	Council *Proposal for the Production of a Systematic Review of the Effect of Salmon Aquaculture on Wild Atlantic Salmon Populations*	**CNL(22)07** **Agenda item: 4 a**

Proposal for the Production of a Systematic Review of the Effect of Salmon Aquaculture on Wild Atlantic Salmon Populations

Purpose

The purpose of this paper is to provide Council with information on an approach to develop a publication detailing the latest scientific knowledge on the impacts of sea lice and escaped farmed salmon on wild salmon.

Decision

The Council may wish to approve the approach laid out in the paper and the funding requested.

Introduction

NASCO held a Theme-based Special Session in May 2021 entitled '*Minimising Impacts of Salmon Farming on Wild Atlantic Salmon: Supporting Meaningful and More Rapid Progress Towards Achievement of the International Goals for Sea Lice and Containment'*. Following the 2021 Theme-based Special Session (TBSS), the Council agreed to one of the draft recommendations from the Steering Committee, CNL(21)62 (paragraph 5.10): '… to establish a Working Group to draft a NASCO report which provides the latest scientific knowledge on the impacts of sea lice and escaped farmed salmon on wild salmon.' The Parties noted that they wanted such a report to 'be scientifically robust and peer reviewed'; 'that ICES should be involved, noting that the report needs scientific credibility'; 'the report needs to be perceived as independent and scientific'; and 'representatives on the Working Group should be chosen due to their expertise'. The Secretariat was asked to work with the TBSS Steering Committee to identify experts to be invited to serve on the Working Group and to liaise with ICES.

The Secretary explored with ICES whether an ICES Working Group or Workshop could be convened to draft such a report for NASCO. However, it emerged that ICES Workshops are fully open to the public for registration and Working Groups rely on nominations from ICES member countries. As such, collecting the ideal group of experts to conduct this work via an ICES process could prove challenging to NASCO. Additionally, it was acknowledged that, to have the degree of impact that the Council wants, the output of any convened group of experts would really need to be submitted as a manuscript for consideration in a high-impact peer-reviewed scientific journal, rather than as an ICES or NASCO report in the grey literature. Therefore, in discussion with the President of NASCO and the Chair of the 2021 TBSS Steering Committee, an alternative proposed approach was developed, whereby a suitably qualified scientist could co-ordinate a small group of experts, initially to discuss their interest in the production of a manuscript for submission in a high-impact scientific journal.

Following recommendations from the members of the Steering Committee, the following scientists accepted an invitation to sit on an expert group to draft a state of knowledge paper.

Dr Ian Bradbury, DFO, Canada
Dr Damien Brady, University of Maine, USA
Dr Simon Jones, DFO, Canada
Dr Sten Karlsson, NINA, Norway
Dr Eva Thorstad, NINA, Norway
Dr Knut Wiik Vollset, NORCE, Norway
Dr Paddy Gargan, Co-ordinator

This document has been developed by the group as a proposal to the NASCO Council on how a paper can be developed which provides the latest scientific knowledge on the impacts of sea lice and escaped farmed salmon on wild salmon.

Background

Salmon aquaculture is becoming more and more important to food production and expanding across the world. At the same time, many wild salmon populations decline and approach extirpation in some areas. Over the last few decades studies on the environmental impacts of salmonid fish farming have increased dramatically with a large number focusing on the impact of salmon lice (Vollset *et al.* 2016, Johnsen *et al.* 2021) and escaped farmed salmon. Despite a myriad of well-designed and supported studies there remains a lack of clarity regarding the presence and magnitude of an effect of salmon aquaculture on wild salmon populations.

This paper proposes to apply a systematic review on the research on the two most extensively researched routes of interaction between aquaculture and wild fish, namely the impact of sea lice and escapees. The goal is to use a weight of evidence approach to explore the presence and magnitude of any impact salmon aquaculture, in this case sea lice and escapees, are having on wild populations. If the systematic review provides sufficient quantitative data the study will continue to do a meta-analysis on the effect of these factors on the populations of wild fish. The role of NASCO is to conserve, restore, enhance and rationally manage Atlantic salmon though international co-operation, taking account of all available scientific information. The approach taken in this review will provide NASCO with an up to date scientific review of the impacts of salmon aquaculture on wild salmon populations.

Motivation

The large scale of the salmon aquaculture industry has allowed the potential impact of Atlantic salmon farming on wild Atlantic salmon to be studied internationally. Atlantic salmon is the model organism for aquaculture-wildlife interaction and there is a need for a comprehensive review of the large body of scientific knowledge gained, for an improved trajectory of salmon farming in particular and for aquaculture in general. Particularly the impacts of salmon lice and escaped farmed salmon have received a lot of scrutiny and served as model systems to understand such mechanisms as pathogen spillover/spillback effects (Groner *et al.* 2016), human induced evolution (Besnier *et al.* 2014), and how genetic introgression into wild populations impacts population productivity and persistence (Bolstad *et al.* 2017, 2021, Wacker *et al.* 2021). Over the last two decades, studies on these two environmental impacts of salmonid fish farming have increased dramatically and studies that quantify effect sizes on population levels of wild salmon have been increasingly common. For example, for salmon lice, randomised control trials (Vollset *et al.* 2016) and combinations of modeling methods (Johnsen *et al.* 2021) have started to put numbers to how large the impact is on the recruitment of salmon. Similarly, effects of genetic introgression on the productivity and demography of salmon populations are emerging both from experimental, field-based empirical data (e.g., Fleming *et al.* 2000; McGinnity et. 2003), and modeling studies (Castellani *et al.* 2018). However, a thorough evaluation of the impact of these two factors, both individually and their combined impact on wild salmon populations remains lacking. From a management point of view getting a correct assessment of the actual potential risk fish farming may pose is therefore of utmost importance as many wild salmon populations across the North Atlantic decline (Lehnert *et al.* 2019).

Early review publications have described the current state of knowledge (e.g. Torrissen *et al.* 2015). However these earlier studies have not done so in a systematic or quantitative manner, emphasising different studies based on expert opinions. The current state of research on these

topics can provide ample effect size estimates of these impacts on wild fish that can describe the current state of knowledge in a quantitative way. A systematic review and meta-analysis of salmon lice and genetic introgression of fish farming may help provide such information.

Methods

Systematic Review & Meta-Analysis

The goal of this review is to systematically review all relevant literature and where there is sufficient data, a meta-analysis will be conducted to quantitatively assess the impact of salmon lice from aquaculture on wild Atlantic salmon. Systematic reviews aim to answer a specific question as precisely as possible in an unbiased way (i.e. what is the impact of [intervention/exposure] on [population]?). This method critically appraises (assesses the risk of bias for each study) and synthesises (quantitatively using meta-analysis if possible) all available evidence relevant to the question. Studies are weighted based on outcome of the critical appraisal, with less weight given to lower quality studies and more weight to higher quality studies. In addition, knowledge gaps are highlighted to provide guidance for future research.

Outputs

1. ***Systematic Review – What are the impacts of salmon lice from aquaculture on wild Atlantic salmon populations?***

Substantial research over the last decade in Norway, Scotland, and Ireland has demonstrated significant demographic impacts to wild salmon due to sea lice associated with salmon aquaculture in wild Atlantic Salmon populations (e.g. Shephard and Gargan 2017; Thorstad and Finstad 2018). The magnitude of wild population decline in years of sea lice outbreaks in salmon farms has been reported to be between 12-50% (Shephard and Gargan 2017; Thorstad and Finstad 2018). Within the literature there are examples of studies that conclude that the effects of these impacts are miniscule (Jackson *et al.* 2013) to dramatic (Shephard and Gargan 2017), giving an impression of scientific disagreement and large uncertainty. In reality, it is not unexpected that studies may produce a large heterogeneity in effect sizes given that effects may be strongly context dependent (Vollset *et al.* 2018). Here the goal will be to conduct a meta-analysis to quantitatively assess the impact of salmon lice from aquaculture on wild Atlantic salmon across studies and regions of the North Atlantic.

Examine effects and effect sizes of salmon lice on populations such as:

- on marine survival;
- on reduction in numbers of adult spawners;
- failure to meet conservation limits;
- effects on age of return of adult spawners; and
- any evidence of secondary effects of lice, or reduction in length & weight.

2. ***Synthesis Paper – What evidence exists on the impact of genetic introgression of farmed salmon escapees on wild salmon populations?***

The escape of farmed salmon has been documented everywhere salmon farming occurs and they have repeatedly been shown to interbreed with wild salmon, resulting in genetic changes to wild populations (Karlsson *et al.* 2016, Glover *et al.* 2017). The resulting offspring of escaped farmed salmon display reduced survival in comparison to wild salmon (Fleming *et al.* 1996; Fleming *et al.* 2000; McGinnity *et al.* 2003; Sylvester *et al.* 2019, Wacker *et al.* 2021) and resulting population decline has been demonstrated both experimentally and through

simulation studies (Bradbury *et al.* 2020; Castellani *et al.* 2015, 2018; Fleming *et al.* 2000; McGinnity *et al.* 2003; Skaala *et al.* 2019). In contrast to the effect of salmon lice, the effect of genetic introgression is a much broader research question as the impacts may span various life history stages differently (Bolstad *et al.* 2017, 2021). Consequently, although there are numerous studies on the effect of genetic introgression on wild fish, it may be a more difficult topic to conduct a meta-analysis on. In that case, the paper will review the large body of work evaluating the impact of escaped farmed salmon on wild salmon populations focusing on the presence of escapees in the wild, evidence for hybridisation and introgression, and the consequences for wild populations and where possible focusing on the mechanisms and magnitude of effect.

Review the effects of genetic introgression such as:

- data on number or presence of escapees in wild rivers;
- genetic estimates of introgression in the wild;
- modeling the population impacts of escapees and introgression;
- estimates of hybrid survival and reproductive success;
- experimental and modeling evidence of population response to hybridisation;
- changes in life history traits of wild salmon populations exposed to escapees;
- changes in other traits including immune response, lipid storage, gene expression, or behavior (including increased predation risk) due to hybridisation;
- the combined effect of introgression and supplementary stocking; and
- the geographic extent of impact in terms of how far escaped farmed salmon spread.

3. Comprehensive assessment on the impacts of aquaculture on Atlantic Salmon

With the above two syntheses complete, the team will have the reliable and objective evidence needed to confidently assess the overall impact of aquaculture on Atlantic salmon. It is likely that as the study develops, other experts will be invited to contribute to the paper. The study will provide NASCO with the State of Knowledge paper on the impacts of sea lice and escapes on wild salmon populations. This paper will be written by the team of experts based on the results of the two syntheses and published in a high impact journal.

Costings

It will be necessary to contract a scientist to undertake the systematic review and synthesis analysis and undertake meta-analysis before the expert group assess the findings and contribute to the paper. The scientist will also undertake the majority of report collation and writing. Costs will be in the form of contracted hours. There will also be costs associated with the expert group and co-ordination of the process.

Description	Cost Estimates (EUR)	Details
Expert meetings	10000	Costs associated with the expert group and online meetings
Search term development and literature review	10000	Costs for standard search term development (including librarian costs)
Data extraction and analysis	25000	Costs of identifying data and conducting standard meta-analysis,
Writing of manuscript	30000	Writing and co-ordinating

Publication fee (e.g. Nature/Science/Science advances	8000	Costs for publication of paper in high ranking journal
Total Estimated Cost	**83000**	

Timeframe

Month	***Task Identified***
1	***Search term development and literature review***
6	***Identifying relevant data and conducting a Meta-analysis***
12	***Report writing and liaison with other experts***
15	***Submission to high ranking journal***
18 - 20	***Publication of final scientific paper***

References

Besnier, F., Kent, M., Skern-Mauritzen, R. *et al.* 2014. Human-induced evolution caught in action: SNP-array reveals rapid amphi-atlantic spread of pesticide resistance in the salmon ecotoparasite *Lepeophtheirus salmonis*. *BMC Genomics* **15,** 937

Bolstad G. H., Hindar K., Robertsen G., Jonsson B., Sægrov H., Diserud O. H., Fiske P., Jensen A. J., Urdal K., Næsje T., Barlaup B. T., Florø-Larsen B., Lo H., Niemela E., Karlsson S. 2017. Gene flow from domesticated escapes alters the life history of wild Atlantic salmon. *Nature: Ecology & Evolution;* Volume 1.

Bolstad, G. H., Karlsson, S., Hagen, I. J., Fiske, P., Urdal, K., Sægrov, H., ... & Hindar, K. 2021. Introgression from farmed escapees affects the full life cycle of wild Atlantic salmon. Science advances, 7(52), eabj3397.

Bradbury, I. R., Burgetz, I., Coulson, M. W., Verspoor, E., Gilbey, J., Lehnert, S. J., Kess, T., Cross, T. F., Vasemägi, A., Solberg, M. F., Fleming, I. A., & McGinnity, P. 2020. Beyond hybridization: the genetic impacts of nonreproductive ecological interactions of salmon aquaculture on wild populations. Aquaculture Environment Interactions, 12, 429-445. doi:10.3354/aei00376

Castellani, M., Heino, M., Gilbey, J., Araki, H., Svasand, T., & Glover, K. A. 2015. IBSEM: An individual-based Atlantic salmon population model. *PLoS ONE*, **10**(9), e0138444

Castellani, M., Heino, M., Gilbey, J., Araki, H., Svåsand, T., & Glover, K. A. 2018. Modeling fitness changes in wild Atlantic salmon populations faced by spawning intrusion of domesticated escapees. Evolutionary Applications, 11(6), 1010-1025.

Costello, M.J. 2006. Ecology of sea lice parasitic on farmed and wild fish. Trends in Parasitology 22, 475–483.

Fleming, I. A., Jonsson, B., Gross, M. R., and Lamberg, A. 1996. An experimental study of the reproductive behaviour and success of farmed and wild Atlantic salmon (*Salmo salar*). Journal of Applied Ecology, 33: 893-905.

Fleming, I. A., Hindar, K., Mjolnerod, I. B., Jonsson, B., Balstad, T., and Lamberg, A. 2000. Lifetime success and interactions of farm salmon invading a native population. Proceedings of the Royal Society of London Series B-Biological Sciences, 267: 1517-1523.

Glover, K. A. 2014. Human-induced evolution caught in action: SNP-array reveals rapid amphi-atlantic spread of pesticide resistance in the salmon ecotoparasite *Lepeophtheirus salmonis*. BMC genomics, 15(1), 1-18.

Glover, K. A., Solberg, M. F., McGinnity, P., Hindar, K., Verspoor, E., Coulson, M. W., Svåsand, T. 2017. Half a century of genetic interaction between farmed and wild Atlan tic salmon: Status of knowledge and unanswered questions. *Fish and Fisheries*, **18**(5), 890– 927.

Groner, M. L., Rogers, L. A., Bateman, A. W., Connors, B. M., Frazer, L. N., Godwin, S. C., ... & Schlägel, U. E. 2016. Lessons from sea louse and salmon epidemiology. Philosophical Transactions of the Royal Society B: Biological Sciences, 371(1689), 20150203.

Jackson D, Cotter D, Newell J, McEvoy S, O'Donohoe P, Kane F, McDermott T, Kelly S & Drumm A. 2013. Impact of *Lepeophtheirus salmonis* infestations on migrating Atlantic salmon, *Salmo salar* L., smolts at eight locations in Ireland with an analysis of lice-induced marine mortality. Journal of Fish Diseases 36 (3), 273-281.

Johnsen, I. A., Harvey, A., Sævik, P. N., Sandvik, A. D., Ugedal, O., Adlandsvik, B., Wennevik, V., Glover, K. A., and Karlsen, Ø. 2021. Salmon lice-induced mortality of Atlantic salmon during post-smolt migration in Norway. ICES Journal of Marine Science, 78: 142–154.

Karlsson S., Diserud O. H., Fiske P. & Hindar K. 2016. Widespread genetic introgression of escaped farmed Atlantic salmon in wild salmon populations. ICES Journal of Marine Science. doi:10.1093/icesjms/fsw121.

Lehnert, S.J., Kess, T., Bentzen, P. *et al.* 2019. Genomic signatures and correlates of widespread population declines in salmon. *Nat Commun* **10,** 2996. https://doi.org/10.1038/s41467-019-10972-w

McGinnity, P., Prodohl, P., Ferguson, K., Hynes, R., O'Maoileidigh, N., Baker, N., Cotter, D., *et al.* 2003. Fitness reduction and potential extinction of wild populations of Atlantic salmon, *Salmo salar*, as a result of interactions with escaped farm salmon. Proceedings of the Royal Society of London Series B-Biological Sciences, 270: 2443-2450.

Shephard, S. and Gargan, P. 2017. "Quantifying the contribution of sea lice from aquaculture to declining annual returns in a wild Atlantic Salmon population." Aquaculture Environment Interactions **9**: 181-192.

Skaala, Ø., Besnier, F., Borgstrøm, R., Barlaup, B. T., Sørvik, A. G., Normann, E., Østebø, B. I. *et al.* 2019. An extensive common-garden study with domesticated and wild Atlantic salmon in the wild reveals impact on smolt production and shifts in fitness traits. Evolutionary Applications, 12: 1001–1016.

Taranger, G. L., Karlsen, Ø., Bannister, R. J., Glover, K. A., Husa, V., Karlsbakk, E., ... & Svåsand, T. 2015. Risk assessment of the environmental impact of Norwegian Atlantic salmon farming. *ICES Journal of Marine Science*, *72*(3), 997-1021.

Thorstad, E. B. and B. Finstad. 2018. "Impacts of salmon lice emanating from salmon farms on wild Atlantic salmon and sea trout." NINA Report **1449**: 1-22.

Torrissen, O., Jones, S., Asche, F. *et al.* 2013. Salmon lice – impact on wild salmonids and salmon aquaculture. Journal of Fish Diseases 36, 171–194.

Vollset KW, Krontveit RI, Jansen P, Finstad B *et al.* 2016. Impacts of parasites on marine survival of Atlantic salmon:a meta-analysis. Fish Fish 17: 714−730

Vollset, K.W. 2019. Parasite induced mortality is context dependent in Atlantic salmon: insights from an individual-based model. *Sci Rep* **9,** 17377.

Wacker, S., Aronsen, T., Karlsson, S., Ugedal, O., Diserud, O. H., Ulvan, E. M., Hindar, K., Næsje, T. 2021. Selection against individuals from genetic introgression of escaped farmed salmon in a natural population of Atlantic salmon. *Evolutionary Applications,* 14: 1450-1460.