on the reproductive trajectories of individuals, on the migration routes and their vulnerability to fisheries and on the dynamics of the population. The timing of the maturation decision results from an interplay between the genotype and growth-related environmental conditions. Maturation decision controls the duration of the marine sojourn, and thus the size of returning fish, which positively correlates to fecundity and reproductive success. The advantage of a larger size in late maturing individuals in terms of per capita fecundity is counterbalanced by a higher mortality with longer time spend at sea and generally higher fishing mortality due to the selectivity of fisheries for larger fish. Maturation is also a sex-specific decision that is partly controlled by some major effect genes with sex-specific dominance (Barson *et al.* 2015). As a result of those genotypic interactions, the threshold of physiological condition that trigger maturation decision is higher in females than in males (Tréhin *et al.* 2021). This mechanism explains the high proportion of females in multi-sea-winter salmon observed in most populations. All these elements support the idea that any change in the growth condition at sea affects the sex-ratio and the fecundity of salmon returning to the river, i.e. potential egg deposition. Furthermore, poor diet at sea by females might limit the energy content of the eggs, hence their quality, with potential consequences on the progeny (Maamela *et al.* 2023).

The timing of the return migration and entry in fresh water is another life history trait that may influence the sensitivity of salmon to environmental pressure and hence salmon productivity. It illustrates another carry-over effect, where the legacy of salmon life at sea persists beyond freshwater entry. The spawning migration phenology is strongly correlated to the age at maturation, with one-sea-winter (1SW) salmon generally returning later, i.e. in the summer, than multi-sea-winter (MSW) salmon. This difference is particularly large in southern Europe where the long-lasting spring-summer season allows MSW to run as early as February or March and peak in April-May, while 1SW peak run is in July. For a given sea-age class, we also observe high variability in the timing of return migration between individuals and between years. Temporal trends are likely to be associated with climate change in the ocean (Valiente *et al.* 2011; Dempson *et al.* 2017), and trophic conditions in particular, as individuals in low body condition may delay their return migration (Todd *et al.* 2012; Bal *et al.* 2017). As a first approach the phenology of salmon return migration does not seem to constrain the success of the reproduction as it occurs months in advance of the spawning activity, especially in southern Europe where reproduction generally takes place as late as mid-December. However, the time of river entry may be critical in determining the survival of pre-spawning salmon, by controlling the duration and the timing of the freshwater sojourn, and thus the exposure of salmon to environmental stressors like temperature or diseases and in-river fisheries. Salmon entering fresh water in summer may suffer from high temperatures in the estuary and lower reaches, sometimes exceeding thermal tolerance, when early migrants have already reached cooler habitat far upstream (Baisez *et al.* 2011). Thermal stress is amplified in small river systems where thermal refuges may be absent.

Towards an integrative approach of the salmon population dynamics, using life cycle models

Climate change affects daily salmon life, both in fresh water and in the marine environment. Because these interacting effects differ in intensity, direction, duration and in their consequence on population dynamics, studying a single effect in isolation may result in inaccurate and misleading conclusions.

As a rough figure, let's say that survival from egg to smolt is about 3 %, survival at sea is about 10 %, while survival from return in fresh water to spawning is often ignored but may likely sit somewhere above 50 %. Therefore, in a simplified representation of the life cycle with multiplicative effect of transition rates from eggs to eggs, increasing any of the transition rates by the same factor would ultimately have the same effect on the productivity from eggs to eggs. However, the different rates of transition that shape population dynamics throughout the life cycle are clearly not independent, as any change that affects one life stage can have multiple repercussions on the subsequent life stages. It is thus extremely difficult to anticipate the response of a population to a given change and identify leverages that would have a positive impact on its dynamics and resilience (Piou and Prévost 2013). To grasp this extremely complex picture of interacting effects and long-term consequences throughout the salmon life cycle, life cycle models offer a relevant tool for integrating available knowledge throughout the salmon life cycle (Bull *et al.* 2022).

Life cycle models, whether they are individual (e.g. Piou and Prévost 2012) – or population-based (e.g. Rivot *et al.* 2004; Massiot-Granier *et al.* 2014), propose a unified framework that can be applied across different scales of time and space (e.g. index river, stock unit, oceanic basin). Age and stage-based life cycle models are useful tools to explore the influence of environmental changes on eco-evolutionary process that shape population dynamics and productivity. They are key tools to represent how the articulation of transition rates and their dependence throughout the life cycle control population dynamics and productivity. Retrospective models may have the potential to assess what transition contributed the most to past change in population growth rate, given a selected set of hypotheses.

Life cycle models have the great advantage to provide a more realistic representation of the composition of the population, i.e. the diversity in individual characteristics that are of demographic relevance (e.g. sex, age, growth, genotype). This is critical as population dynamics and resilience is not only a matter of salmon abundance, as a given number of adults can produce a different number of eggs. For instance, marine return rate is not merely quantified as the ratio between the number of smolts and the number of returning adults. It is considered as the result of post-smolt survival, 1SW maturation, dispersal and balance between immigration and emigration, later survival, including fisheries. Thus, such models can allow to better assess the potential demographic mechanisms driving observed changes in salmon abundance and productivity. As an illustration, the life cycle model developed by Olmos *et al.* (2019) pointed at a decline in post-smolt survival concomitant to the increase in 1SW maturation in most North Atlantic salmon stock units. Life cycle models also can integrate new knowledge gained from the recent development of molecular sexing, providing further support for sex-specific maturation decision, but also similar post-smolt survival in females and males (Tréhin 2022).

By adding external forcing of climate change within the model, it is possible to investigate stage-specific response to climate change and compare the relative contribution of different drivers to the population dynamics. Using an individual-based life cycle model, Piou and Prévost (2013) simulated the response of a salmon population from southern Europe to different scenarios of climate change in fresh water and in the ocean. Within the context of the scenarios tested, they found that climate-induced change in the freshwater environment (water temperature and flow) during the juvenile stage alone would not lead to extinction of the population, while reduced oceanic growth appeared as a more significant threat for population persistence. In contrast, the large-scale multi-population model developed by Olmos *et al.* (2020) is not very specific about salmon life in fresh water. However, the explicit representation of successive oceanic domains used by salmon at sea pointed at temporal variations of sea surface temperature on feeding grounds common to multiple populations as a main driver of large-scale change in marine survival (Olmos *et al.* 2020).

Finally, many of the observed changes in salmon are affecting traits that have a heritable component, e.g. growth, migration timing, age at maturation. This is a reminder that the phenotype of an individual results from the interaction between its genotype and the environment. For example, following the theory of proximate mechanisms, smoltification and maturation decision is conceived as a comparison of the current status of the salmon (e.g. energy content) with a genetically determined threshold, which triggers a change of state (Thorpe *et al.* 1998). More and more studies shed light on the mechanisms and genetic architecture behind these life history decisions (e.g. sex-dependent dominance at a single locus for the age at maturation, following Barson *et al.* (2015)). An explicit representation of these evolutionary processes in the framework and time frame of population dynamics models is therefore necessary to better understand the phenotypic and demographic changes observed in the past and to evaluate the capacity to respond to climate change. If the environment changes, the set of life history traits that may maximise an individual's fitness (i.e. contribution to next generation) may change, as well as the selective pressure acting on those traits. Eco-evo models extend life cycle population models and allow to estimate the selectivity of different forcing factors, and to investigate the evolution of traits and population resilience or adaptability for different scenarios (Lamarins *et al.* 2022).

A key challenge in investigating eco-evolutionary processes that shape population dynamics and productivity of salmon populations comes from the difficulty to observe individuals in the wild across the large range their spatial distribution. Embedding mechanistic life cycle modelling approaches within a statistical framework to derive inferences in the process remains a huge challenge. Building upon available knowledge of the biology and the ecology of Atlantic salmon, modern statistical tools relying on hidden state variables to embed complex eco-evo demographic and population models within statistical modelling can accommodate a variety of data, such as catch statistics and scientific surveys (Rivot *et al.* 2004; Peyrard and Gimenez 2022). They are powerful tools for both stock assessment and exploration of the consequences of possible scenarios combining climate change, exploitation regulation and mitigation measures (Piou *et al.* 2015).

Toward predictive ecology to forecast effects of climate change in fresh water and at sea on North Atlantic salmon populations

Atlantic salmon is one of the most studied vertebrate organisms worldwide. Currently available knowledge already fuels models of an increasing complexity. Life cycle models, whether individual or population-based, can be statistical, allowing inferences to be drawn from data on the processes that govern the eco-evolutionary dynamics of populations and the factors that condition them (e.g. effects of temperature on survival, growth on maturation). They are typically hindcast oriented but can be used to make short-term projections. Life cycle models can also be simulation-oriented by relying on data-estimated processes and parameters. They can aim at forecasting population futures (over several generations) in response to different scenarios of change in the environment and in management practices. These two approaches are thus complementary, despite having different goals.

Noteworthy, these models are still in their infancy relative to those used for climate predictions. Their ability to predict the fate of Atlantic salmon in the future remains an unachieved goal and this is not necessarily their main strength or interest. Indeed, predicting the physical characteristics of future climate and their consequences on the functioning of the ecosystems salmon live in remains highly uncertain as illustrated by the range of scenarios assessed by the Intergovernmental Panel on Climate Change (IPCC). Instead, life cycle models can be primarily useful for exploring and contrasting the potential consequences of scenarios on the future state of salmon populations and guiding managers in the choice of management measures favouring resilience and robustness to uncertainties. This approach is illustrated by Piou *et al.* (2015), which showed that current fishing practice is likely to worsen the effects of climate change in the marine environment. In this study, only scenarios of reduced fishing mortality on multi-sea-winter would ensure population resilience towards a degradation of marine growth conditions. In response to the difficulty in assessing which is the most important transition in the life cycle, modellers and managers should better identify which transition we can reasonably expect to act on.

Uncertainties also arise from the complexity of the response of salmon to climatic conditions, and from their interaction with the response of other organisms, including anthropogenic activities. The difficulty in predicting the response of salmon to future changes is exacerbated by the fact that salmon are facing a set of environmental conditions that have never been encountered before, i.e. for which no historical observations are available. There is a clear need to increase the overall eco-physiological knowledge base, especially tolerance thresholds for major environmental stressors and how such stressors affect performance within, and beyond, their tolerated range (McKenzie *et al.* 2016). In addition, our understanding of the eco-evolutionary processes and mechanisms that govern population functioning (e.g. the influence of environmental effects vs. genetic changes) remains limited, restricting our ability to anticipate population response. Methodological developments are still needed to better integrate different types of available data and knowledge (Bull *et al.* 2022). This requires mobilizing data that embraces all life stages in both freshwater and marine phase, across a large range of scales and ecosystems (Diack *et al.* 2022). This would allow for changes in spatial scales within the model structure - from population (Rivot *et al.* 2004; Piou and Prévost 2012) to metapopulation (Lamarins *et al.* 2022) to regional stock unit (Massiot-Granier *et al.* 2014) and to the Atlantic basin as a whole (Olmos *et al.* 2020), and to develop indicators relevant for ecological, evolutionary and management perspectives.

In this context, both scientists and managers need to develop an honest and critical appraisal of model outputs, in order to not over-state their usage and realism in forecasting salmon's future. Still, life cycle models are great tools to run projections under alternative scenarios of climate change. They also provide a platform to foster co-operation between scientists and stakeholders and to guide management action (Bull *et al.* 2022).

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Question and Answer Session for Invited Speakers in the session 'Current and predicted impacts of climate change on Atlantic salmon productivity across North Atlantic freshwater and marine environments.'

Questions to Speaker Tim Sheehan following his presentation:

Todd Broomfield (Canada): thank you. Hello. Very interesting. And looking at the long-term, quite scary if you look at the low-end even, which is not going to happen because we still have a heavy reliance on fossil fuels. I agree with your comment that it's not going to just affect salmon; we're seeing that in my area in Northern Labrador. There are other things that are going to happen in the ocean that will also affect salmon. What we're seeing, I'd say in the last five years with the ocean getting warmer, is sharks that like to eat salmon and char.

Normally, we wouldn't have seen them. Maybe once every 10 or 15 years somebody would catch a shark and it wasn't a big deal. But nowadays, they're almost a nuisance and they like to eat the fish. They destroy nets when you catch them by accident. It's things like that that we're not even thinking of that will be huge factors for salmon in the future. So, I agree with your statements and the presentation was very informative. Thank you.

Tim Sheehan (USA): Thank you very much, and I completely agree. The idea of these indirect impacts is really important, and that's predator dynamics, prey dynamics. And that's separate from how salmon are swimming through the ocean. And if currents are changing, is that changing energetic requirements? There's a lot there to untangle, and it's a really complicated web.

Questions to Speaker André St Hilaire following his presentation:

Todd Broomfield (Canada): thank you, Todd Broomfield, Nunatsiavut Government. The time period for the eggs, of 100 days, seems very long. Is that standard in all rivers?

André St Hilaire (Institut national de la recherche scientifique, Canada): no, that's very local. You're right, this is data from New Brunswick, so it probably is very different from one area to the other. But the required degree days that we based this on was from the literature, we said that it was 470 degree days. We know there's quite a bit of variability around that number.

Ben Wilson (United Kingdom): hi, Ben Wilson, Natural Resources Wales. We're almost definitely seeing, already, poor winter survival of eggs due to warm temperatures. Probably more temperature than discharge. How do we create those thermal refugia in the winter? I can get it in the summer but what about winter temperatures?

André St Hilaire (Institut national de la recherche scientifique, Canada): yes, that is a very good question. Even creating thermal refuges in the summer is not that simple, protecting those which exist is not that simple. As far as winter is concerned, we'd like to trust the fish, we like to think that they will adapt eventually, if the collapse doesn't happen before. That they would adapt and find the right spot for their redds in the river system. But we have to provide adequate conditions, and it means getting back to the key habitat variables, looking at where we have sustained flows. Can we look at the substrate, and making sure that it is of spawning condition and hope that the fish will be in those right spots.

Questions to Speaker Torbjørn Forseth following his presentation:

Lawrence Talks (United Kingdom): Lawrence Talks from the Environment Agency in UK. You mentioned about barriers being an issue, obviously in terms of fish passage, but also in terms of holding back water, and that water getting warmer with climate change. Are you aware of any studies that link beaver dams and the warming of water and any issues relating to that and salmon?

Torbjørn Forseth (Norwegian Institute of Nature Research): no, I don't know. I know there have been some concerns about connectivity, but I haven't seen any studies looking at thermal stress effects related to that, no.

André St Hilaire (Institut national de la recherche scientifique, Canada): it's actually a comment. There was a study by Daniel Casey *et al.* here in New Brunswick that looked at the thermal impact of beaver impoundments. So, we could chat, and I could provide the reference if you want.

Dave Meerburg (Atlantic Salmon Federation): Dave Meerburg with the Atlantic Salmon Federation. My question before was just going to be at the end of the last speaker's talk, but I think it's also relevant to this speaker's talk and the solution to things which we're going to talk about later. It seems that we should be saturating the freshwater environment with as many spawners as we can, to make sure that all the different areas of the watershed are covered to allow the selection pressures to take place. Then the ones that survive the newer conditions that are in place in the future will be better for the whole ecology of the species.

Torbjørn Forseth (Norwegian Institute of Nature Research): I completely agree with that. The major thing is to ensure that the fish can adapt. And to adapt, they need genetic variation. And to have genetic variation, they need to have as large a population size as possible. Which means that the attainment of conservation limits and regulation of the fisheries are extremely important in the future.

Dave Meerburg (Atlantic Salmon Federation): I don't think just attainment of the conservation limits is important because that's the lower limit. I think we need to be exceeding those conservation limits to some higher standard.

Questions to Speaker Marie Nevoux following her presentation:

Nigel Milner (Institute of Fisheries Management, UK): it's Nigel Milner speaking from the Institute of Fisheries Management. Do you have an opinion about the use of machine learning or other forms of artificial intelligence for future prediction or simulation modelling?

Marie Nevoux (Institut national de la recherche agronomique, France): that's a really good question, but I have to admit I don't have a clear idea about what this could do. I don't know any tests or anything like that for the purpose of planning population dynamics. But maybe you have an idea.

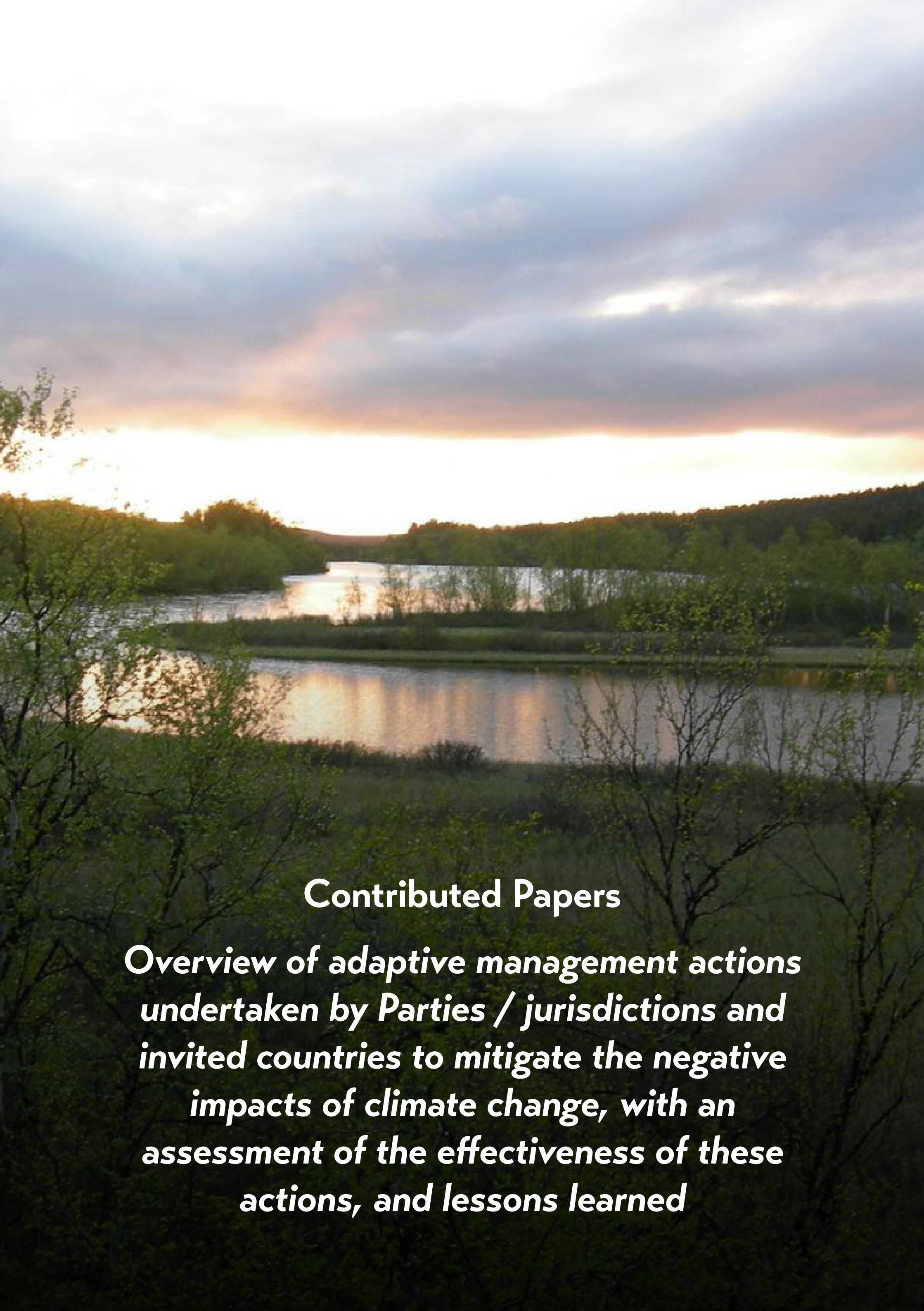
Nigel Milner (Institute of Fisheries Management, UK): I presume the data will limit the starting point there.

Conclusions of the Steering Committee on the session 'Current and predicted impacts of climate change on Atlantic salmon productivity across North Atlantic freshwater and marine environments'

Collectively, the five presentations by the expert invited speakers generated four high-level key points.

- **climate change is already altering the marine and freshwater environments that wild Atlantic salmon inhabit. These changes are predicted to become more variable and extreme over the course of this century.** Within the freshwater environments, models have predicted further changes in the flow rates of rivers, as well as positive correlations with temperature extremities. Within the marine environment, climate change will push oceanic conditions in the North Atlantic beyond bounds that have been experienced during the observational record for Atlantic salmon.
- **the anadromous life cycle of Atlantic salmon makes the species particularly vulnerable to climate change. Individuals will experience the interactive effects of multiple direct and indirect changes across two very distinct environments.** Within the freshwater environment, the Atlantic salmon populations are adapted to the environmental conditions of their local river, which makes changes in environmental conditions, as a result of climate change, particularly challenging on Atlantic salmon populations. These changes can directly affect life functions – such as reproduction, growth and development, and thus impact on the success in survival migrating downstream and the return upstream. The Atlantic salmon marine environment is extremely complex and expected changes will vary within regions of the North Atlantic used by this species. Rising temperatures, changing stratification and shifts in ocean currents will impact salmon directly through altered growth, maturation and survival schedules, as well as indirectly through spatial and temporal distribution shifts.
- **Atlantic salmon are also exposed to several other human-induced stressors in both the freshwater and marine environment. These other stressors can directly and / or indirectly interact with climate change, which can further impact Atlantic salmon productivity.** Examples of these stressors include salmon lice and infections related to fish farming, habitat alterations, invasive species, hydropower regulations, mitigation barriers, predators, watershed run off and escaped farmed salmon.

- we move forwards with this understanding that climate change is occurring at an unprecedented rate, and that it is impacting – and will continue to impact – Atlantic salmon productivity. **To better understand and predict the impacts of climate change on Atlantic Salmon populations there is a need to move towards an integrated approach that considers the cumulative influence of environmental conditions throughout the whole life cycle of the salmon, in both marine and freshwater environments.**



Contributed Papers

Overview of adaptive management actions undertaken by Parties / jurisdictions and invited countries to mitigate the negative impacts of climate change, with an assessment of the effectiveness of these actions, and lessons learned

Photo: Rory Saunders, NOAA Fisheries Service

Overview

Session two of the TBSS requested Parties / jurisdictions and invited countries, to provide an overview of the Atlantic salmon related adaptive management actions that have been enacted, or that they plan to implement in the future. An assessment of what has been successful, what hasn't been successful and the lessons learned from these management actions were also requested to support in knowledge sharing across the NASCO parties for future improvements. Similar to Session one, all Parties / jurisdictions and invited countries provided a paper to NASCO prior to the TBSS.

Parties / jurisdictions

Parties / jurisdictions were invited to present a paper to NASCO and / or deliver a short presentation at the TBSS to provide an overview of adaptive management actions undertaken to mitigate the negative impacts of climate change on Atlantic salmon populations. Nine papers were received, and eight presentations were given at the TBSS, the details of which are set out below. Given the different climatic conditions experienced within and across the countries within the European Union (EU), the Steering Committee supported the EU's request to deliver three papers and presentations.

- **Canada:** Livia Goodbrand presented 'Overview: Climate Change in Canada';
- **European Union North:** Seán Kelly presented 'Overview of adaptive management actions undertaken by Ireland to mitigate the negative impacts of climate change, with an assessment of the effectiveness of these actions, and lessons learned';
- **European Union South:** Bénédicte Valadou presented on 'Overview of adaptive management actions undertaken by France to mitigate the negative impacts of climate change';
- **European Union South:** Julián García Baena presented on 'Overview of adaptive management actions undertaken by Spain to mitigate the negative impacts of climate change, with an assessment of the effectiveness of these actions, and lessons learned';
- **Norway:** Peder Fiske presented on 'Management actions to mitigate the effect of climate change on salmon';
- **United Kingdom:** Faye Jackson, Lawrence Talks and Iain Malcolm presented 'Development of evidence-based management strategies to protect salmon populations from the effects of high river temperatures under climate change through targeted riparian tree planting; case studies from Scotland and England'; and

- **United States:** Dan Kircheis presented 'Atlantic Salmon (*Salmo salar*) Conservation and Management in a Changing Climate: The U.S. Approach to Insert a Climate Focus into Ongoing Salmon Conservation Effort'.

CNL(23)53

Overview: Climate Change in Canada

Livia Goodbrand and Rachelle Duval, Fisheries and Oceans Canada

Canada's climate is changing at an alarming rate. Temperatures are rising twice as fast as the global average, and three times faster in the North. Higher temperatures are, in turn, driving more frequent and intense weather events that affect our physical environment and pose real and increasing risks to Canada's biodiversity, including wild Atlantic salmon. Canada's ecosystems are already experiencing significant impacts from climate change. For example, in September 2022, Hurricane Fiona battered the Atlantic Provinces and Eastern Quebec with high winds and heavy rainfall, causing widespread damage to infrastructure and ecosystem, including those relied upon by Atlantic salmon. The scale and impact of this storm was unprecedented in Atlantic Canada. However, Hurricane Fiona is only one of many recent examples of an increasing number of catastrophic climate events that are impacting coastal and riparian zones and, ultimately, Atlantic salmon. Climate change is also driving gradual, but more pervasive, impacts, such as permafrost thaw in the North, sea level rise and coastal erosion, invasive species, the spread of diseases and pathogens like sea lice and shifting habitats and seasonal patterns of productivity (Government of Canada Adaptation Action Plan 2022).

Canada's National Adaptation Strategy was released in November 2022 to provide a roadmap for whole-of-society action on adaptation. It establishes a shared vision of Canada's path for a more climate resilient future. The foundation of the Strategy is its four guiding principles:

1. Respect jurisdictions and uphold Indigenous rights.
2. Advance equity and environmental justice.
3. Take proactive, risk-based measures to reduce climate impacts before they occur.
4. Maximize benefits and avoid maladaptation.

These principles guide Canada's climate change actions, including those for Atlantic salmon.

Climate change impacts on Atlantic salmon

Climate change has dramatically affected the fresh, estuarine and marine ecosystems inhabited by Atlantic salmon in Canada. These impacts can be profound; for example, atypical spring weather in 2018 caused more than 4,000 tonnes of debris into the Chéticamp River in Cape Breton Highlands National Park, completely blocking upstream fish passage. To restore fish passage in time for migrating Atlantic salmon, Parks Canada reacted quickly removing the debris and stabilizing the bank, also supporting the climate change resiliency of this important salmon river.

Understanding how these activities impact the abundance and diversity of Canada's Atlantic salmon populations requires large scale collaboration. The Atlantic Salmon Research Joint Venture (ASRJV) was established to forge the partnerships and collaboration sufficient to address urgent and unresolved scientific questions, including climate change impacts, that might otherwise not be undertaken. The ASRJV recently held a workshop to address the effects of climate change on freshwater habitats of Atlantic salmon and to identify research gaps and priorities. Their findings are summarized here, to describe the most important climate change impacts on Atlantic salmon in Canada (Gillis *et al.* 2023):

(1) Effects of climate change on in-river habitat conditions: with temperature and water discharge being recognized as the most important factors for Atlantic salmon to complete their freshwater life cycle;

(2) Physiological and behavioral responses of salmon to temperature: recognizing that Atlantic salmon are cold water, obligate ectotherms with a narrow range of thermal preference, from 16° to 18° C; and

(3) Population-level responses of salmon to climate change: considering the potential for Atlantic salmon to adapt to changing climate in light of the genetic diversity, life history characteristics, physiological and behavioral plasticity at the individual-level required for adaptation.

Canada's climate adaptive management measures for Atlantic salmon

Wild Atlantic salmon is an important icon for the people of Atlantic Canada and Québec. People care about and benefit from salmon for many different reasons. For instance, it is fished for food, social and ceremonial purposes by more than forty First Nations and many Indigenous communities in eastern Canada. In central and coastal Labrador it is relied on for local community food fisheries. Moreover, salmon angling is a valued recreational activity by both local residents and non-residents. Salmon are considered an indicator of environmental quality, an animal of respect, an attraction for eco-tourism and have an importance beyond economic returns.

In order to protect these values, Canada takes action under three main categories to support adaptive management of this important species in the context of climate change:

i. Fisheries management activities.

ii. Habitat restoration, management & activities.

iii. Monitoring, modelling & research to support adaptive management.

i. Fisheries management activities.

On a river-by-river basis, catch and release mortality is highly variable, both in terms of region, and the times fish are caught and released during the angling season. Adaptive fisheries management activities are underway across the Canadian range of Atlantic salmon to reduce mortality in consideration of warming waters. These management approaches consider the best available science on the impacts of recreational fishing for salmon under different temperature scenarios. It is now understood that river warming can increase mortality in Atlantic salmon that are caught and released. For example, in Newfoundland, catch and release mortalities for Atlantic salmon are predicted to be low (<0.05) when river temperatures are less than 12 °C. As river temperatures warm (between 18 °C and 20 °C), mortality predictions increase and range from 0.07 to 0.33 (Van Leeuwen *et al.* 2020). Angler education is an important component of successfully implementing any fisheries management activity; in Québec for example, Fédération Québécoise pour le Saumon atlantique has undertaken specific actions to assess the challenges, concerns, impacts and solutions of adaptive management actions undertaken in relation to climate change. In light of Canada's understanding of incidental mortality of Atlantic salmon that are caught and released in warm water, several management measures are undertaken:

Adaptive environmental protocols (a.k.a. warm water protocols): result in recreational fishery closures when water exceeds a warm water threshold. The threshold varies within and between provinces, but generally falls between 18 °C and 20 °C. For example, in Newfoundland, protocols vary by river class and can be triggered when water temperatures exceed a threshold after 2-3 days. Secondary parameters such as water levels and weather forecast may also be considered. River temperatures over the salmon season in some regions have increased over time, leading to a greater number of days closed to angling over the past decade.

Seasonal variation orders: can be used to restrict a season to specific times of year, to protect Atlantic salmon when they are most vulnerable to stress imposed by warming waters. For example, salmon angling in Eastern Cape Breton is limited to a fall season: October 1-31, when waters are cool.

Gear restrictions: are intended to further reduce harm caused by catch and release angling. For example in New Brunswick, Atlantic salmon angling is limited to barbless hook with artificial fly.

ii. Habitat restoration, management & protection activities.

In Canada, the responsibility for mitigating against climate change is shared between federal and provincial jurisdictions. Activities that support climate change mitigation through habitat restoration, management and protection, are undertaken by many different government departments, Indigenous communities and non-government organizations. These activities benefit Atlantic salmon, whether or not the action was specifically undertaken in support of Atlantic salmon, or to more broadly support healthy, resilient ecosystems in the context of climate change. Examples include:

- **national** goal to conserve [30 % of Canada's land and water by 2030] to fight climate change, reverse declines in biodiversity and maintain a strong sustainable economy;
- **provincial** climate change action plans outline how provincial governments will help to address climate change by establishing their own targets relating to (e.g. land protection, carbon emissions and other provincial priorities); and
- **local** habitat restoration activities that support resiliency. Specifically related to Atlantic salmon, these include but are not limited to: the identification and protection of cold water refugia; restoring connectivity within freshwater environments and between freshwater and marine environments; riparian planning and regulation of development in riparian zones, including salmon fishing lodges; and river and pool restoration activities.

iii. Monitoring, modelling & research to support adaptive management

Canada has a robust and diverse science and research sector that includes scientists working within government, non-government, academic and Indigenous organizations. This research supports adaptive management actions. Examples of recent areas of focus include:

- **thermal refugia:** studying the importance of, inventorying and protecting these areas in Atlantic salmon rivers;
- **temperature effects on catch and release fishing:** understanding how warming waters can impact stress, survival and reproductive success of Atlantic salmon;
- **linking environmental changes to changes in biology and ecology of Atlantic salmon:** for example, how warming waters affect distribution, abundance, physiology, growth, stress, etc;
- **modelling climate vulnerability & risk assessments,** through both quantitative and qualitative techniques, to better understand where climate change will have the greatest impact; and
- **tracking salmon migration patterns of Atlantic salmon in relation to changing environmental conditions at-sea.** Using both conventional satellite and acoustic technology deployed through large-scale partnership (e.g. case study on Atlantic salmon tagging), as well as research and development initiatives to support technological advances in tagging technology.

Best practices from the most effective climate actions in Canada

For the purpose of this report, Canada will summarise four best practices with supporting case studies, that explore how to effectively support climate resiliency for Atlantic salmon:

1. Supporting Indigenous data, knowledge and leadership.
2. Innovation and use of emerging technologies.
3. Supporting Atlantic salmon conservation through dedicated funds.
4. Partnership and collaboration.

Best practice: Supporting Indigenous data, knowledge and leadership

Case Study: Unama'ki Institute of Natural Resources

Unama'ki Institute of Natural Resources (UINR) is Unama'ki's Mi'kmaq voice on natural resources and the environment. By integrating Netukulimk (traditional Mi'kmaq management) with traditional and conventional ways of understanding, known as Etuaptmumk (Two-Eyed Seeing), UINR takes the lead on best-management practices in Unama'ki. UINR is responsible for aquatic research and stewardship, species management, traditional Mi'kmaq knowledge, conserved and protected areas, water quality monitoring and environmental partnerships. All of this work in conducted in the context of climate change, noting that Indigenous communities are particularly affected by climate change impacts due to their limited infrastructure funding and land base (Davies *et al.* 2016).

Best practice: Innovation and use of emerging technologies

Case study: University of New Brunswick

Under current and future climate change scenarios, Canada's Atlantic salmon rivers are warming. Rising river temperatures will negatively impact Atlantic salmon, especially in summer months, which often correspond to recreational angling seasons. The University of New Brunswick has been testing various remote sensing techniques to map the frequency, distribution and utility of thermal refuges at the river-scale. This research includes innovative application of drone-based infrared and topobathy sensors, as well as publicly accessible, free data available on Google Earth. Understanding the effectiveness of different tools that are accessible and feasible for potential practitioners is top-of-mind for UNB researchers, who envision this research being used to support comprehensive GIS-based aquatic monitoring plans for Atlantic salmon. For example, data on the Miramichi has already been used by the North Shore Micmac District Council, to enhance cold-water habitats on Canada's most prolific Atlantic salmon river (O'Sullivan *et al.* 2019; O'Sullivan *et al.* 2020; O'Sullivan *et al.* 2021a; O'Sullivan *et al.* 2021b).

Best practice: Supporting Atlantic salmon conservation through dedicated funds

Case study: Atlantic Salmon Conservation Foundation

In 2007, The Atlantic Salmon Conservation Foundation (ASCF) was awarded $30CAD million by the Government of Canada to create a trust fund intended to support wild Atlantic salmon conservation projects, in perpetuity. The Foundation funds its project grants from income earned on the trust fund, in support of its overall mission: *To promote enhanced community partnerships in the conservation of wild Atlantic salmon and its habitat in Atlantic Canada and Quebec*. Given that Atlantic salmon are under increasing pressure from climate change, the Foundation has funded an increasing number of climate change related projects over time. Over 70 Atlantic salmon projects have been funded by the ASCF that relate directly to climate change, including (but not limited to): climate change impact and vulnerability assessments, habitat restoration and impact mitigation projects, Indigenous traditional knowledge studies and the identification, restoration and protection of thermal refuges.

Best practice: Partnership and collaboration

Case study: Atlantic salmon migration at-sea research, an Environmental Studies Research Fund project

Of the Atlantic Canadian fish species, Atlantic salmon has one of the most complex life histories and migration patterns. Post-spawned adult (kelt) and juvenile (post-smolt) salmon migrate from their native freshwater river to the Atlantic Ocean to feed, sometimes even as far as the Labrador Sea. This project uses acoustic and satellite telemetry to better understand the migratory behavior (location and habitat use) of salmon while at sea. The objective of this project is to determine when, where and for how long Atlantic salmon from different life stages (juvenile post-smolt, post-spawned kelt and multi-sea-winter adults) are in the Eastern Canadian offshore regions. Achieving this objective requires collaboration across the entire Canadian range of Atlantic salmon; over 20 project partners contribute to tagging efforts and research on their local rivers, including Indigenous communities, Indigenous organizations, non-government organizations and several provincial and federal government departments. The results will support regulatory decision making in Canada’s areas of offshore oil and gas activity.

Lessons learned from Canada’s climate change management actions to improve our effectiveness

Atlantic salmon are already experiencing the effects of climate change and these effects will continue to grow well into the next century. Canada’s adaptive management measurements to date are helping us understand how our climate is changing, the impacts and risks to Atlantic salmon and the opportunities to take action for this iconic species. Below are some lessons learned through Canada's ongoing efforts:

Low populations & continued declines hinder the resiliency of Atlantic salmon in Canada: To ensure the survival of Atlantic salmon into the future, we must rebuild and protect the biological foundations of wild Atlantic salmon today.

Managing competing interests: Atlantic salmon are of social, cultural, ecological and economic value in Canada. Protecting these values in the context of continued development of coastal and riparian zones will continue to be a challenge, especially if social and cultural connections to Atlantic salmon are lost.

Facilitating & including Indigenous data, knowledge, & leadership for better outcomes: The Government of Canada has passed legislation (e.g. Fisheries Act) that require Indigenous Knowledge to be considered in project reviews and regulatory decisions. This represents a significant and positive change to how fish and fish habitat is managed; it requires Canada to move from decisions made solely based on Western science and perspectives, to decisions that incorporate a broader body of Indigenous knowledge and values.

Translating climate change science into management action: There exists a wealth of research and scientific evidence to support climate resilient management actions. How we apply and translate what we are learning into actions on the ground needs further consideration.

Co-ordination, tracking & reporting: In a large country with shared jurisdictions for climate change, the environment and Atlantic salmon, how we track, monitor and adapt our actions requires consideration.

Conclusions from Canada

Climate action requires a whole-of-government approach and buy-in from all Canadians, including Indigenous peoples, partners and stakeholders within the Atlantic salmon community. Given their iconic status and reliance on clean, cool, healthy freshwater and oceans, Atlantic salmon are a useful lens through which we can motivate climate action. Finally, Canada recognizes that hope and action are symbiotic elements of seeing salmon persists for many human generations to come.

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Overview of adaptive management actions undertaken by Ireland to mitigate the negative impacts of climate change, with an assessment of the effectiveness of these actions, and lessons learned

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Background

This paper accompanies the upcoming presentation to be given at the Theme-based Special Session (TBSS) at NASCO 2023, entitled 'Informing a Strategic Approach to Address the Impacts of Climate Change on Wild Atlantic Salmon'. It provides an Irish perspective on the impacts of climate change on Atlantic salmon (hereafter salmon) and on the development of management measures that can improve the resilience of salmon and their habitats to ongoing climate change.

Introduction

Prior to implementing climate mitigation measures, an assessment of the mechanisms through which changes in climate impact salmon and their habitat must be completed. Management actions must be customised not only to specific regions and jurisdictions but in some instances to individual river basins and coastal habitats occupied by salmon. Decision-making must incorporate localised climate information as well as the specifics of non-climatic human pressures that may compromise the resilience of individual salmon populations to climate change impacts. Not all salmon populations will face the same degree of climate exposure and in a pragmatic sense, not all proposed mitigation solutions can be successfully implemented in every circumstance. In this regard, the process of designing and implementing management actions that will prove successful is an intricate and evolving process. However, such a thorough approach at this stage is warranted – mitigation strategies implemented now must continue to provide current conservation benefits under future climatic conditions, with climate change providing the backdrop against which the success or failure of management actions will be determined.

In Ireland most salmon-relevant adaptation work that has taken place to date has focused on firstly establishing an evidence-base that will inform effective mitigation strategies tailored to Irish salmon populations. The aim of this contribution is to provide a synopsis of current actions underway in Ireland related to climate change and Irish salmon. In response to each area, a brief summary of management actions is outlined, the rationale for their initiation discussed and some potential benefits and challenges to their implementation and success are reviewed.

How will climate change impact Ireland?

Action: Increase certainty in predicting the future climate conditions Irish salmon populations will experience

Ireland experiences a maritime climate dominated by the North Atlantic ocean-atmosphere system, resulting in cooler summers and milder winters than would normally be anticipated based on latitude alone. Owing to this complicated influence of North Atlantic variability, accurately forecasting the effects of climate change on Ireland is a difficult but critical step if effective climate mitigation solutions are to be tailored to Irish salmon populations. An important step in this regard was the initiation of a four-year project in 2022 between Met Éireann (Ireland's state meteorological agency) and the Irish Centre for High-End Computing (ICHEC) based in the University of Galway. The project aims to improve model representations of the North Atlantic ocean-atmosphere system in global climate models under different emissions scenarios and use this improved accuracy to simulate Ireland's future climate. Crucially, this will include providing specific localised climate knowledge. The outputs will inform updates to salmon conservation strategies, as the more accurate model predictions will greatly decrease uncertainty surrounding the precise nature of future climate challenges facing Irish salmon populations. It is anticipated that this action will provide stakeholders, including fishery scientists and managers, with the most cutting-edge projections of Irish climate in the coming century to guide appropriate management strategies.

Evidence-based research programmes to inform mitigation strategies

Action: Establishing a national monitoring programme for delineating climatically vulnerable salmon habitat and for mitigation prioritisation

Inland Fisheries Ireland (IFI), the state agency tasked with the conservation, protection and management of wild salmonids, established a research programme in 2019 to ascertain the impacts of climate change on Irish fish stocks (Barry *et al.* 2022). In late 2020, a service-level agreement was entered between IFI and the Office of Public Works (OPW), the state agency responsible for the management of channelised rivers for land drainage purposes, to expand this research into reengineered rivers with altered hydrology and ecological functioning (Kelly *et al.* 2021).

To date these programmes have enabled IFI to develop a nationwide environmental monitoring network in 12 salmon catchments. There are currently *c.* 380 environmental sensors collecting data in salmon river habitat across Ireland, measuring a range of salmon-relevant metrics including water temperature, water levels, dissolved oxygen and meteorological data. IFI's National Climate Mitigation Research Programme is using the recorded data and subsequent analytical techniques to develop maps identifying salmon river basins and habitat locations most at-risk from climate change impacts. Resulting habitat 'risk-maps' have already been developed for several important salmon catchments. By delineating cold-water refugia and vulnerable river reaches experiencing excessively warm temperatures in an easily visualised manner, the programme has received positive reactions from fishery and catchment managers and will greatly assist with resourcefully targeting mitigation measures in future.

Two state-of-the-art lake monitoring platforms in regionally important salmonid lakes have been installed which can transmit water quality and temperature data in real-time to inform management practices. In 2023, a further 2 monitoring stations with live data transmission will be installed in rivers. These sensors inform fishery managers of harmful climate and environmental conditions for salmon as they occur in real-time, and can prove effective as accurate, evidence-based 'climate warning' systems. These warnings can initiate reactive management measures such as the initiation of protective angling restrictions whenever water temperatures exceed harmful conditions for salmon.

Action: Development of the National Salmonid Index Catchment (River Erriff) as a centre for salmon-climate research excellence

A dedicated IFI field research facility located in the River Erriff, designated as the National Salmonid Index Catchment (NSIC), has maintained a complete census of the migration of juvenile and adult salmon populations, along with other pertinent salmon biology records, for the past four decades (Millane *et al.* 2023). Recent management actions have included further investment in the research infrastructure including upgrades to trapping and lab facilities and in 2019 a catchment-wide environmental sensor network was installed to monitor environmental parameters in the catchment and to track the impacts of climate change. Salmon tagging programmes (including the NASCO co-ordinated EU-funded SMOLTrack project) have been initiated to improve understanding of climate and temperature impacts on marine and freshwater survival. A primary aim of the NSIC is to improve public and stakeholder perception and awareness surrounding the strong influence of climate on salmon ecology. The effectiveness of this implementation will continue to strengthen with the extension and further analyses of these invaluable long-term ecological datasets.

Identifying and remediating anthropogenic stressors that compromise salmon resilience to climate change

In Ireland, poor water quality and modified hydromorphology are ostensibly the most important pressures that compound negative climate impacts on salmon. The primary issue underlying both of these pressures relates to the large-scale modification of land, usually for intensive agricultural practices (e.g. grazing pastures) with urbanization and forestry also playing a role. In terms of water quality, excessive loading of phosphates and nitrates increase plant and algal biomass in Irish coastal and freshwaters, which can decrease water oxygen content. In combination with warm, dry weather spells during summer that will occur as a consequence of climate change, the risk of low oxygen, warm water conditions is heightened in waters with poorer water quality.

Debilitated hydromorphology is another large concern with some 28.5 % of the total watershed area in Ireland currently managed by the OPW for land drainage purposes (primarily to prevent flooding of agricultural land). This simplification of the complex riverscape through reengineering typically removes riparian vegetation and pool habitat, which in combination often provide salmon populations a refuge to recover from heatwave events. In addition, river barriers can compromise the thermal integrity of salmon river habitat, increase stress in fish attempting to pass barriers during warm summer spells and prevent fish from migrating to colder stream habitat.

Action: Regulations to protect waterbodies from nutrient pollution arising from agricultural sources

The Irish government published the fifth iteration of the *Nitrates Action Programme* in 2022[3]. The programme was informed by the Environmental Protection Agency's (EPA) findings that only just over half of the surface water bodies in Ireland have satisfactory water quality status. Notable new measures include an improved compliance and enforcement programme, with inspections to increase by 5-10 %. Additional measures will include new excretion rate bands for livestock as means to monitor numbers of allowable livestock per unit area and limits to chemical fertiliser application. The anticipated outcome of these actions will rely entirely on how strictly the compliance programme is enforced. Despite the EPA urgently stressing the need to address poor water quality issues, trends in water quality remain a concern with a 39 % increase in nitrates and 17 % increase in phosphorus loading based on data from the most recent monitoring period (2019-2021) published.

[3] https://www.gov.ie/en/publication/f1d01-fifth-nitrates-action-programme-2022-2025/

Action: Applied research programmes to assess hydromorphological recovery strategies aimed at improving salmon habitat resilience to climate change

Inland Fisheries Ireland and the OPW have renewed a shared service agreement – Environmental Research & Monitoring Programme (Fleming *et al.* 2022), which is now in its fourth cycle (2023-2027). A primary objective of the research programme is to develop an understanding of how river remediation works and modification of current river engineering practices may alleviate the compounding effects of climate change and channelisation. This programme complements IFI's core hydromorphology research, which assesses similar issues in more near-natural salmon rivers, as well as the CatchmentCARE[4] programme, a cross-border, multi-agency EU INTERREG funded initiative which aims to improve the resilience of debilitated, agriculturally intensive river systems. These programmes are achieved primarily through targeted applied research. The anticipated result for stakeholders is that a protocol will be developed containing direct measures and recommendations proven through research to improve climate resilience of salmon rivers. It is envisaged that such protocols will form the basis of a more ecologically sustainable way to manage channelised rivers in future.

In addition, IFI has established the National Barriers Programme[5], aimed at reducing the impact of barriers on fish migration. This action has thus far created a barriers assessment tool and a national database of river barrier locations. Guidance documents are also in preparation that will inform on appropriate practices for barrier-mitigation techniques. The anticipated effectiveness of the programme is an amelioration of the additional stress barriers can impose upon salmon populations, particularly during warm, dry weather spells associated with climate change.

Conclusion

In Ireland, most management actions aimed as mitigating climate impacts on salmon have so far focused on implementing applied, evidence-based research programmes to inform best practices (e.g. Inland Fisheries Ireland 2020). Many of these research programmes are well underway and have already begun to inform effective mitigation strategies (e.g. identifying and prioritising habitat restoration in climatically vulnerable sites, conserving climate resilient sites, informing angling practices and fishery management, raising public and governmental awareness). The continuation and evolution of these programmes are essential to continue to provide updated, cutting-edge scientific information for salmon conservation purposes. Additional longer-term environmental monitoring (e.g. of water temperature, water quality and salmon population dynamics) also provide critical baselines which can continue to raise awareness on the negative implications of climate change in combination with other aggravating pressures for salmon. The role

[4] https://www.fisheriesireland.ie/what-we-do/research/catchmentcare

[5] https://www.fisheriesireland.ie/what-we-do/research/national-barriers-programme

of policy makers, resource managers and stakeholders in taking this advice onboard and implementing it through new regulations and incorporating it into environmental management legislation is now urgent, given the impending threat that climate change poses to Irish salmon populations.

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Met Éireann

Office of Public Works

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Overview of adaptive management actions undertaken by France to mitigate the negative impacts of climate change

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Background

Like Ireland and Spain, France will present elements of the management measures put in place to mitigate the effects of climate change on *Salmo salar*'s habitats, which are not, at this stage, targeted at the species but which *de facto* contribute to its maintenance in French rivers.

This presentation will be held at the NASCO 2023 Theme-based Special Session (TBSS), entitled 'Informing a strategic approach to addressing climate change impacts on wild Atlantic salmon'.

Introduction

This session follows the one more focused on Research issues, which highlights the fact that climate change is already having observable effects on salmon populations. Although it is considered as a major concern, it is extremely difficult to anticipate the response of a population to a given change, and to identify management levers that would have a positive impact on population dynamics and resilience (Piou and Prévost 2012).

To understand the impact of climate change on salmon populations, it is first and foremost necessary to have observation data on the populations' evolution. In this, there is a critical need to maintain and even expand observatories over the long term, which requires maintaining sufficient levels of logistical, technical and scientific investment to do data bases that will inform effective mitigation strategies; these data should encompass all life stages, across a wide range of scales and ecosystems (Diack *et al.* 2022). The previous session states that life history models can aim to predict the future of populations in response to different scenarios of environment change or management practices (Bull *et al.* 2022).

In metropolitan France, water resource management is managed by watersheds policy, delimited by surface water divides. The 5 river basins where salmon are present are Adour-Garonne, Artois-Picardie, Loire-Bretagne, Rhin-Meuse and Seine-Normandie. Each of these watersheds has set up planning documents: the master plan for water development and management (SDAGE) and the strategic facade document (DSF) in response to European directives such as the Water Framework Directive (WFD) and the Marine Strategy Framework Directive (MSFD) and a management document: the migratory fish management plan (plagépomi).

At the national level, the second national action plan for adaptation to climate change[6] (PNACC 2) and the national plan for migratory species[7] (PNMA) are framework documents on which management is also based.

Finally, the Interreg program Diadromous fish and Ecosystem Services[8] (DIADES) calls for international co-operation to better understand the effects of climate change.

It is through the construction of these documents that the effects of climate change are perceived and measures proposed and implemented in France. The objective of this contribution is to present these different tools and measures.

Where is France on taking into account the adaptation of aquatic environments to climate change?

Measure: Implementation of the national plan for adaptation to climate change (PNACC) 2 and implementation of the watershed plans for adaptation to climate change.

By 2070-2100, climate experts estimate that water resources will be scarcer, with 10 % to 50 % less low-water flow for the major French rivers and up to 30 % less for groundwater. France is located at the southern limit of the salmon's distribution area. In this respect, the impacts of environmental changes induced by climate change are likely to be more important than in other watersheds of the distribution area.

Thus, one of PNACC 2 objectives is to allow the healthy functioning of aquatic ecosystems, which is at the origin of a multitude of ecosystem services, thus constituting one of the keys to better mitigation and adaptation. It is therefore necessary to strengthen the resilience of these ecosystems in the face of climate change, with a view to maximizing synergies between ecosystem preservation and human use, by anticipating future transformations. The proposed measures favour nature-based solutions wherever relevant and must be supported by legislation and tools deployed such as the monitoring of river thermals by the National River Thermal Network (NRT).

To this end, at the level of watersheds mentioned above, each SDAGE proposes a climate change adaptation component. Within the framework of their eleventh intervention program (2019-2024), the water agencies support actions taking into account the impacts of climate change on the preservation of water resources and the restoration and preservation of aquatic and wetland environments. In France, most of the recommended adaptation actions in the water component are eligible for support from the water agencies: nearly €500 million per year are mobilized for operations contributing to climate change adaptation.

6 https://www.ecologie.gouv.fr/sites/default/files/2018.12.20_PNACC2.pdf

7 https://professionnels.ofb.fr/sites/default/files/pdf/PNMA_Projet-Approuve_11_02_2022_Vanglais.pdf

8 https://diades.eu/

Many actions of restoration of watercourses with restoration of ecological continuity have been financed and realized. For example, the Orne River's restoration in Normandy[9], where almost the entire length of the river was under reservoirs influence, causing the disappearance of riffles and an increase in the warming and evaporation of the water, has allowed salmon to return to the riffles in the restored sectors. Or the Gave de Pau's restoration of the ecological continuity project[10], in Nouvelle-Aquitaine, which is included in the national program 'Nature 2050', supported by CDC Biodiversity, which aims to restore biodiversity and strengthen the adaptation of territories to climate change by 2050.

How is climate change addressed in the various tools dedicated to migratory fish?

Measure: Take into account the need for adaptation in the measures identified

The PNMA was developed in line with the National Strategy for Biodiversity (SNB2030), which promotes the need to integrate 'biodiversity' issues into French policy to combat climate change.

This national plan proposes concrete actions such as, for example,

> *'improving knowledge on migratory species, particularly in marine environments and transitional waters, or guaranteeing a high level of protection and restoring the functionality of environments and ecological continuity in territories with high stakes and particularly resistant to climate change'.*

It is indeed impossible to ignore the global warming effects which will lead, for example, to the modification of migration corridors and functional areas or accelerated habitats degradation (migration, reproduction, growth). Because of the reduction of the impacts of some key structures for the future of migratory fish, these actions will allow access to many habitats, the improvement of the functionality and the resistance of the territories for migratory fish in a context of climate change. This has already been demonstrated in the context of the removal of Sélune dams[11], in Normandy, by a decrease in average summer temperatures after the removal of dams: the presence of the reservoirs caused the warming of the water up to +2 °C downstream in summer.

To date, some of the plan's actions have been integrated into France's application to the European LIFE program via the LIFEBIODIV'France project, whose general objective is to fully implement the SNB2030 in order to halt the decline in biodiversity and improve the conservation status of habitats

[9] https://www.eau-seine-normandie.fr/actualites/DTMBN/effacement_seuil_Hom_orne

[10] https://www.institution-adour.fr/continuite-ecologique-forward/op%C3%A9ration-gave-de-pau.html

[11] https://programme-selune.com/

and species (particularly of community interest) in metropolitan and overseas France. This project will use the results of ongoing LIFE projects such as LIFE Artisan, a program that participates in the implementation of PNACC 2, in particular by accompanying and amplifying nature-based adaptation solutions projects throughout the national territory, such as the Ellé River re-meandering[12], in Brittany, for example. Thus, the LIFE BIODIV'France project has used the results of various LIFE ARTISAN projects highlighting that biodiversity issues must be linked to other environmental and climatic issues in order to be heard by local authorities, businesses and citizens.

At the watershed level, the plagépomis complete the water resource management tools by setting measures related to climate change more focused on migratory fish, including salmon. In addition, more local actions are set up in consultation between actors in order to mitigate the more and more frequent low water levels; thus, managers of water reservoirs are requested to set up objective flows for low water support and thus maintain the good functioning of aquatic ecosystems downstream.

What monitoring of the effects of climate change on salmon?

Measure: scientific studies underway to guide management

Within the Observatory for Environmental Research on Diadromous Fish (ORE DiaPFC) and the Pole for the Management of Migratory species in their Environment (MIAME), French researchers are studying the evolution of migratory fish populations under the effect of environmental changes affecting the rivers they frequent. The ORE is based on four coastal rivers of the Atlantic coast, the Bresle and the Oir in Normandy, the Scorff in Brittany and the Nivelle in Nouvelle-Aquitaine. These four rivers, equipped with monitoring stations for migratory fish, have been subject to recurrent biological and physicochemical monitoring since the early 1980s. These rivers are associated with experimental facilities in Rennes and Saint-Pée-sur-Nivelle. The whole is completed by individual-centered demo-genetic simulators for experimentation on virtual populations. The work carried out on these workshop sites is integrated into regional, national and international research projects that emphasize the fundamental nature of maintaining long-term observation systems and the need to pool data at the international level (Diack et al. 2022) to allow for the generalization of results and the integration of ecological mechanisms and issues into a multi-scale approach.

Conclusion

In France, management measures aimed at mitigating the effects of climate change on aquatic habitats and, therefore, on salmon habitats, are the result of consultations at the watershed or national level and benefit from funds from water agencies and other funds including European funds. At the same

[12] https://rmcom.bzh/le-remeandrage-sur-le-bassin-versant-de-lelle

time, applied research programs are being developed to set up predictive life cycle models. Feedback on the measures to be put in place, such as the preservation of territories with high stakes and that are particularly resistant to climate change, will be necessary to ensure that what needs to be done is properly impregnated throughout the French territory. Consultation is a key word in the challenge of mitigating climate change and it is necessary to better understand this phenomenon in all management documents for migratory fish and therefore for salmon.

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CNL(23)56

Overview of adaptive management actions undertaken by Spain to mitigate the negative impacts of climate change, with an assessment of the effectiveness of these actions, and lessons learned

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Background

This paper accompanies the upcoming presentation to be given at the Theme-based Special Session (TBSS) at NASCO 2023, entitled 'Informing a Strategic Approach to Address the Impacts of Climate Change on Wild Atlantic Salmon. It provides a Spanish perspective on the impacts of climate change on Atlantic salmon (hereafter salmon) and on the development of management measures that can improve the resilience of salmon and their habitats to ongoing climate change.

Introduction

The Atlantic salmon finds the southern limit of its natural distribution in the Iberian Peninsula, which means that its populations are small when compared to the populations of other rivers in Northern Europe, also very vulnerable to climatic and hydrological changes. The fact that salmon is in its southern limit of distribution in Spain makes climate change an important issue for the future of the population.

Spain is a country with a decentralized administrative organization, made up of 17 Autonomous Communities (hereinafter CCAA), each with its own government and competences over the conservation of biodiversity and habitats for salmon and aquaculture, for this reason there are 5 Spanish jurisdictions in NASCO.

The salmon populations are located in the five autonomous communities of the Cantabrian coast, Asturias, Cantabria, Navarra, Galicia and the Basque Country, from all of them the one that represents the greatest number of salmon, with a great difference over the rest, is Asturias, which brings together in its rivers most of the salmon population of Spain, especially in three rivers, Sella, Deva-Cares and Narcea-Nalón (the largest and most important basin).

In Spain, in general, in the last 5 years, rainfall has decreased considerably, and long periods of drought have been recorded, both phenomena related to climate change, which have very negatively affected salmon. In the Cantabrian rivers, the long series of rainfall and therefore the circulating flows hardly decrease, although in the last 5 years rainfall has decreased.

The situation in relation to the status of salmon populations is different depending on the jurisdiction that is considered.

In Navarra, the salmon population in the Bidasoa basin is going through a critical situation, due to the fact that negative factors have come together in the last two years such as the significant shortage of broodstock and a series of negative environmental conditions (low rainfall and high-water temperatures during the dry season) that limit the survival of the fry, which can cause their collapse.

The data from the main basins in Asturias show a decrease in all rivers (more pronounced in the river Sella), but with a tendency to population stabilization if we consider the last five years 2018-2022. In addition, in this jurisdiction, with regard to the production of juveniles in the fluvial environment, there is no record of a decrease in their survival after reproduction in recent years, nor of the density of fry, which logically depends on the existence of a minimum number of spawning females, the first factor that conditions population sustainability.

In the case of Cantabria, in the main rivers, Deva and Asón, the biomass of Atlantic salmon shows a slight decrease, although in the last three years it has remained stable.

Galicia and Gipuzkoa also show significant declines in their populations.

Adaptive Management Actions Undertaken by Spain

Spain has a Climate Change Adaptation Plan, **The National Climate Change Adaptation Plan 2021-2030 (PNACC)**, which constitutes the basic planning instrument to promote co-ordinated and coherent action against the effects of climate change in Spain. Without prejudice to the competences that correspond to the Autonomous Communities, the PNACC defines objectives, criteria, areas of work and lines of action to promote adaptation and resilience to climate change. Specifically, the PNACC defines 18 areas of work, specifying objectives for each of them.

The PNACC does not include specific measures for the adaptation of the Atlantic salmon to climate change, however, some of these measures, aimed at restoring the hydrological cycle and recovering fluvial connectivity, including the elimination of artificial barriers and the restoration of areas of floodplains and wetlands and the protection of natural heritage, biodiversity and protected areas, directly affect their adaptation and conservation.

The PNACC also has specific measures to help the Spanish aquaculture sector to adapt to climate change effects both for marine aquaculture and freshwater aquaculture.

LINE OF ACTION: INCORPORATION OF THE CLIMATE CHANGE FACTOR IN NATIONAL CONSERVATION STRATEGIES AND PLANS FOR THE CONSERVATION AND RECOVERY OF THREATENED SPECIES.

It is intended to contribute to the strategies and plans of catalogued species being carried out and / or updated, taking into account the demands imposed by the current context of climate change, reducing their impact on them and increasing their resilience.

It is considered important to update the studies of potential distribution of wild species, and their key habitats, using the most recent climate models provided by the Intergovernmental Panel on Climate Change (IPCC), so that the information provided is useful to manage the biodiversity in a more complete and sustained manner over time.

Within this line, the following **actions that affect salmon** will be carried out:

1. Updating of the atlases of the State Inventory for Natural Heritage and Biodiversity considering the information available on the main climate scenarios.
2. Identification of solutions based on nature, as a reference for good practices for adaptation to climate change.

LINE OF ACTION: PLANNING AND MANAGEMENT OF PROTECTED AREAS WITH ADAPTIVE CRITERIA.

All Spanish salmon rivers are located in Special Conservation Areas (ZEC) designated under the EU Habitats Directive (92/43/EEC). Therefore, included in the main European Conservation Network Natura 2000.

According to the Habitats Directive, EU member states are called upon to establish the necessary conservation measures and, if necessary, appropriate management plans with the aim of achieving a favourable conservation status for species and habitat types.

The conservation status of the salmon will be determined with special assessments and evaluation keys in the Management Plans of each ZEC. The management objective will be a favourable conservation status of salmon stocks.

In addition, the Water Framework Directive (Directive 2000/60/EC) establishes that monitoring of fish populations, invertebrates, chemical state of the water, morphology, in each individual body of water (including rivers and streams) must be carried out.

Any body of water classified as unfavourable must have corrective measures prepared through the Program of Measures to meet the objectives established to obtain Good Ecological Status.

On the other hand, climate change constitutes a major challenge for these areas, as it causes environmental changes that can substantially modify their own starting conditions (zoning, restrictions established in management plans, etc.). Despite all this, there are still few protected areas that deeply incorporate the climate change factor into their planning and management.

Within this line, the following **actions that affect salmon** will be carried out:

1. Preparation of management guidelines for the Natura 2000 Network with criteria for adaptation to climate change.
2. Support for the inclusion of climate change adaptation criteria in protected area management plans and instruments.
3. Evaluation of the future representativeness of the networks of protected natural spaces under different climatic scenarios.
4. Implementation of the Framework for Action against climate change of the Natura 2000 Network.

LINE OF ACTION: IMPROVING THE ADAPTIVE CAPACITY OF GREEN INFRASTRUCTURE

Included measures aimed at restoring the hydrological cycle and recovering fluvial connectivity, including the removal of artificial barriers and the restoration of floodplains and wetlands.

The Green Infrastructure supposes, within its multifunctional character, an enhancement of the important relationship between connectivity and the configuration of the landscape and how this affects the movement and dispersion of species.

Therefore, in this line of action there will be room for:

- interventions aimed at maintaining or improving the provision of ecosystem services, mainly those of regulation;
- interventions aimed at improving the ecological permeability of the territory and ecological connectivity;
- interventions aimed at reducing pressures on natural systems (changes in agricultural practices, livestock management, forest management, hunting and fish farming management, etc.); and
- interventions aimed at the ecological restoration of ecosystems.

Within this line, the following **actions that affect salmon** will be carried out:

- development of green infrastructure adapted to climate change; and

- integration of the improvement of knowledge on the vulnerability and resilience of wild species and habitats in the face of climate change in the National Green Infrastructure Strategy.

LINE OF ACTION: INCORPORATION OF THE CLIMATE CHANGE FACTOR IN THE CONSERVATION OF THE TYPES OF NATURAL AND SEMI-NATURAL HABITATS AND IN THEIR ADAPTIVE MANAGEMENT

The incorporation of the 'climate change' factor in the conservation and adaptive management of habitat types can take the form of actions such as the identification, restoration and protection of especially important areas to mitigate the impacts of climate change.

Adaptation measures of habitat types to climate change. It would include, among other adaptive management measures, those aimed at reducing the non-climatic pressures that act on the types of habitats; improve the resilience of habitat types; maintain the abiotic conditions required by the types of habitats; reduce the impact of extreme weather events or identify climate refuges.

Within this line, the following **actions that affect salmon** will be carried out:

- promotion of the creation of 'climate refuges' as a tool for adaptation to climate change of biodiversity. In this sense, protected areas and breeding refuges for salmon have been increased; and
- in relation to this, small dams (smaller than 80 – 90 cm), can create pools and in summer contribute to creating micro-habitats protected from thermal rises and that contribute to being shelters due to their depth therefore keeping them should be considered rather than tearing them down.

LINE OF ACTION: STRENGTHENING THE ADAPTATION TO CLIMATE CHANGE OF THE COMMON FISHERIES POLICY IN THE AQUACULTURE SECTOR.

Climate change and ocean acidification are profoundly altering marine ecosystems, with consequent impacts on fisheries and aquaculture. The effects on the coasts, on river ecosystems and on the people who live in these areas test the resilience of the blue economy and of society as a whole and threaten the sustainability of aquaculture activity.

Different studies have indicated the repercussions of climate change on aquaculture, and the need to adapt the activity to face risks from a biological, economic and social point of view:

To promote the adaptation of aquaculture to climate change in Spain, the new Spanish Aquaculture Strategy, the Contribution of Spain to the Strategic Guidelines for a more Sustainable and Competitive EU Aquaculture 2021-2030 includes actions to incorporate the climatic variable into the spatial planning of aquaculture, both marine and freshwater aquaculture, that means the identification of the areas least exposed to the effects of climate change for the development of aquaculture.

In this regard, the following actions are planned:

1. Diagnosis and risk assessment in the coastal marine environment due to climate change, in current and future areas of marine aquaculture.
2. Diagnosis and risk assessment, due to climate change, in current and future areas of continental aquaculture.

Conclusion

The number of salmon in Spain is decreasing and the **environmental conditions derived from climate change seem the most logical explanation, although for the moment it lacks a sufficient scientific basis.**

Climate change is negatively influencing salmon dynamics, affecting:

- weather conditions, which determine the flow and temperature of the water;
- oceanic conditions, which determine the success of migrations and the availability of food in growth areas;
- conditions of the fluvial habitat, which determine its availability and quality for reproduction and fry; and
- increase in predation in rivers and estuaries (otter, cormorant).

Influencing the first two groups of conditioning factors (climatic and oceanic) require the assumption of global measures, many times outside the scope of the competent administrations in terms of conservation and recovery of the species, so the efforts of international administrations and organizations that ensure the conservation of the species focus on the recovery of the fluvial habitat and the reduction of mortality caused by human beings.

But while the impact of river habitat restoration measures on the salmon population often takes longer periods of time, reducing mortality, especially that of spawners, can offer more immediate results as increased production of fry will be directly reflected in the next cohort.

Finally, the adaptive measures that also seem effective are the reduction of catches and days of fishing, the limitation in the use of fishing gears and even the carrying out of biological stops such as the one proposed for the Bidasoa river in 2023.

Acknowledgements

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CNL(23)57

Management actions to mitigate the effect of climate change on salmon

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The Scientific advisory board recently made an assessment of likely effects of climate change on Norwegian salmon populations (Vitenskapelig råd for lakseforvaltning 2021). Their summary of the likely impacts was as follows:

> *'Climate change is a global threat, which is already impacting salmon populations, and will impact salmon populations to a great extent in the future. Climate change impacts the life of the Atlantic salmon at all life stages, through changes in water temperature, precipitation, water quality and other environmental factors. There is extensive knowledge on how these factors impact Atlantic salmon in the freshwater phase, but less knowledge on the marine phase. There is also little knowledge on how climate change will impact long-term genetic and ecological changes and adaptations in different populations. Since salmon populations are genetically different, and will experience different changes in climate, it is likely that different populations will respond differently to climate change.*
>
> *Climate change amplifies the negative effects of other threats to Atlantic salmon populations. Threats like escaped farmed salmon, salmon lice, other infections related to salmon farming, habitat alterations, negative impacts of introduced species, pollution and others become even larger when occurring in a changing climate. This is also the case for river regulation for hydropower production, but such regulation can also in some cases be adapted to help reduce the impacts of climate change.*
>
> *Climate change is a threat that increases the importance of having large and genetically variable populations to enable them to meet the rapid changes in the best possible way. Hence, it is important to protect and preserve the size and genetic variation and integrity of salmon populations, and thereby the abilities of populations to adapt to new and changing conditions. Climate change increases the needs to reduce the impacts of other threats to Atlantic salmon.'*

Action 1. Get an overview of the situation and possible mitigation efforts

In 2010 and 2020 the Scientific advisory board was asked to provide an assessment of what challenges the climate change predicted from scenarios posed for the management of salmon populations and propose mitigating measures. The advice from the board was broadly similar in the two reports (Vitenskapelig råd for lakseforvaltning 2011, 2021) and can be summarized as follows:

1. Norway is expected to have a larger proportion of the European salmon stocks in the future, because climate change may affect stocks south of Norway harder than Norwegian stocks. Norway's responsibility for the protection of salmon is therefore expected to increase in the future.
2. At sea survival of Atlantic salmon may decrease because of climate change, but this prediction is very uncertain. Furthermore, targeted measures to increase at sea survival are difficult. Measures should therefore be taken to ensure that a maximum number of smolts leave the rivers.
3. The long-term development of the salmon populations may be affected by their genetic composition. Therefore, it is important to maintain genetic integrity and variation to allow adaptations to altered conditions to occur. This should involve continued efforts to reduce genetic introgression from escaped farmed salmon, a critical evaluation of the use of hatchery fish and ensuring that spawning populations are sufficiently large to avoid loss of genetic variation and maintain life history variation.
4. Water discharge regimes in rivers developed for hydropower production should be adapted to protect salmonids in the river. More water available due to increased precipitation in parts of Norway may open opportunities for adjustment of discharge regimes to the benefit of salmon when the rules for the hydropower plants are revised.
5. Increased sea temperatures may increase infestation pressures from sea-lice from salmonid farming. Planning of new aquaculture facilities should take this into account.
6. Elevated freshwater temperature may increase juvenile growth and, in some cases, lead to younger and smaller smolts that are more susceptible to negative impacts from sea-lice. Altered temperature in fresh water and changes in waterflow may lead to earlier smolt migration. The mitigation measures to reduce negative impacts from salmon-lice in aquaculture should take that into account and adjust their timing accordingly.
7. More frequent and large floods because of more intense rainfall will increase the need for flood protection measures. Such measures should consider habitat conditions for fish. River flow concentrations, channelisation and the use of culverts should be avoided. Instead, flood protection measures should be based on restoring the original river course and avoid building of infrastructure and houses in the floodplains.

Measures to reduce erosion should also consider fish habitat requirements by, for example, allowing for riparian vegetation.

Following these recommendations, the salmon management in Norway has:

1. **Recommendation 1, 2 and 3.** To ensure that stocks in rivers are above the Conservation Limits (CL), fishing regulations are used. This is done by reducing exploitation on salmon from rivers that have not reached CLs through reductions of fishing time and effort in the rivers, and reductions or closure of sea-fishery in areas were the stocks are exploited. Furthermore, in-season regulatory measures are taken if information suggests CL is not likely to be achieved if fishing continues unchanged. This is monitored by a yearly assessment of the CL-attainment in more than 200 rivers (Hjem - Vurdering av enkeltbestander (vitenskapsradet.no)). The proportion of rivers attaining their CLs has increased, and the number of spawning salmon in Norwegian rivers has increased over time despite the pre-fishery-abundance being reduced (Vitenskapelig råd for lakseforvaltning 2022).
2. **Recommendation 4.** The terms of operations for hydropower regulations are currently, and within the next decade or so, under revision in many of the regulated salmon rivers in Norway. The aim of the revisions is to improve environmental conditions, and production of salmon is a central theme. So far, this has resulted in new minimum flow stipulations and other measures in some rivers, whereas hydropower production has been given priority over environmental flow in others.

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Development of evidence-based management strategies to protect salmon populations from the effects of high river temperatures under climate change through targeted riparian tree planting; case studies from Scotland and England

Faye Jackson, Ian Malcolm (Marine Scotland, Pitlochry) and Lawrence Talks (Environment Agency, Hampshire)

Introduction

River temperature is a key control on freshwater ecosystems, influencing species survival, distribution, abundance and growth. Across the UK many native freshwater species, including Atlantic salmon, are adapted to live in cool clean water habitats. During the summer of 2018, it is estimated that around 70 % of Scotland's rivers experienced temperatures that exceeded the threshold for thermal stress in juvenile Atlantic salmon (Jackson *et al*. 2020). UK climate change projections provided by the MET Office (UKCP18) indicate that summers like 2018 could occur every other year by 2050, with increasingly high air temperatures (Ta) and low summer flows. There are thus increasing concerns over the potential impacts of rising river temperature under climate change. In recognition of these challenges, and within the broader context of national climate adaptation programmes and associated resources (see for example Natural England and RSPB 2019), management strategies that seek to improve the climate resilience of rivers are a key component of efforts to protect and recover salmon populations across the UK (see Scottish Wild Salmon Strategy, England's Salmon 5 Point Approach and the Welsh Salmon and Sea Trout Plan of Action).

Alongside the management of flows and abstractions, riparian tree planting provides one of very few management options available to reduce river temperature. Riparian trees can shade river channels, reducing the amount of solar radiation reaching the water surface, thereby reducing temperatures. In addition, shading can help mitigate the negative effects of other pressures, expected to be exacerbated by climate change, such as eutrophication and algal blooms.

Increasing amounts of river restoration are being undertaken in the UK, which often includes riparian tree planting. Financial support comes from a variety of sources, including government grant schemes and local charitable fundraising. Commitments, such as in Scottish Forestry's Implementation Plan (2022-2025) to develop 'an integrated approach to riparian management to improve the climate resilience of rivers, water quality, river morphology and the availability of habitat networks', also aspire to support further expansion of riparian woodlands.

There is considerable potential in the UK to increase riparian woodland. Due to the time taken to plan and implement appropriate tree planting, and for trees to reach heights where they provide meaningful shading, it is important that efforts are made to increase the spatial extent of riparian woodland as a matter of urgency. However, given constrained resources, it is also important to prioritise planting to river reaches where trees can deliver the greatest benefits in terms of temperature moderation.

Substantial technological and statistical developments have enabled significant advances in large-scale river temperature monitoring and modelling, in addition to the availability of large-scale shading models. This provides a strong scientific evidence base on which to build climate adaptation strategies. This presentation provides an overview of two case studies from different parts of the UK.

Scotland Case Study

The Scotland River Temperature Monitoring Network (SRTMN) was established in 2013 as a collaboration between the Scottish Government directorate Marine Scotland, fisheries managers and the University of Birmingham (Figure 1). It includes (1) a strategically designed monitoring network (Jackson *et al.* 2016) supported by quality controlled data collection and database storage, (2) spatio-temporal statistical models to identify which rivers are hottest and most sensitive to climate change (Jackson *et al.* 2017; 2018), (3) simplified process-based shading models to identify where rivers can be most effectively cooled by riparian woodland (Jackson *et al.* 2021) and (4) national scale mapping tools to prioritise management to areas where riparian tree planting will have the greatest overall benefits in terms of protecting Scotland's rivers from the adverse effects of high summer river temperatures under climate change (SRTMN 2023).

To our knowledge, SRTMN was the first strategically designed, quality controlled national river temperature monitoring network in the world. It was designed to cover the environmental range of river characteristics that previous studies showed to be good predictors of temperature in near-natural rivers (Jackson *et al.* 2016). This approach minimises site redundancy and maximises statistical power to make predictions to unmonitored locations. Data collection is undertaken through collaboration with local fisheries managers. Since its initial deployment in 2014 / 15, the core network of 223 sites has been expanded to include short-term deployments (~ 1 year) in unmonitored catchments and monitoring of catchments influenced by natural and modified standing waters where predictions are less accurate.

Data from SRTMN have supported the development of spatio-temporal statistical river temperature models (see Jackson *et al.* 2018 for details). These can be used to understand and predict river temperature across the country. In brief, maximum daily river temperature was modelled as a function of air temperature, time of year and landscape characteristics (elevation, channel orientation and riparian woodland). Spatial correlation (non-independence of sites close to each other) was encompassed at river network and regional scales. Temporal correlation (the non-independence of observations over time) was addressed through an autoregressive (AR1) error structure. The resulting models allowed prediction of maximum river temperature and climate sensitivity across Scotland.

The effects of riparian woodland on channel shading depend on complex interactions between channel width, orientation, aspect, gradient, tree height and solar geometry. The subsequent effects on river temperature are influenced by water volume and residence time. By combining the results of a simplified process-based shading model with information on water volume and residence time the effects of solar radiation on river temperature can be modelled. By comparing scenarios with and without trees it is possible to identify rivers that can be effectively cooled by riparian woodland (Jackson *et al*. 2021). When the outputs of the statistical and process-based models are combined it is possible to identify priority river reaches for management, specifically, where rivers are hottest, most sensitive to climate change and where planting is likely to be most effective in reducing temperatures.

Data and analyses from SRTMN have been disseminated through a variety of media tailored to different audiences interested in the management of river temperature under climate change. This includes peer reviewed publications, R Shiny Applications, web pages, spatial data layers (e.g. online GIS, web-based mapping services) and non-technical documents (e.g. end user friendly leaflets).

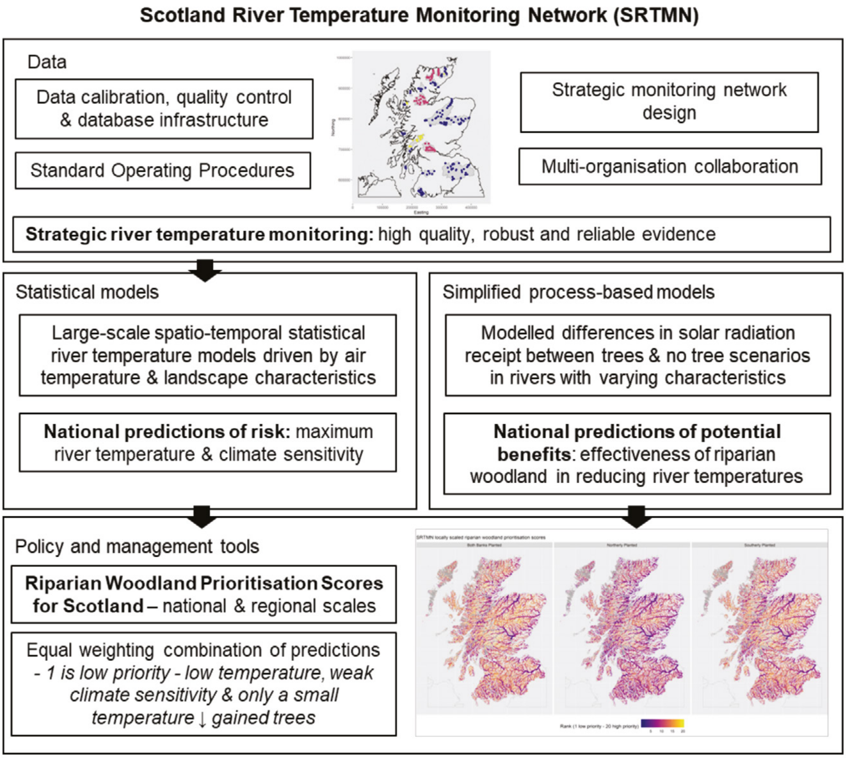

Figure 1. *Schematic of Scotland River Temperature Monitoring Network.*

England Case Study – Keeping Rivers Cool

The Keeping Rivers Cool (KRC) project is a nationwide initiative. It aims to increase the resilience of sensitive ecosystems and freshwater wildlife, particularly salmon and trout, to the impacts of climate-change-induced temperature increases by using riparian shading to cool rivers.

KRC provides practical support to encourage landowners and conservation managers to increase riparian shading, by providing (1) Riparian shade maps, which can be used by land managers to target areas in a catchment which are exposed most to sunlight. Shade maps grade the river on a spectrum from red (low shading) to blue (high shading) to indicate the degree of relative shading (Figure 2), (2) Best practice guidance, which is now administrated by The Woodland Trust and (3) A direct link to funding, including via the England Woodland Creation Offer, which is focussed on rivers less than seven metres wide.

In the initial demonstration projects on the Ribble, Hampshire Avon, Wye and Tyne river catchments, 55,000 trees were planted and 37 km of fencing erected between 2012-2016. Since then, KRC has expanded exponentially with, for example, the Rivers Trust planting 277,520 trees in 2021.

During 2021-22, 68 hectares (Ha) were planted to Keep Rivers Cool with funding from a number of government tree planting schemes. For example, in the Mid-Ribble catchment (Bier Beck, Savick Brook, Showley Brook, Porters Brook, West Clough, Greystonely Brook, Hodder) funding was provided via SITA Trust's Enriching Nature Programme, Defra Catchment Restoration Fund and the Woodland Trust's MOREwoods. Planting was further supported by 36 volunteer days. Combined this resulted in installation of 10 km of fencing across 13 sites and 10,000 trees planted, improving over 9 Ha of riparian habitat.

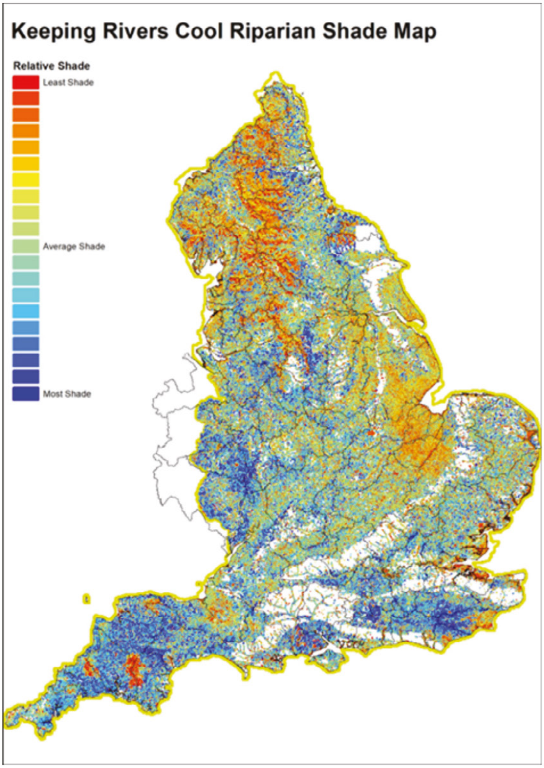

Figure 2. *Keeping Rivers Cool riparian shade map.*

To provide an up to date and more accurate riparian shade map, an England-wide detailed (1 m resolution) lidar survey was undertaken between 2017-2022 to map the vegetation and a first-return Digital Surface Model (DSM) was employed to give a more accurate depiction of vegetation height. Multidirectional sun-shading was then applied to a Digital Terrain Model (DTM) and first-return Digital Surface Model (DSM), based on sun-angles throughout the day over the summer months, to determine the degree of shading. The 2nd generation KRC riparian shade map and accompanying Vegetation Object Model are now available directly from the Environment Agency and by late 2023 will be available to download via the government's Open Data portal (Environment Agency 2021).

Conclusions and future look

Appropriate monitoring approaches provide reliable and unbiased quantitative data on river temperature variability. As timeseries of quality-controlled data build, they also provide valuable information on trends and the efficacy of management. When combined with appropriate statistical and process-based models these data can be used to guide policy and target management action. Where river temperature data and associated modelling are not available shading potential maps can be used to target resources. However, as they only provide sunlight exposure, alone they may not identify the highest temperature locations or locations where trees can reduce temperatures most. Depending on data availability, priorities and resources, there is potential to extend river temperature modelling approaches to explore future river temperatures using climate change projections (UKCP18), support other environmental assessment methods and explore opportunities for 'real-time' monitoring and management (e.g. within season close times for angling as seen in other countries such as Canada; Breau 2013).

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CNL(23)59

Atlantic Salmon (Salmo salar) Conservation and Management in a Changing Climate: The U.S. Approach to Insert a Climate Focus into Ongoing Salmon Conservation Efforts

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Introduction

This paper describes the U.S. approach to integrate climate planning into existing Atlantic salmon management actions with the goal of promoting and enhancing climate resilient populations. This paper highlights a five-step approach that we are using to advance climate mitigation ideas into tangible climate actions. The approach has helped inform climate-focused recovery actions that were integrated into the Final Recovery Plan for Endangered Salmon (USFWS and NMFS 2018), coalesced scientist and managers around a shared vision to mitigate climate impacts on salmon and provided the foundation to integrate climate measures into continued strategic planning efforts, regulatory measures and proactive restoration actions.

The five-step approach starts with developing a national level climate strategy and culminates with the development of species-specific science and management actions (Figure 1).

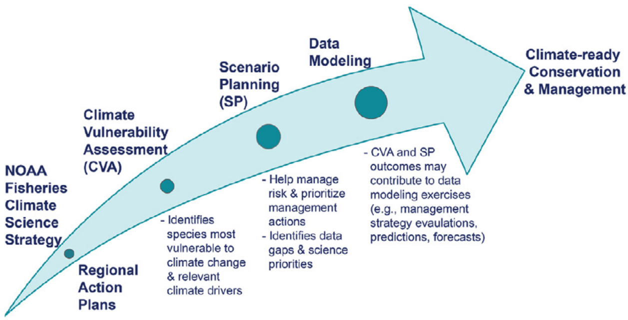

Figure 1. *The five-step approach used to advance climate mitigation ideas into tangible climate actions (see Borggaard et al. 2019).*

These five steps are designed to complement and build off each other as the focus becomes more regional. NOAA Fisheries' National Climate Science Strategy outlines a process to guide the five regions of the United States (e.g., Northeast, Southeast, West Coast, Alaska and Pacific Islands) in the development of Regional Action Plans. This includes approaches for integrating climate change into resource management and highlights activities such as conducting Climate Vulnerability Analyses and Scenario Planning exercises. Results from the Climate Vulnerability Analysis and Scenario Planning direct and inform science and modeling that can inform the development of climate-ready conservation and management actions. The following sections walk through each of these steps, detailing how they advanced the consideration and inclusion of climate science into management actions for Atlantic salmon.

National Climate Science Strategy and Regional Action Plans

The NOAA Fisheries National Climate Science Strategy (the 'Strategy') and the Climate Science Regional Action Plans (RAPs) provide a national and regional approach to guide climate-smart resource management and implementation. The goal of these efforts is to increase the production, delivery and use of climate-related information to support science, stewardship and management of living marine resources (Link *et al.* 2015).

The Strategy identifies national-level climate objectives that are needed to inform management and stewardship (Link *et al.* 2015). The Strategy provides the goal posts for developing RAPs. The RAPs are five-year plans that identify priority science and management needs and specific actions to implement the Strategy in the five U.S. regions. The Northeast U.S. RAP (Hare *et al.* 2016; Saba *et al.* 2023) identified a number of regional climate planning and management actions, including Climate Vulnerability Analyses and Scenario Planning, both of which inform climate considerations within our overall management structure for Atlantic salmon.

Climate Vulnerability Assessment

Climate Vulnerability Assessments evaluate the vulnerability of species to changing climate conditions over time, taking into account the species exposure and sensitivity to climate stressors. In the Northeast United States, a climate vulnerability assessment was completed for 82 managed fish and invertebrate species that included exploited, foraged and protected species (Hare *et al.* 2016). Species vulnerability was determined by the extent that a species abundance or productivity could be impacted by climate change and decadal variability. Exposure variables include factors such as changes in sea surface temperature, air temperature, precipitation, ocean acidification, ocean currents, sea level rise and salinity. Sensitivity variables include life history attributes such as a species mobility, habitat specificity, prey specificity, spawning cycle and reproductive strategy. Other sensitivity factors include population size, growth rate and early life history survival. Upon completion, all species were assigned a relative vulnerability score based on their exposure and sensitivity factors. Atlantic salmon were determined to be one of the two most vulnerable species. Conducting the vulnerability assessment on Atlantic salmon provided a structured framework to document systematically the life history of Gulf of Maine Atlantic salmon as it relates to its exposure to a number of different climate variables. The assessment also laid the foundation for understanding how climate change may affect salmon in the future.

Scenario Planning

Scenario planning is a structured process used to explore plausible alternative future conditions under different assumptions and to help identify and prioritize potential future management actions with a focus on minimizing risk (Schwartz 1996; Peterson *et al.* 2003). Scenario planning can be an effective tool to identify common science and management actions that can be taken proactively to mitigate the impacts of climate change across multiple plausible future scenarios. After finding Atlantic salmon to be highly vulnerable to climate change, NOAA Fisheries conducted scenario planning to explore what the agency can do to improve U.S. Atlantic salmon population resilience to changing climatic conditions (Borggaard *et al.* 2019). The objectives of the effort were to further understand the challenges of managing Atlantic salmon in a changing climate, identify management actions and research opportunities and increase collaboration and co-ordination on climate-related recovery actions (Borggaard *et al.* 2019). Atlantic salmon was the first species on which NOAA Fisheries conducted scenario planning and stemming from its success, scenario planning has been used to inform climate decision-making for many other species. Scenario planning has become a major tool in NOAA Fisheries climate planning portfolio.

The basic approach to scenario planning is to identify two primary but independent drivers impacting the condition of interest (i.e. Atlantic salmon productivity) into the future given changing conditions. These drivers can be visually represented as axes on a graph to form four quadrants, each representing a different plausible future scenario. Guided conversations are then conducted to explore what risks and opportunities each scenario / quadrant provides, what preparations are needed and what indicators should be tracked over time (Borggaard *et al.* 2019). For Atlantic salmon, the two selected drivers were climate change and connectivity. We selected connectivity as our second axis as it continues to be a high priority threat to salmon survival in the United States (NMFS 2009). A key outcome of this exercise was a number of science questions that were prioritized to understand and mitigate the effects of climate change. Some of these questions included:

- What are the projected future conditions for both freshwater and marine habitats?
- What are the life stage specific environmental thresholds (e.g. temperature, flow, etc.?)

- How will Atlantic salmon behaviour change in response to a changing climate?
- How will habitat productivity change?
- Where and why are salmon dying in the ocean?
- How will a changing climate further affect survival?
- Are there ways to increase marine survival generally and in light of climate change?

Many of these science questions were tailored into recovery actions that were incorporated into the Final Atlantic Salmon Recovery Plan (USFWS and NMFS 2018).

Science and Modelling

Since the completion of the Scenario Planning effort we have proceeded to address many of the resulting science questions. We highlight three of those efforts below:

Life stage specific vulnerabilities: The synthesis of Atlantic salmon life stage specific vulnerabilities to climate change helps address our questions regarding life stage specific environmental thresholds and how U.S. salmon productivity may change in response to a changing climate (Henderson *et al.* 2023). Refined understanding of these vulnerabilities is helping to inform short- and long-term conservation planning and management action implementation, as well as identify data gaps where more information is needed.

Baseflow modelling: Baseflow modelling is a tool to help inventory and prioritize climate resilient freshwater habitats (Lombard *et al.* 2021). Water temperature is an important limiting factor of Atlantic salmon abundance based on the therma-maxima of the species (Elliot and Elliot 2010) and baseflow has been shown to be an influential element of water quantity and water temperature, particularly in the summer months (Hodgkins and Dudley 2011). The baseflow modelling effort in Maine helps us identify stream reaches that are richer in cold-water habitat, which can in turn be prioritized for conservation and restoration (Lombard *et al.* 2021). Enhancing access to cold-water refugia is a priority management action to mitigate the impacts of future climate-induced warming stream temperatures.

Impacts of delay at dams: Warming rivers due to a warming climate will likely further increase environmental stressors on Atlantic salmon and increase mortality. Dams can significantly delay passage of upstream migrating adults (Noonan *et al.* 2012; Izzo *et al.* 2016). These delays increase the time that adult salmon spend in warmer waters and increase their migration times. A recently completed study of the impacts of delay and water temperature on the Penobscot River, Maine, concludes that Atlantic salmon that experienced delays below dams of 16 – 23 days lost between 11 % and 22 % of their fat reserves; this loss could be consequential to spawning success and post-spawn survival (Rubenstein *et al.* 2022). These results highlight the importance of implementing management actions to minimize delays for migrating pre-spawned adult salmon due to dams, particularly in areas with warming waters.

Climate-Ready Conservation and Management

The fifth element of the climate-ready approach is applying the threat identification, planning and science from the first four elements to inform conservation and management actions. Here, we provide three examples of how this strategic approach is informing the development of climate-ready conservation and management actions for Atlantic salmon.

Strategic Planning: Improving connectivity at dams and road crossings has been a priority for the U.S. salmon program since 2006. Where dam removal is not possible, we work to improve passage at those dams, both in terms of efficiency and timing. To provide the greatest benefit to salmon and increase their resilience to climate change, we must be strategic in our efforts to restore connectivity by targeting areas that will afford the greatest conservation benefit. The base flow modelling provides us with information we can use to focus connectivity efforts that help ensure access to the most climate resilient areas.

Regulatory Measures: Through the authorities of the U.S. Federal Power Act and the Endangered Species Act, we work to implement measures at hydro-electric dams that are necessary for the protection of endangered salmon, including measures to improve passage rates and reduce delay. Previous studies have quantified the negative impacts associated with dams and the effects on emigration of juvenile salmon to the ocean. The recent study on the impact of delays at dams for adult salmon has expanded our knowledge on the energetic cost of those delays. We will continue to use the best available scientific information to inform the management and regulatory actions implemented at dams, including consideration of climate science and how warming waters can exacerbate existing threats.

Proactive Conservation: Maine's rivers and streams were heavily modified during 100+ years of log drives. Today, these modified rivers continue to be over-widened, straightened, lack habitat complexity and lack riparian and in-river cover. These factors increase the sensitivity of rivers and streams to warming conditions. Given that there are over 16,000 kilometers of river and stream networks in Maine, new information on life history vulnerabilities and on the current and projected habitat conditions helps to identify where habitat restoration projects are most needed and will afford the greatest benefit to salmon. In addition, this new information helps with identifying what habitat features are needed to afford the most protection to the most climate sensitive life stages.

Conclusion

The Climate Vulnerability Assessments and Scenario Planning exercises resulted in a convergence of knowledge and ideas to formulate an approach to mitigate the impacts of climate change on Atlantic salmon in the Gulf of Maine. Although both efforts involved salmon experts, they also involved numerous individuals from a wide range of disciplines not previously represented within the salmon program. Of note, the Scenario Planning exercise involved people and agencies not typically involved in Atlantic salmon science and management. These meteorologists, hydrologists, geomorphologists and ecologists were able to provide meaningful science support to the salmon program in unexpected ways. Although some of the actions and science needs that came out of the Climate Vulnerability Assessments and Scenario Planning had been discussed previously, these exercises helped unify and build partnerships both within the salmon program as well as with other participating entities. These partnerships and the resulting science efforts have contributed valuable information that is being integrated into existing proactive and regulatory management actions. This information has also enabled us to provide better guidance to stakeholders on where and what types of management actions will afford the greatest benefits to salmon now and into the future.

Next Steps

At present, modelling efforts are continuing to refine our understanding of where climate vulnerable and climate resilient habitats are located and how that may change in light of climate projections. We are also pursuing a Management Strategy Evaluation (MSE). MSEs are a modelling exercise that allows fishery managers to compare different management strategies, taking into account risks and trade-offs, to achieve a specified management objective (Punt *et al.* 2016). By incorporating resource constraints, including uncertainties associated with climate change, into the operating models of an MSE, managers can use the outputs from applying the MSE to identify the best, most effective management strategy to achieve identified conservation and management objectives. Development and use of an MSE is an appropriate next step in determining the most effective strategies to advance our conservation objectives for Atlantic salmon in the face of identified uncertainties related to climate change and other factors. As we build our knowledge base on the current and projected impacts of climate change on salmon and salmon habitat and increase the tools in our toolbox for managing these impacts, we will need to be strategic in maximizing the limited resources available for conservation.

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Invited countries

The Steering Committee wanted to promote discussions and knowledge sharing of effective climate adaptive fisheries management measures with countries outside of the NASCO Parties / jurisdictions, and, therefore, extended the invitation to countries of interest to present a paper to NASCO and / or present at the TBSS. Guðni Guðbergsson, representing Iceland, presented on ‘The status of Atlantic salmon stocks in Iceland Past and present management actions to mitigate the effect of climate change on Atlantic salmon’ – CNL(23)60.

CNL(23)60

The status of Atlantic salmon stocks in Iceland

Past and present management actions to mitigate the effect of climate change on Atlantic salmon

Guðni Guðbergsson and Hlynur Bardarson, Marine and Freshwater Research Institute (MRFI), Iceland

Introduction

Five native species of freshwater fishes are found in Iceland. Three species of salmonids, Atlantic salmon (*Salmo salar*), brown trout (*Salmo trutta*) and Arctic charr (*Salvelinus alpinus*). The other two are, European eel (*Anquilla anquilla*) and three-spined sticklebacks (*Gasterosteus aculeatus*). Arctic charr and brown trout can have both resident and migratory components. Atlantic salmon, Arctic charr and brown trout have stocks in both rivers and lakes that are being harvested in Iceland. In the most recent years European flounder (*Platichthys flesus*) has been common, mostly at river estuaries, and pink salmon (*Oncorhynchus gorbuscha*) is rapidly increasing in numbers and distribution (Gudbergsson and Antonsson 1997; Gudbergsson 2015).

From the first settlement in the 9th century, salmon fishing has been highly evaluated as food resource. In the first law, written in the year 1200, it is stated that fishing trap fence were only allowed out to 2/3 of a river width to allow migrating fish to pass to the upper regions of the river.

The fishing rights belong to the owner of the land adjacent to the rivers. The landowners are usually farmers. All the landowners of the fishing rights, in a river system, have by law to form a fishery association, which manages the exploitation of the fish stocks, within the frame set by the law. Most commonly the river's fishery association rents or leases the fishing rights to angling syndicates, angling clubs or directly to anglers. The entire riverbank is accessible to the limited number of rod fishermen that have fishing permit each day.

The fishing season for salmon in Icelandic rivers is at the maximum of 105 days in the period from 20 May to 30 September. In rivers where salmon fishery is mainly based on release of hatchery reared salmon smolts (ocean ranching) the fishing season can be extended to 120 days and throughout October with permission from the Directorate of Fisheries (Fiskistofa). The daily fishing period is 12 hours for seven days a week for a total of 84 hours each week. In most Icelandic rivers, rod and line is the only fishing gear allowed. A limited number of rods are allowed in each river. The old historic limit for conservation was attained by limiting the fishing effort in terms of number of rods. For the decision, taken by the Directorate of Fisheries, one fish per rod per day was used as a rule of thumb. In most rivers fishing effort has remained almost unchanged from 1970, while changes in the numbers of landed catch have at the same time been going down as many river associations apply catch and release of all salmon in their harvest plans. Each fishery association needs to make a harvest plan that outlines the management strategy to sustainable fishery. The management plan needs approval by the Directorate of Fisheries after a review by the Marine and Freshwater Research Institute (MRFI).

Net fishery is almost exclusively bound to the large glacial rivers where angling possibilities are limited due to turbid water. In the net fishery, gillnets are the most common fishing method. The weekly net fishing period lasts from Tuesday morning at 10 am to Friday evening at 10 pm. The weekly fishing period in net fisheries is 84 hours, the same number of hours as the weekly fishing opening is in the rod fishery. The weekend closure, in the net fishery, is to reduce fishing effort and enhance fish migration to the river upper regions and tributaries.

There has been a general ban, by law, on ocean salmon fishing in Icelandic waters since 1932. An exception to that were five localities (farms) in West Iceland with coastal fishery. At these localities coastal gillnets set from land were used. These fishing rights were permanently bought out in 1997 by fishery associations in nearby rivers and with governmental support. This was possible since salmon caught by anglers are of much higher economic value than salmon caught in the net fishery. All salmon harvested in Iceland is in freshwater and mostly based on exploitation of a single stock.

Lease of net fishing rights by owners of rod fishing rights in clear water tributaries have been practised in the Hvita River system in Borgarfjordur, SW-Iceland since 1991 (32 years). The net lease is based on an agreement where the fishery associations of clear water tributaries pay 8-10 % of the income value from rod fishing licences to the net owners of net fishing rights for not fishing. The net lease has reduced the net catch and increased the rod catch by 28-35 % (Einarsson and Gudbergsson 2003).

Enhancement actions taken to increase population size of Atlantic salmon

The geology of Iceland is relatively young. Rivers in Iceland are of various origin including, spring-fed rivers, direct run-off rivers and glacier rivers and waterfalls are numerous. At present 78 fish passages have been built, which opens up 900 km, resulting in a total of 3000 km of river length accessible for anadromous fish in Iceland. The construction of fish ladders has, with only few exceptions, been successful in increasing population size of salmon, angling opportunities and economic value of the angling fishery in Iceland.

Enhancement programs

Enhancement of salmon has been practiced in Iceland for the past century. Initially with fry from hatcheries and later (after 1960) with parr and smolts.

In the latest years enhancement is mainly by utilizing areas above waterfalls by moving adults for spawning or stocking with parr or eggs. By the operation eggs are moved from lower part of rivers to unreachable upper parts but does not add to the spawning stock. Ocean ranching for harvest with rod and line is practiced in a few rivers at the south coast of Iceland. The operations are mainly bound to two rivers, rivers with poor nursery areas not supporting wild salmon, but good angling opportunities. Annually 500 thousand smolts are released in each of the rivers giving from six to ten thousand fish caught annually with rod and line. The ocean ranching increases the total number of salmon caught in the angling fishery in Iceland by 20 to 25 %.

Water temperature and salmonids thermal optima

The Marine and Freshwater Research Institute (MRFI) has, for the past 20 years, operated a net of temperature loggers in more than fifty rivers in Iceland. Information from the Icelandic Meteorological Office show an increase in annual average air temperature for the past twenty to thirty years. The temperature increase is mainly shown during wintertime and is reflected by the in-river water temperature that shows higher water temperature in spring and autumn while summer temperature has been more stable. There is a strong relationship between spring temperature and the size of juvenile salmon measured in the annual autumn surveys. The optimal water temperature differs for the three salmonids species, with salmon tolerating the highest temperature out of the three and Arctic charr the lowest with brown trout being intermediate. The long-term measurements around Iceland seldom reach the upper temperature limits for salmon but may in some cases have constrained the cold adapted Arctic charr. Higher temperature has been observed to result in many different physiological changes in salmonids such as changes in growth rate, time of spawning, egg hatching time and emergence of larvae (Jonsson and Jonsson 2009). In some rivers in Iceland, mostly in the south and west, higher spring temperature has indirectly contributed to changes in age-at-smolting by increasing juvenile growth rate. This can be observed by analysing scales from returning adults, as well as from smolt traps in one of our ICES index rivers, Ellidaar.

Furthermore, there are indications that higher water temperatures may have indirect negative effects on salmon. For example, a recent study on the Proliferative Kidney Disease indicated a very high proportion of infections among salmonids in Iceland but since the symptoms need temperatures above 15 °C to develop, the majority of the individuals were not affected by the infection (Kristmundsson *et al.* 2011, 2023). The PKD disease has caused severe mortality in rivers in northern Norway (Sterud *et al.* 2007) and with such high numbers of infected individuals in the studied rivers and lakes it should be considered likely to have negative effects on salmon populations with increasing water temperatures expected with climate change.

Wild salmon in Iceland

The average number of wild salmon migrating into Icelandic rivers is close to 80 thousand fish in the period from 1971 to 2021 (Figure 1). A declining trend is seen for the whole time-series with a period of higher fluctuations and some of the lowest numbers in the most recent years. This high fluctuation between years can clearly be seen from 2012 to 2015.

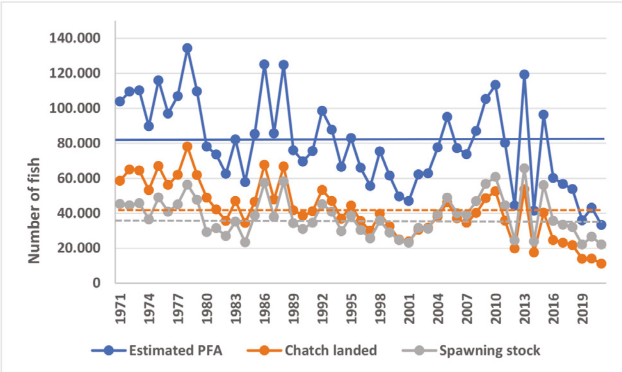

Figure 1. *Estimated pre fishery abundance (PFA) of wild salmon in Icelandic rivers, catch and spawning stock from 1971 to 2021.*

Sea age composition

The salmon stock in Iceland consists of one-sea-winter (1SW) and two-sea-winter-salmon (2SW) (Figure 2). Longer sea age than 2SW is very rare and repeated spawning is in low proportions.

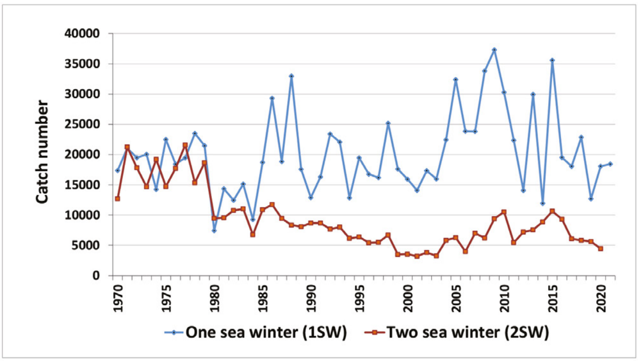

Figure 2. *The number of one-sea-winter (1SW) and two-sea-winter (2SW) salmon in the angling fishery of wild salmon in Icelandic rivers 1970-2021, shown for the same smolt cohort.*

In the 1970s, 48 % of the angling catches of wild salmon was 2SW salmon. After a very cold period in the early 1980s a clear decline was seen in both stock components. The 2SW stock component did not recover like the 1SW and was down to 19 % of the total catch at the average from 2000 to 2010 (Thordardottir and Gudbergsson 2022).

In 2000 a **management action** was taken in co-operation between the Institute of Freshwater Fisheries, the Federation of Icelandic River Owners and the Association of Angling Clubs to encourage catch and release of 2SW salmon. The management action involved changing the fishing regulations to mandatory release of large salmon (>69 cm) a size group which is almost entirely comprised of 2SW salmon. It needs to be noted that the genetic inheritance of sea age, as later described by Barson *et al.* (2015), was not known at that time. In the light of Barson *et al.* (2015) findings these actions can be regarded as successful and a clear sign of recovery of the 2SW can be seen and from 2010 to 2020 (Figure 3).

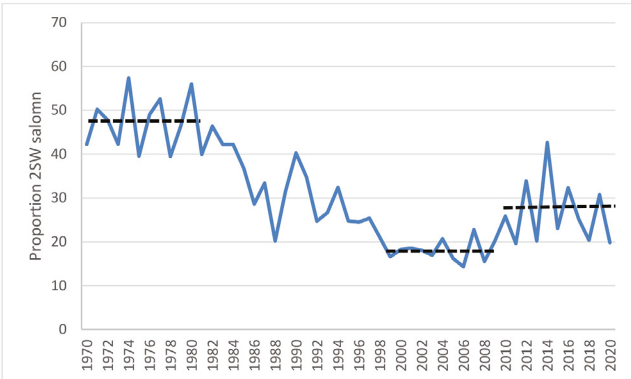

Figure 3. *The proportion of two-sea-winter salmon in the angling catches in Icelandic rivers from 1970 to 2020. The average proportions were 48 % from 1970-1980, 19 % from 2000-2010 and 28 % from 2010-2020.*

Furthermore, to decrease the fishing pressure on the 2SW salmon in the few rivers that net fisheries were still in operation a **management action** in which a delay of the opening of the net-fishery to the end of June, was taken. The purpose is to allow the 2SW fish, which usually arrive earlier then the 1SW, to migrate up rivers to clear water tributaries and lower the fishing pressure on that component.

Catch and release is mandatory for all salmon catches in numerous Icelandic rivers and for the past few years more than 80 % of all wild 2SW salmon and 50 % of the 1SW salmon are released in the angling fishery. As can be seen on Figure 1, catch and release has led to increase the spawning stock and the number of eggs spawned annually.

Case study on rivers in NE-Iceland show that the after catch and release commenced the juvenile densities has increased (Figure 4) (Bardarson *et al.* 2017). The smolt production has increased and helped to keep the number of migrating adult fish although the ocean mortality of salmon has increased in general in the North Atlantic (ICES 2023).

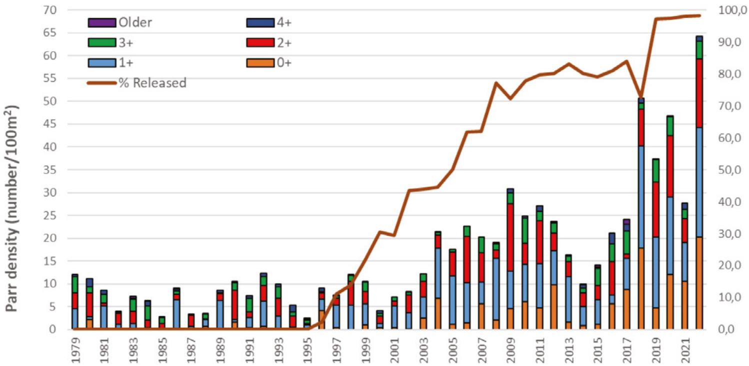

Figure 4. *The proportion of catch and release and densities of juvenile salmon in river Selá in NE Iceland.*

Ice-free winters – higher predation pressure

Warmer winters has led to longer ice-free periods of rivers in Iceland. This opens for predation on salmon juveniles. In river predation, especially during the smolt run, is likely to be a bigger problem than previously anticipated. MRFI has installed three, pit-tag antennas, in the ICES index river Vesturdalsá, in NE-Iceland to investigate parr migrations and mortality during the smolt run. For the past three years the smolt mortality has on a five km at the lower part of the river has been from 44 % and 65 % (Bardarson *et al.* 2023). In river mortality has also been seen in other rivers (Flávio *et al.* 2020). The study in river Vesturdalsá will continue in the coming years for further estimation of in-river mortality and for further understanding of the reason for the mortality.

Less snow fall during winter can also result in less river runoff during vulnerable periods in the life cycle of salmons such as during the smolt runs and it can even end with a severe drought in smaller rivers. This was for example the case in many of the salmon rivers in West Iceland with some experiencing severe drought that have been linked to worse recruitment than was expected based on the size of the spawning cohorts in the rivers (Gudmundsdottir *et al.* 2023.).

The **management action** taken by the river fishery association in river Vesturdalsá and other rivers in the area is to overwatch the rivers especially during the smolt run and scare away bird predators and to minimize the abundance of the invasive American mink (*Mustela vision*) which is an introduced alien species in the Icelandic environment.

Pink salmon

The first pink salmon was caught in Iceland in 1960. Since then, pink salmon have been periodically reported in the catch and almost exclusively males. The males have distinctive humpback, and it is likely that the female pink salmon has been mis-identified as sea-run Arctic charr. From 2015 the number of pink salmon caught in Icelandic rivers has been increasing and they are now being reported in many Icelandic rivers. Furthermore, pink salmon smolts have been caught indicating successive spawning and reproduction (Skóra *et al.* 2023). The impacts of pink salmon on the ecology of Icelandic salmon rivers are still not known. It is likely that the sudden increase in number and distribution of pink salmon may be related to climate change (Irvine and Fukuwaka 2011). It is also a burning question why pink salmon is doing well in the North Atlantic at the same time the Atlantic salmon is struggling as the two species reside in the same marine area and utilising to large extent the same food items.

Local fishery associations are willing to remove pink salmon from their rivers and by that delay the colonisation of pink salmon in their rivers.

A **management action** has been taken by the Ministry of Food, Agriculture and Fisheries to give the fishing associations permits for fishing pink salmon in rivers with seines and nets, equipment that otherwise would be illegal to use. A proposed change to the Salmon, trout and charr fishing act is now going through parliamentary procedure in the Icelandic parliament. It is regarded likely that necessary changes to the act will be agreed and in place before the fishing season.

In summary

The question asked by NASCO regarding management actions undertaken to mitigate the negative impacts of climate change was a wakeup call for the parties involved in research and management of Atlantic salmon in Iceland. Partly, this is because climate related changes, in relation to salmon stocks, is currently not having affects that are considered substantial. Although warmer climate can be welcomed by people living in cold northern countries, climate change can have negative impacts on the environment including harvested fish stocks. Seeing the negative effects that warmer climate is having on salmon populations across the North Atlantic, especially in the southern part, it is of high importance for Iceland to closely follow lessons learnt in other countries. The invite to take part in the discussions on the topic within the NASCO community is therefore welcomed. Furthermore, we surely hope that the political decision taken by the minister of Food, Agriculture and Fisheries to rejoin NASCO will be a good step for salmon research and sustainable management of the country's valuable salmon resources.

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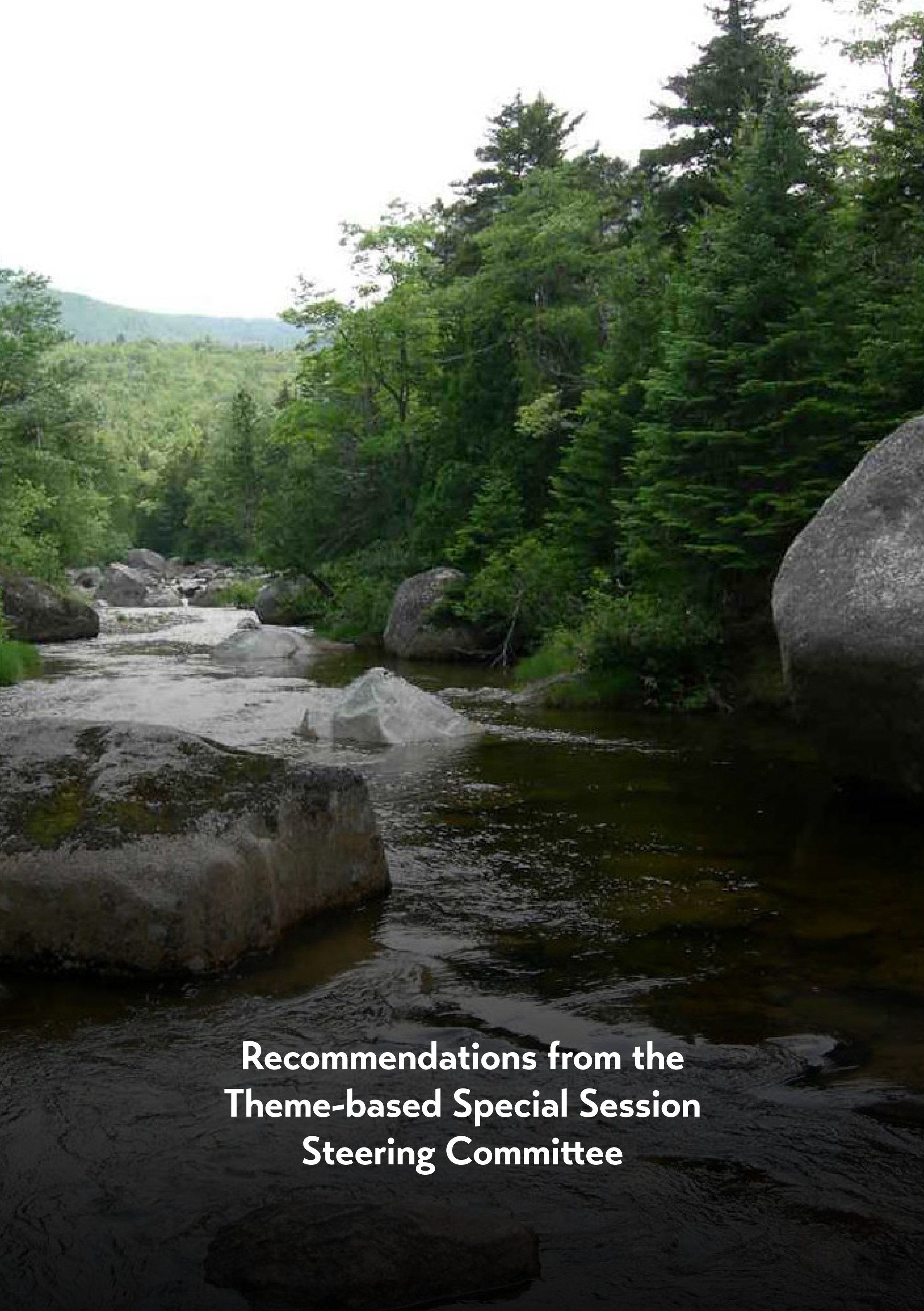
Conclusions of the Steering Committee on the session 'Overview of adaptive management actions undertaken by Parties / jurisdictions and invited countries to mitigate the negative impacts of climate change, with an assessment of the effectiveness of these actions, and lessons learned'

Time limitations prevented a question and answer session (Q&A) for the Parties / jurisdictions and invited countries within this session. However, from the papers that were received prior to the TBSS, the Steering Committee was able to review the different climate adaptative management strategies that Parties / jurisdictions and invited countries had implemented (or plan to be implemented) to assess commonalities. This rapid review was subjective and based only from the information provided within the TBSS papers. Nevertheless, it did highlight four key areas that are already being driven forwards by the NASCO Parties / jurisdictions and invited countries.

- **Collaboration:** there is notable collaboration ongoing within the NASCO Parties / jurisdictions, to develop climate adaptative management strategies. These collaborations span different sectors, with relationships being built across agencies, the general public, industry and academia.
- **Geographic Information Systems (GIS):** the use of GIS appeared to play a central and valuable role across many climate adaptative management strategies. For example, GIS is being used to map Environmental change, Salmon habitats, Salmon vulnerability, Priority areas, Anthropogenic damage, Biodiversity and Salmon refuges
- **Evidence-based Management:** the use of research and evidence to support and tailor management approaches was seen across many of the papers. Areas of science that are being notably improved are the monitoring of climate, life cycle analysis, migrations and life stages, climate change predictions across fine scales, climate change effects on hydrology and climate indexes for rivers.
- **Practical Management Measures:** the diversity of practical management measures that have been / plan to be implemented was evident across the papers. A significant number of these measures are focused on protecting the life stages of the Atlantic salmon whilst in freshwater environments, rather than the marine environment. Often these measures offer generic benefits to fauna and flora that may be the primary drivers for change, rather than salmon.

Moving forwards, with this baseline knowledge of the climate adaptative management strategies that are / plan to be implemented across the NASCO Parties / jurisdictions, an integral next step will be to determine their effectiveness and share this knowledge, including related best practises and lessons learned, across the NASCO Parties / jurisdictions and wider countries.



Recommendations from the Theme-based Special Session Steering Committee

Photo: Rory Saunders, NOAA Fisheries Service

Recommendations from the Theme-based Special Session Steering Committee

The Steering Committee incorporated comments / feedback from Session three of the TBSS into the recommendations. The finalised recommendations to NASCO and to the Parties / jurisdictions were presented to the NASCO Council on 7th June 2023 – CNL(23)77, and are set out below.

Recommendations to NASCO

1. Recommendation to set up a Working Group for three years to co-ordinate NASCO's climate change activities. If this was accepted by Council, the Terms of Reference (Annex 1) may include, but not be limited to, the following tasks:

   a. Draft a NASCO climate change strategy and a roadmap setting out how the strategy could be implemented;

   b. Recommend where meaningful changes can be made within NASCO to manage, use and communicate the information it receives on climate change activities, and to support the Parties' / jurisdictions' abilities to mitigate the impacts of climate change on salmon productivity. For example, consider organising a regular symposium focused on climate change and, if warranted, consider developing a climate change knowledge hub within the NASCO website;

   c. Develop a NASCO resolution on climate change, aligning with those resolutions set out by other RFMOs (for example, ICCAT);

   d. Develop a Carbon Policy to ensures NASCO's carbon emissions are in line with best practices on achieving carbon neutrality (for example, the United Nations Framework Convention on Climate Change's Climate Neutral Now Initiative); and

   e. If deemed appropriate, develop a long-term plan for continuing the work of the WG into the foreseeable future and advise on the most appropriate mechanism to do so (for example, Standing Committee).

2. Recommendation that NASCO produces an overarching statement (Annex 2) highlighting the climate emergency and setting out its commitment to consider climate change impacts. NASCO may wish to include an obligation that climate change is considered systematically in all future decisions and resolutions that are developed by NASCO.

3. Council may wish to consider the incorporation of best practice related to climate change and salmon management into NASCO's relevant Resolutions, Agreements and Guidelines when reviewed and revisited.

4. Recommendation that NASCO recognises the climate change research that is ongoing across the Parties / jurisdictions that can inform drivers of Atlantic Salmon mortality. NASCO may wish to look for opportunities to facilitate funding and increase international scientific collaboration both through the Parties / jurisdictions and the International Atlantic Salmon Research Board.

Recommendation to Parties / jurisdictions

1. Recommendation that Parties / jurisdictions consider taking a strategic multidisciplinary approach when developing and implementing their climate adaptive management measures. All reasonable opportunities should be taken to incorporate wider stakeholder views into decision making, including where appropriate, collaboration with other agencies, Non-Governmental Organizations and all relevant stakeholders.
2. Recommendation that Parties / jurisdictions consider undergoing an aligned exercise to assess which stressors to wild Atlantic salmon would be the most relevant for the Parties / jurisdictions. For example, using the Norwegian ranking stressor assessment across all Parties / jurisdictions. This would inform the Parties / jurisdictions which stressors are most impactful on their salmon stocks and are likely to increase with climate change, as well as where climate change ranks within the range of stressors experienced by salmon populations.
3. Recommendation that Parties / jurisdictions consider incorporating the below identified best practices, as reported on in the TBSS papers, as part of their climate adaptive management strategy:
   a. Increase access to and implement protection of thermal refuges to mitigate effects of increases in water temperatures in salmon rivers;
   b. Restore and maintain connectivity when it is compromised by climate change related effects. For example, river flows, estuarine thermal barriers, renewable energy infrastructures;
   c. Develop a strategically designed, quality controlled national river temperature monitoring network;
   d. Develop 'warm water protocols' for recreational fishing to minimize the negative impacts of catch and release on recreationally caught salmon;
   e. Management strategies that seek to improve the climate resilience of rivers with consideration for nature-based solutions[13];
   f. Ensure that genetic and phenotypic diversity of all salmon populations is maintained to optimize their adaptive capacity;

[13] Nature-based Solutions are actions to protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously benefiting people and nature.

   g. Maintain existing and, where appropriate, initiate new long-term population monitoring programs (e.g. life stage abundance and distribution, life history traits, harvest, origin) to provide critical data needed to evaluate population dynamics in the face of a changing climate; and
   h. Identify actual or potential invasive biota and pathogens presenting risk to wild salmon, whose occurrence may be increased by climate change; develop and apply remedial measures.

4. Recommendation that Parties / jurisdictions consider identifying knowledge gaps through implementing the above recommendations, and through other means, that are preventing effective management actions to mitigate the impacts of climate change. These knowledge gaps could be collectively reviewed to assess if NASCO can facilitate the information sharing needed, or if a request for scientific advice from NASCO to ICES would be needed.
5. Recommendation that Parties / jurisdictions implement management to reduce anthropogenic stressors on salmon populations.

Discussion on recommendations

Feedback on the recommendations provided during the Q&A in Session Three did not result in any major changes or additions to the recommendations. The inclusion of the wording 'climate emergency' was incorporated into the NASCO recommendation 2 to highlight the state of urgency we are in. For the recommendations to Parties / jurisdictions, additional best practice actions were incorporated to emphasise the need to continue and initiate long-term monitoring programmes, to protect the genetic diversity of stocks, and to consider the application of nature-based solutions as appropriate. Details of the Q&A held during Session Three are set out below.

Question and Answer Session on the Recommendations to Council from the Steering Committee

Specific Questions to Speaker Tim Sheehan on the Steering Committee's Recommendations for NASCO:

Niall Greene (Salmon Watch Ireland): Niall Greene, Salmon Watch, Ireland. I'd like to start by going back to the summations. The summations for the first session, and I don't mean this in a disparaging way, but they could have been written before the session took place. What struck me most about the first session was the more granular detail that began to emerge about the nature and the effects of climate change such as smaller smolts, less productive capacity from adults and the effect on feed stock, etc.

I suppose it boils down to what one sees the summation being used for. And in my case, I would have hoped to use it as part of the briefing for my Board on what transpired in NASCO. They know all that in that summation already. So, I do think it lacks some granular detail that could give a bit more drama.

On the second list of summations, the first heading is collaboration, if I remember correctly. I think it was Canada that referred to the need for a whole government approach, and either stated, as in the case of Ireland or implied in some of the other contributions, there was a suggestion that maybe a whole government approach is not so easily achieved. So, collaboration is not all about clapping and commending the collaboration that's taking place. It's also noting that in some areas, there's a lack of collaboration.

On that summation as well, I did think that the issue buried down in the middle of the last paragraph about public opinion and informing us, is a major issue. That is a big political issue for those of us involved in salmon conservation, and it needs to be elevated.

Finally, the subject that I was invited to comment on which is the recommendations to NASCO. I've only one comment on that, and it probably reflects the frustration that an awful lot of people feel with the IP / APR process. Some rejigging of the template for the IPs should include climate change. It can be included and is included in some of the IPs and in the APRs under habitats and other things, but it's a wider issue than that. I think that deserves to be dealt with in the recommendations.

Livia Goodbrand (Canada): My first question was actually the same as the last gentleman's. I was curious whether or not the Working Group considered the addition of a climate change metric on the IP / APR process. So, noted.

Secondly, this is a question more for the Secretariat, but I'm curious to know how this work is being considered in the context of the larger strategic planning exercise that’s under way. So, how will this, or will this flow into that larger exercise? Thank you.

Emma Hatfield (Secretary): you'll just have to wait and see until tomorrow.

Michael Millane (European Union): Recommendation 3. As far as I'm aware, there's no direct reference to climate change in the NASCO guidelines. Is that correct? So, there's great scope to include them in the Habitat Guidelines and things like that. I think that’s important to look at. I don’t know the mechanism for that. Do they get revised, or does it need its own separate guideline on climate change? But it does cover many different areas as we saw today. Thanks.

Tim Sheehan (USA): We did have a lot of discussion about that, and we were very keen to not come up with recommendations that would need to go and change everything. Because changing everything wasn’t actually going to change anything. So, one of the potential recommendations that was discussed was having a dedicated group to consider climate change within NASCO. We went so far as suggesting potential membership, how long it could go on for and some tasks. Such a group could give it a lot more thought and be a lot more prescriptive and, hopefully, have a lot more benefit coming out of it.

But the idea was, instead of changing a directive that isn't in the current conversation, let’s focus on the things that are in the current conversation. I think what you're saying is that there aren't clear guidelines. Climate change is not mentioned in a lot of these agreements and resolutions and guidelines. When they were written, we were woefully ignorant about what was going on. We're less so now. So, the idea was we could probably view those guidelines with a very different lens and maybe write them a little differently.

Kim Blankenbeker (USA): hi. This is Kim Blankenbeker from the US National Marine Fisheries Service, International Office. Can you describe a little more or explain a little bit, how Recommendation 1C is different from Recommendation 2. 1C is developing a NASCO resolution on climate change aligning with those resolutions set up by other RFMOs. And here's your problem, you mentioned ICCAT, and that’s a bad thing to do when I'm in the room. Number 2 was a recommendation that ICCAT produce an overarching statement setting out a commitment to consider climate change impacts etc. In fact, ICCAT's measure, kind of did number 2, and, so, I was trying to wrap my head around exactly what the group thought the difference between 1C and Recommendation 2 is from a substantive perspective. Thanks.

Tim Sheehan (USA): We did discuss this, and my simple understanding was that the overarching statement was something relatively simple that could go out today, if we wanted to, or tomorrow, if there was agreement, where the resolution was a little more formal, a little more well thought out in terms of setting a direction and a stage as to how the Organization might operate. In my rudimentary thinking, the resolution would be more formal with longer term thinking, and the statement more an immediate response.

Alan Walker (United Kingdom): thank you. Alan Walker from the UK delegation. Very much along the same lines as Kim, I think A and E could merge because A is a draft strategy and roadmap, and E is develop the plan to implement the strategy and roadmap.

Tim Sheehan (USA): so, possibly E isn't clear enough. But E was really what was going to happen to this Working Group. We recognised that this is fairly bureaucratic, but a Working Group might not be the right instrument to go on for ten years. So, we put in, for an example, the Steering Committee. Or is there some other body that should be formed within the structure of NASCO that would be better positioned for a longer-term marathon of setting up that roadmap and deciding how it should be operating to get the process going.

So, it was fairly bureaucratic, but there could be two different vehicles that would be needed for those two different time frames and longevity of effort.

Katrine Kærgaard (Denmark (in respect of the Faroe Islands and Greenland)): thank you. Katrine Kærgaard from the government of Greenland. So, if your recommendation is that we should implement climate change into everything that we do in NASCO, what would we need a working group and a standing committee for?

Tim Sheehan (USA): one of the things that this group could do is be more focused on climate change. It would potentially prevent the need for another group to work on that guideline, another group to work on that resolution, another group to work on that other agreement. It would be more singularly focused, but a little holistic on what NASCO is doing. In some of the other recommendations we're looking at the carbon footprint of the Organization. So, you could form a carbon footprint group, or you could have this one group be a little more all-encompassing. We are very conscious about finding how climate change could be considered in our work, but trying to not have blanket efforts that are meaningless, because if it's everywhere, it's nowhere. There could be a lot of Resolutions, Guidelines or Instruments that never get touched because they don't need to be, but let's focus on where it could make a difference.

Arnaud Peyronnet (President): so, thank you, Tim. A question, one thing that is missing is the idea that we're not the only one doing this. Everybody is looking at that. I don't see anything in relation to international co-operation outside of NASCO. Trying to see if people in the Pacific are doing the same, trying to see if people dealing with all fish or other type of species are doing the same. I think there's a scope there to really co-operate.

Tim Sheehan (USA): I would agree. The Steering Committee was really engaged. We've had a lot of conversations about this, and this is a topic that we did address. So, two quick responses. I do think that this is something that the Working Group could consider. They could investigate it a little more and evaluate if the benefit from the effort is going to be worth it.

One of the things that we talked about within the Steering Committee was that many of the RFMOs are very different to NASCO, either in function, but also in the species we're working with. The diadromous nature provides some unique challenges given the different environments. So, we didn't have a conclusion that there would be large benefit for the effort that would be needed to formalise such engagement. Also, there is engagement with the other RFMOs on an annual basis. It might not be engagement under the umbrella of climate change, but considering that climate change is going on, this engagement does include how they're operating, acting and how we could possibly learn from that.

We didn't put it as a recommendation because the Working Group thought it wasn't on their Terms of Reference. But that's certainly an idea that we talked about and would be worth exploring more.

Specific Questions to Speaker Tim Sheehan on the Steering Committee's Recommendations for Parties / jurisdictions:

Alan Walker (United Kingdom): thanks, Tim and everyone. Alan Walker from the UK again. There was one thing that I think was missing there – the importance of protecting the genetic diversity within a stock as the primary means of protecting the resilience of that stock to climate change. I don't think I saw that there, but I think it's an important point to include somewhere.

Tim Sheehan (USA): yes, I would wholly agree, Alan, and I thought that a few times during the presentations. I brought up the idea of protecting the phenotypic variation, which is generated through the genetic variation. You want that variation to be there to allow the population the greatest ability to evolve with changing environmental conditions. Yes, I wholly agree. Thanks.

Bénédicte Valadou (European Union): Maybe we can introduce a theme nature-based solution in the recommendations because to me that's very important. And it's less difficult than to do some other actions. Thank you.

Michael Millane (European Union): I want to reiterate the importance of long-term data gathering exercises to recommend to the Parties, that would be very valuable. Thanks.

Alan Walker (United Kingdom): I want to add to what Mick just said there. It's important to reflect that a long-term dataset has to start with the first datapoint. Therefore, it shouldn't be seen as an excuse not to do something, because we haven't got the data for the last 20 or 30 years. If we have to start the data today, or we have to start the data tomorrow, and then collect it and manage it in a way that it becomes a long-term dataset, that's important. So, fully supporting Mick, but it doesn't mean that we can only use stuff that's been there for a long time. Thank you.

Gemma Cripps (Chair of the TBSS Steering Committee): this draws the Theme-based Special Session to a close. We would like to take this opportunity to thank the Speakers in Session One for providing a very thorough and informative overview of the impacts of climate change to salmon productivity. We would also like to thank the Parties and the jurisdictions, as well as the invited countries, who presented in Session Two – setting out the existing and planned climate adaptive management measures to support and sustain wild Atlantic salmon. We would also like to thank yourselves in the room and those online for providing feedback so that we can take that into consideration when we amend our recommendations this evening.

We want to say a big thank you to NASCO for giving us this opportunity as the Steering Committee; we have really enjoyed working together over this last year to develop the TBSS and the relevant, tangible recommendations and we very much hope this proves useful to yourself. Thanks to Emma who has been very integral to the development of the TBSS and provided some very helpful steers along the way. I'd also like to give a thank you to Simon and his team who have been extremely helpful, very calm and have provided a lot of help during the session today.

In terms of next steps, the Steering Committee will be taking into consideration the feedback you have provided and will be meeting tonight to amend the recommendations.

Thank you very much everybody.

Annex 1

Draft Terms of Reference for a Working Group on Climate Change and Salmon

Purpose

The purpose of the paper is to provide Draft Terms of Reference (ToRs) for the Working Group to develop and co-ordinate NASCO's climate change related activities.

Decision

The Council may wish to:

- consider and agree to the Draft Terms of Reference;
- ask the Parties to nominate members of the Group as appropriate; and
- ask that the Secretary facilitate the work of the Group as required.

Background

In 2021 the Council of NASCO agreed that a TBSS would be held in 2023 on the overarching theme of climate change. It agreed that:

> *'A Steering Committee would be established to consider the appropriate structure to ensure that tangible recommendations from the TBSS would be available to NASCO', CNL(21)62 (paragraph 5.20).*

As a result, a Steering Committee (SC) was formed in 2022, which developed and organized a Theme-Based Special Session (TBSS) for the 2023 Annual Meeting entitled 'Informing a Strategic Approach to Address the Impacts of Climate Change on Wild Atlantic Salmon' CNL(23)19). The objective of the TBSS was to exchange information on the current and future impacts of climate change on salmon productivity in the North Atlantic and on management measures being implemented by NASCO Parties / jurisdictions, to identify best practices and inform the development of a strategic approach by NASCO. The TBSS Final Report has provided a number of tangible recommendations to NASCO and to Parties / jurisdictions on tangible actions that could be taken to help mitigate the challenges of managing Atlantic salmon under climate change.

The first tangible recommendation provided by the Steering Committee to NASCO was to set up a Working Group (WG) for 3 years to co-ordinate NASCO's climate change activities. The recommendation outlined a number of tasks that the WG should consider undertaking and these tasks have been included in the expanded Draft Terms of Reference (ToRs) below.

Draft ToRs for the Working Group to Develop and Co-ordinate NASCO's Climate Change Related Activities

The Working Group will:

- draft a NASCO climate change strategy and a roadmap setting out how the strategy could be implemented;
- recommend where meaningful changes can be made within NASCO to manage, use and communicate the information it receives on climate change activities, and to support the Parties' / jurisdictions' abilities to mitigate the impacts of climate change on salmon productivity. For example, update Resolutions, Agreements and Guidelines with climate implications when appropriate, consider organizing a regular symposium focused on climate change and, if warranted, consider developing a climate change knowledge hub within the NASCO website;
- develop a NASCO resolution on climate change, aligning with those resolutions set out by other RFMOs (e.g. ICCAT);
- develop a Carbon Policy to ensures NASCO's carbon emissions are in line with best practices on achieving carbon neutrality (e.g. the United Nations Framework Convention on Climate Change's Climate Neutral Now Initiative); and
- if deemed appropriate, develop a long-term strategic plan for continuing the work of the WG into the foreseeable future and advise on the most appropriate mechanism to do so (e.g. Standing Committee).

Membership

- NASCO Secretary
- one representative from each of the Parties;
  - Canada, Denmark (in respect of the Faroe Islands and Greenland), European Union, Norway, Russian Federation, United Kingdom and the United States of America;
    - if the membership of NASCO changes during the time this Working Group is active, a representative may be removed or added as appropriate;
- one representative from the NGOs;
- one representative from the Finance and Administration Committee (FAC);
- one representative from the International Atlantic Salmon Research Board (Board); and
- one representative from the Implementation Plan (IP) / Annual Progress Report (APR) Review Group.

Work Schedule

The WG will co-ordinate a series of inter-sessional meetings to conduct its work. The meeting(s) may be in-person or virtual as decided by the Chair (to be determined later) in consultation with the Secretariat. The WG's work will be supported by the NASCO Secretariat.

The WG will report to the Council on progress of their work during the 2024, 2025 and 2026 Annual Meetings as appropriate. The WG will provide a written report with an overview of the previous year's work, a summary of topics considered and discussed, conclusions reach and recommended actions for consideration by the Council.

Annex 2

Theme-based Special Session Steering Committee's Draft Statement for NASCO on Climate Change

Statement from the North Atlantic Salmon Conservation Organization on the Continuing Threat of Climate Change

Climate change is an omnipresent and increasing influence, which is altering the productivity of Atlantic salmon across its entire North Atlantic range through a variety of indirect and direct mechanisms. Atlantic salmon are uniquely challenged by climate change given the species reliance on both freshwater and marine ecosystems and the wide and varied impacts being felt within these two environments. In many areas, the greatest threat to the continued existence of Atlantic salmon is climate change. As an international leader in Atlantic salmon conservation and management, NASCO will support efforts designed to mitigate the impacts of climate change by facilitating domestic and international management efforts through increased communication and collaborations across all Parties, as appropriate. In its unique role in the conservation, restoration and enhancement of wild Atlantic salmon populations across the species range, NASCO is fully committed to work with and support its Parties towards the rational management of the species by taking into account the best available scientific information. While the impact of climate change on Atlantic salmon productivity across the species range may seem intractable, NASCO pledges to remain active, vigilant and consistent in supporting the mitigation of this threat through its work.

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