Anthropogenic stressors interacting with climate change

Torbjørn Forseth, Norwegian Institute for Nature Research

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 assess 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.

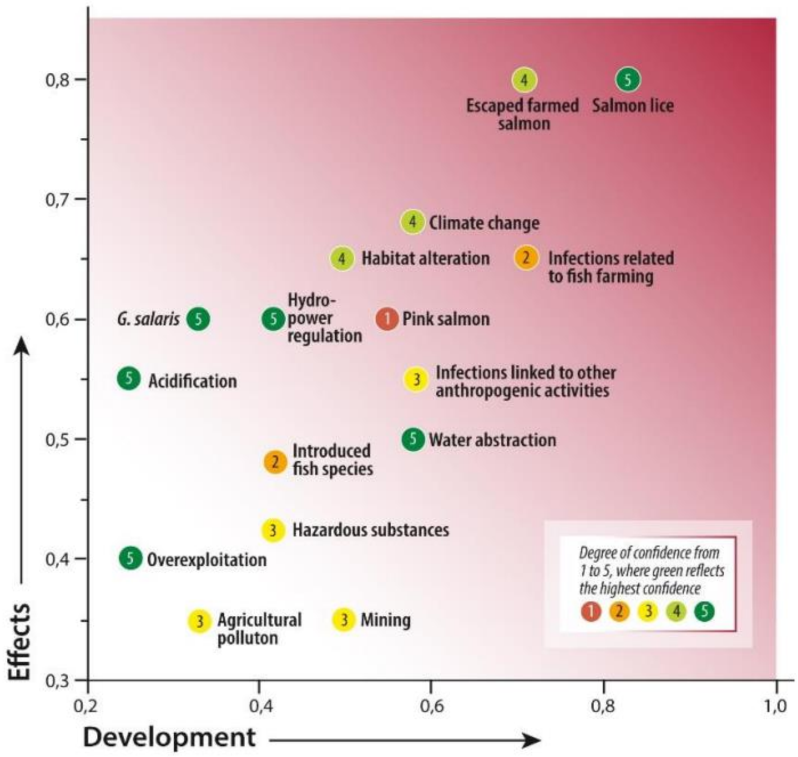

Figure 1. *Ranking of 16 stressors considered in 2021, according to their effects on wild Atlantic salmon stocks, and the likelihood of a further negative development. Confidence for the assessment of effect by each stressor is indicated by the colour of the markers, where green indicates the highest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

[1] The reference Lennox *et al*. 2021 has been added to the References section.

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 was 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 & 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 & 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 in 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 causes 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 (Sandlund *et al.* 2021) 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 & 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) reduce or restricted access to higher altitude tributaries and thermal refugia may become increasingly important for salmon (Dugsdale *et al.* 2016, Wilburn *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 & 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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