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

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

Thursday 27 May 2021

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

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

Thursday 27 May 2021

Steering Committee

John Campbell (Canada)
Julie Crocker (USA)
Paddy Gargan (Chair – European Union)
Heidi Hansen (Norway)
Paul Knight (Co-Chair of NASCO's accredited NGOs)
Steve Sutton (Co-Chair of NASCO's accredited NGOs)

Edited by J. Campbell, J. Crocker, P. Gargan, H. Hansen, P. Knight, S.G. Sutton, S.L. Forero Segovia, W. Kenyon, V. Newton and E.M.C. Hatfield

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

Contents

Executive Summary

The production of farmed Atlantic salmon in the North Atlantic is now almost 2,000 times greater than the reported catch of wild salmon in the same area. Scientific evidence increasingly confirms the impact of the farmed salmon industry on wild salmon stocks. NASCO has been concerned by these impacts for decades. In 2009, therefore, NASCO and the International Salmon Farmers Association (ISFA) worked together to develop and agree 'Guidance on Best Management Practices to address impacts of sea lice and escaped farmed salmon on wild salmon stocks'. This Guidance established the following international goals:

- **100 % of farms to have effective sea lice management such that there is no increase in sea lice loads or lice-induced mortality of wild salmonids attributable to the farms; and**
- **100 % farmed fish to be retained in all production facilities.**

The aim of NASCO's Theme-based Special Sessions (TBSS) is to allow for greater exchange of information on a topic related to NASCO's agreements and guidelines. The objective for the 2021 session was to stimulate urgent action to implement further measures to protect wild salmon from the impacts of salmon farming, and to ensure demonstrable progress by Parties / jurisdictions towards achievement of the international goals for sea lice and escaped farmed salmon.

The Steering Committee of the 2021 TBSS has noted concerns within the NASCO community related to progress towards these international goals. The Steering Committee of the 2016 TBSS on aquaculture concluded that 'there is now an urgent need for all Parties / jurisdictions to adopt stronger measures if their international responsibilities are to be met which it believes is not currently the case'. Furthermore, the Steering Committee of the 2019 International Year of the Salmon Symposium recommended that 'NASCO should strengthen compliance to the agreed international goals…'. In addition, NASCO's third reporting cycle, covering the years 2019 – 2024, places greater emphasis on actions by Parties / jurisdictions toward the achievement of the international goals than in previous reporting cycles.

Examination of the current state of scientific knowledge on the impacts of salmon farming does nothing to allay these concerns. During the 2021 TBSS, Ørjan Karlsen described the effects of salmon lice on individual wild Atlantic salmon and on stock levels. These effects include growth depression, reduced condition, increased mortality of salmon during their feeding migration in the sea and lower numbers of returning 1-sea-winter salmon. Geir Bolstad concluded that wild fish which show high levels of genetic introgression from farmed fish grow faster and mature at a younger age than genetically wild fish. This supports his hypothesis that selective breeding for fast growth leads to a faster pace of life following farmed genetic introgression in wild salmon populations. He stated that the evolution towards a faster pace of life during the domestication of Atlantic salmon could have ‘dire consequences’ for wild salmon populations affected strongly by farmed genetic introgression. These consequences could include changed foraging behaviour, which probably has cascading effects in the river ecosystem, and other changes that would lead to lowered population viability.

Technological advances may provide means to protect wild salmon from the impacts of salmon farming. The paper provided by Alistair Struthers gave a preliminary assessment of salmon aquaculture technology advancement in Canada, based on a study of land-based and floating closed containment systems, offshore technologies and hybrid systems which combine both land and marine-based systems. Arve Nilsen considered the possible benefits and challenges of semi-closed cage technology. He concluded that if open net cages are replaced with semi-closed cages, the negative impact on wild salmonid populations from heavy sea lice infestations will be significantly reduced. Erik Sterud stated that land-based production (such as recirculating aquaculture systems) for the whole or part of the production cycle will be a useful tool for reducing the conflicts between farmed and wild salmon. Michael Pietrak discussed two programmes, one which incorporates sea lice resistance into a selective breeding programme and a second related to the development of lumpfish broodstock for use as cleaner fish in marine net cages. He argued that both could be important components in effective integrated pest management, but that neither were likely to be a silver bullet to managing sea lice populations on either a local or global scale. Åsa Maria Espmark highlighted the potential of semi-closed systems, where a physical barrier between the farmed fish and its environment prevents lice from entering the system and fish from escaping. She also noted that semi-closed systems used with post-smolts have the added advantage that farmed salmon are kept away from the open sea for longer.

Mark Lane, representing ISFA at the TBSS, discussed the progress made by ISFA to promote the international goals among its members and what more could be done to protect wild salmonids from the adverse impacts of salmon farming.

The Steering Committee has examined the information presented at the Theme-based Special Session, and considers that:

- **the current adherence to NASCO guidelines with regard to salmon aquaculture for the main salmon producing countries is unacceptable and wild salmon stocks continue to decline;**
- **introgression from escaped farmed salmon has caused unacceptable, detrimental genetic changes that are widespread in wild Atlantic salmon populations. New research from Norway reveals that changes in life history parameters (faster growth and younger age at maturity) is one mechanism through which introgression leads to maladaptation and reduced productivity in wild salmon populations;**

- **without significant improvements to sea lice management, there is a high likelihood of sea lice causing even further reductions to wild salmon populations given the continuing increasing trend in farmed salmon output;**
- **a great deal more commitment to wild fish conservation is required from the salmon farming industry; and**
- **there is now overwhelming evidence across the Northern Hemisphere of the adverse impact of traditional salmon farming methods on wild salmon populations.**

The Steering Committee seeks, therefore, to galvanise the pressure that NASCO can bring to bear on its member governments through their representatives in the NASCO Council through the following recommendations:

1. **Council should 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 (State of Knowledge Report on lice and escaped farmed salmon). The Secretariat should explore if this report could be a NASCO / ICES joint venture.**
2. **A NASCO statement should be issued to:**
    - **promote adoption of innovative and alternative technologies, at sea and on land, to help achieve 100 % containment of farmed fish and for 100 % of farms to have effective sea lice management such that there is no increase in sea lice loads, or lice-induced mortality attributed to the farms, for the protection of wild salmon and sea trout; and**
    - **state that any increase in sea lice loads or lice-induced mortality on wild salmon smolts or genetic introgression of salmon stocks caused by salmon farming is unacceptable when referenced as part of an Implementation Plan action and cannot be considered, under the review process, as progressing the relevant party or jurisdiction towards achieving the international goals.**
3. **A renewed request should be made from the NASCO Council that all Parties and jurisdictions with salmon farming produce SMART actions in their revised Implementation Plans for the management of lice and escapes. These actions should reflect strong and sustained progress towards meeting the goals of 100 % containment of farmed fish, and for 100 % of farms to have effective sea lice management. Monitoring of sea lice and escapes should only be a secondary activity to research or assess the effectiveness of the main action.**
4. **Parties / jurisdictions should consider adopting a policy of phasing out open net cage salmon aquaculture over a specified period or licence term and restrict any new licences to those utilising alternative technologies in order to make significant progress towards achievement of the international goals for sea lice and containment. This policy should be**

prioritised in sensitive areas such as the estuaries of NASCO Class I salmon rivers, as defined in the Williamsburg Resolution, or salmon rivers in Special Areas of Conservation and other protected areas and along salmon migration routes.

(Please note that this recommendation was made following the Theme-based Special Session. During the TBSS Steering Committee discussions to agree the conclusions and recommendations, unanimous agreement to include this text was not achieved. Therefore, the Steering Committee has opted by rule of majority to include this recommendation).

Introduction

Photo: 'Salmon post-smolt' courtesy of Terje Aamodt©Nofima

Introduction

The objective of NASCO's Theme-based Special Sessions is to allow for greater exchange of information on a topic related to NASCO's Resolutions, Agreements and Guidelines. In 2021, the focus of the Theme-based Special Session (TBSS) was on supporting meaningful and more rapid progress towards achievement of the international goals on the impacts of sea lice and escaped farmed salmon on wild salmon stocks.

Annual production of farmed salmon in the north Atlantic is currently around 1.82 million tonnes, over 2,000 times the reported catch of wild Atlantic salmon (ICES 2021). Scientific evidence increasingly confirms a range of impacts from the farmed salmon industry on wild salmon stocks. In response to growing understanding of, and increasing concerns about, the adverse impacts of salmon farming on wild stocks, NASCO has devoted considerable effort in developing recommendations designed to address these concerns.

NASCO first reviewed these impacts in 1988 (NASCO 1988) and, in 1994, ongoing concerns led to the adoption of the 'Oslo Resolution' (NASCO 1994). In 2003, the 'Resolution by the Parties to the Convention for the Conservation of Salmon in the North Atlantic Ocean to Minimise Impacts from Aquaculture, Introductions and Transfers, and Transgenics on the Wild Salmon Stocks' – referred to as the 'Williamsburg Resolution' – was adopted. This Resolution was subsequently amended in 2006 (NASCO 2006). In 2009, in response to improved scientific understanding, NASCO and the International Salmon Farmers Association (ISFA) developed and agreed guidance jointly entitled 'Guidance on Best Management Practices to address impacts of sea lice and escaped farmed salmon on wild salmon stocks' (also known as the 'BMP Guidance' (NASCO 2009)), which established the following international goals:

- 100 % of farms to have effective sea lice management such that there is no increase in sea lice loads or lice-induced mortality of wild salmonids attributable to the farms; and
- 100 % farmed fish to be retained in all production facilities.

In 2013, the Council of NASCO clarified its role in relation to aquaculture. The 'Action Plan for taking forward the recommendations of the External Performance Review and the review of the 'Next Steps' for NASCO' (NASCO 2013) states as follows:

> *'Aquaculture remains a focus area for NASCO in terms of concerns over impacts on wild Atlantic salmon. In general, NASCO has established the goal to minimise adverse impacts to wild stocks from aquaculture activities. However, it is for the Parties and jurisdictions to identify and implement appropriate measures to meet this goal. Progress will be tracked as implementation plans and annual reports are submitted'.*

Thus, monitoring progress towards this goal through Implementation Plans is central to NASCO's work in addressing impacts from salmon farming. In 2013, the Council also decided that, while it would not continue with its regular meetings of the Liaison Group with ISFA, it would retain a Council Agenda item to allow for an exchange of information with ISFA on issues concerning impacts of aquaculture on wild salmon. It remains unclear what steps ISFA has taken to promote the BMP Guidance and progress towards the international goals.

In 2016, a TBSS entitled 'Addressing impacts of salmon farming on wild Atlantic salmon: Challenges to, and developments supporting, achievement of NASCO's international goals' was held (NASCO 2016). The latest scientific evidence (as available at that time) on the impacts of aquaculture on wild salmon was considered, as were methods used to support innovation to develop alternative production techniques to promote sustainable salmon farming.

Concerns have been expressed within the NASCO community relating to the lack of progress towards achievement of the international goals. Some examples follow.

First, the Steering Committee of the 2016 TBSS on aquaculture concluded:

> *'In the Steering Committee's view, there is now an urgent need for all Parties/ jurisdictions to adopt stronger measures if their international responsibilities are to be met which it believes is not currently the case.' (p 187).*

Second, in 2019 a two-day Symposium entitled 'Managing the Atlantic Salmon in a Rapidly Changing Environment' was held. The Symposium focused on the challenges facing wild Atlantic salmon and possible responses that could help conserve the resource in a rapidly changing environment. The Symposium Steering Committee's report to Council (NASCO 2020a) contained a recommendation to address future management challenges:

> *'Given the continued impacts of domestic salmon farming on wild salmon, NASCO should strengthen compliance to the agreed International Goals of '100% farmed fish to be retained in all production facilities and, 100% of farms to have effective sea lice management such that there is no increase in sea lice loads or lice-induced mortality of wild salmonids attributable to the farms'. This is as stated in the 2009 'Guidance on Best Management Practices to Address Impacts of Sea Lice and Escaped Farmed Salmon''.*

Third, in the development of NASCO's third reporting cycle (2019 – 2024), the Council of NASCO expressed a wish to strengthen the Implementation Plan / Annual Progress Report (IP / APR) process. The guidelines for the third reporting cycle (NASCO 2018) therefore include a greater emphasis on actions by Parties / jurisdictions working toward the achievement of the international goals for sea lice and containment by the end of the reporting period. To this end, mandatory actions were introduced, which stipulate that where Parties or jurisdictions have salmon farms, the Implementation Plans must contain at least one action related to the international goal for sea lice and at least one action related to the international goal for containment. During its reviews of the IPs submitted under the third reporting cycle, the IP / APR Review Group has expressed concern at the failure by some Parties / jurisdictions to adopt actions in line with the international goals, specifically aimed at protecting wild salmonids. NASCO's accredited NGOs have also expressed concern about Parties' and jurisdictions' lack of commitment to the agreed international goals during the reviews of the Implementation Plans submitted under the third reporting cycle. All Implementations Plans and Annual Progress Reports, along with their reviews, are available at the url: www.nasco.int/conservation/third-reporting-cycle-2.

Given that each year the knowledge base on the interaction between wild and farmed salmon grows, it was noted in Council in 2020 that an examination of the new knowledge gained in this area since the 2016 TBSS on aquaculture would be welcome. Council, therefore, agreed to hold a TBSS in 2021 on aquaculture, adding an extra day to the schedule of meetings to facilitate this (NASCO 2020b).

The overarching objective for the 2021 TBSS was to stimulate urgent action to implement further measures to protect wild salmon from the impacts of salmon farming, and to ensure demonstrable progress by Parties / jurisdictions towards achievement of the international goals for sea lice and escaped farmed salmon, taking into account the recommendations from the Steering Committees of the 2016 Theme-based Special Session (NASCO 2016) and the 2019 IYS Symposium (NASCO 2020a).

This TBSS was developed around invited speakers each presenting in their area of expertise, to enable an update of the current state of scientific knowledge of the adverse impacts of escaped farmed salmon and sea lice on wild Atlantic salmon. The TBSS also considered advances in best management practices and new technologies in salmon aquaculture, their efficacy in mitigating adverse impacts on wild Atlantic salmon and challenges to their urgent implementation. How to incentivise industry to move towards implementing these new technologies and how Parties / jurisdictions can move more rapidly towards the achievement of the international goals were also explored. In addition, the extent to which NASCO Parties / jurisdictions are meeting the international goals for sea lice and escaped farmed salmon was reviewed critically.

This report contains the papers or presentations submitted by the experts invited to speak at the TBSS, a summary of the discussions held during the TBSS and the conclusions and recommendations drawn from the session by the Steering Committee. The papers have been subject to editorial revisions for inclusion in this report.

Setting the Scene

To What Extent Has There Been Demonstrable Progress Towards Achievement of the International Goals for Sea Lice and Containment?

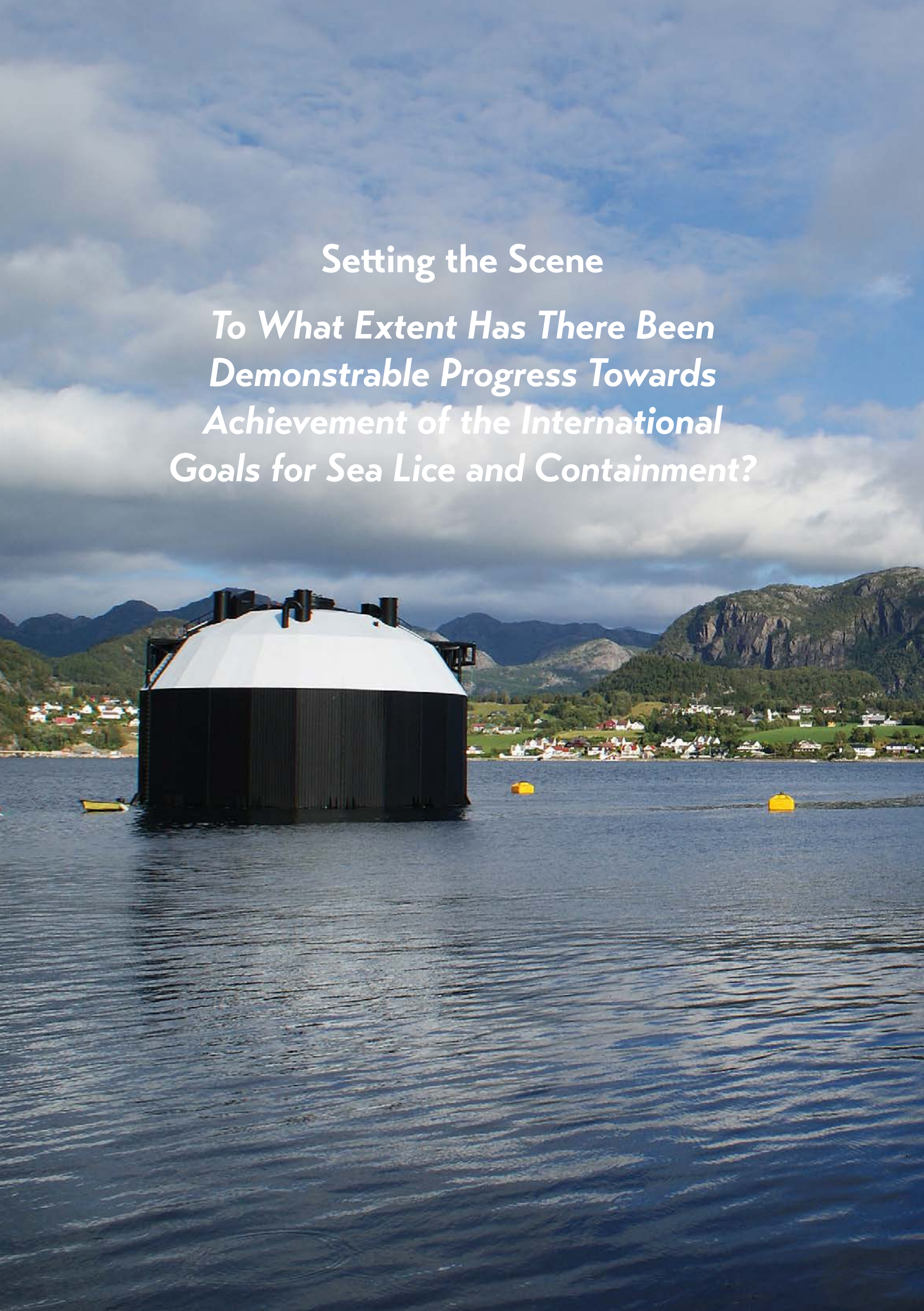


Photo: ‘FishGlobe semi-closed containment system’ ©FishGlobe

To What Extent Has There Been Demonstrable Progress Towards Achievement of the International Goals for Sea Lice and Containment

A Critical Review of Actions in the Third Cycle of Reporting (2019 - 2024)

Presentation by Cathal Gallagher, Chair of the IP / APR Review Group, to the Theme-based Special Session

IP/APR Review Group

Members:		***Co-ordinators:***
Cathal Gallagher	Europe (Chair)	Emma Hatfield
Paddy Gargan	SSC	Wendy Kenyon
Dan Kircheis	North America	
Lawrence Talks	UK	
Michael Millane	Europe	
Katrine Kærgaard	Denmark (FI&G)	
Paul Knight	NGO	
Steve Sutton	NGO	

Introduction and Background

- Entering the third cycle of reporting, the Council's intention was to further strengthen the reporting process by:
  - addressing shortcomings in previous IP / APR as in Annex 1 of the New IP Guidelines – CNL(18)49;
  - progress toward attainment of NASCO's goals can objectively be assessed over time.
- Third cycle is a much more stringent process with:
  - opportunities to demonstrate commitment to NASCO's Resolutions, Agreements and Guidelines; and
  - resources are assigned to actions.

Working Methods

Overview

- Review Group's assessments rely upon instructions for evaluation given in the 'Guidelines for the Preparation and Evaluation of NASCO Implementation Plans and for Reporting on Progress', CNL(18)49, hereinafter the '**IP Guidelines**';
- the IP Guidelines emphasise that Implementation Plans should provide a fair and equitable account of the **actions that each Party or jurisdiction plans to take to implement NASCO's Resolutions, Agreements and Guidelines**.

IP Guidelines Emphasise

Overview

- clearly identify the threats and challenges under each theme area related to NASCO's Resolutions, Agreements and Guidelines;
- include at least one action on sea lice management for those jurisdictions with salmon farms;
- include at least one action on containment of farmed salmon for those jurisdictions with salmon farms;
- including at least one action on mixed-stock fisheries for those jurisdictions that prosecute mixed-stock fisheries;
- among other things (see Section 2.1 CNL(18)49)

SMART Actions

2.8 Identify the threats to wild salmon and challenges for management associated with their exploitation in fisheries, including bycatch of salmon in fisheries targeting other species.	
Threat / challenge F1	**Relevant**
Threat / challenge F2	
Threat / challenge F3	
Threat / challenge F4	

Copy and paste lines to add further challenges which should be labelled F5, F6, etc.

2.9 What SMART actions are planned during the period covered by this Implementation Plan (2019 – 2024) to address each of the threats and challenges identified in section 2.8 to implement NASCO's Resolutions, Agreements and Guidelines and demonstrate progress towards achievement of its goals and objectives for the management of salmon fisheries?		
Action F1:	Description of action:	**Specific**
	Planned timescale (include milestones where appropriate):	**Timely**
	Expected outcome:	
	Approach for monitoring effectiveness & enforcement:	**Measureable**
	Funding secured for both action and monitoring programme?	Choose an item **Ambitious yet achievable**

Overall Process Timelines

Date/Deadline	Major Action	Progress
1 Feb 2019	Deadline for submission of Implementation Plans to the Review Group	10 plans received
28 Feb – 13 May 2019	Review concluded 1st evaluation of the IPs (see CNL(19)14)	20 plans reviewed; 1 IP Acceptable
6 June 2019	IP Review Group presentation to Council	
1 November 2019	Deadline for submission of revised Implementation Plans to NASCO	16 revised Plans submitted
18 to 22 November 2019	Meets and develops its 2nd evaluation of the revised Implementation Plans	Considerable progress by almost all Parties / jurisdictions. Still only 2 IPs acceptable
1 May 2020	Deadline for revised IP to be submitted to NASCO	No Special Session in 2020 – IPs not discussed until November 2020
1 November 2020	Deadline for revised IPs	
16 to 27 November, 4, 11, 16 & 17 December 2020	Review Group meets and develops its 3rd evaluation of the revised Implementation Plans Revised Guidance.	21 IPs reviewed (1 new IP); 12 IPs were revised from 2019. 1 IP satisfactory in all areas
1 April 2021	Deadline for submission of Annual Progress Reports to Secretariat	19 of 21 APRs

19 to 28 April 2021	APR Review Group review progress against IPs reviewed in November 2020	19 of 21 APRs reviewed
1 November 2021 / 2022 / 2023	Deadline for return of modified Implementation Plans to NASCO for review	
31 December 2021 / 2022 / 2023	Deadline for return of modified Implementation Plans to NASCO for inclusion in APR template	

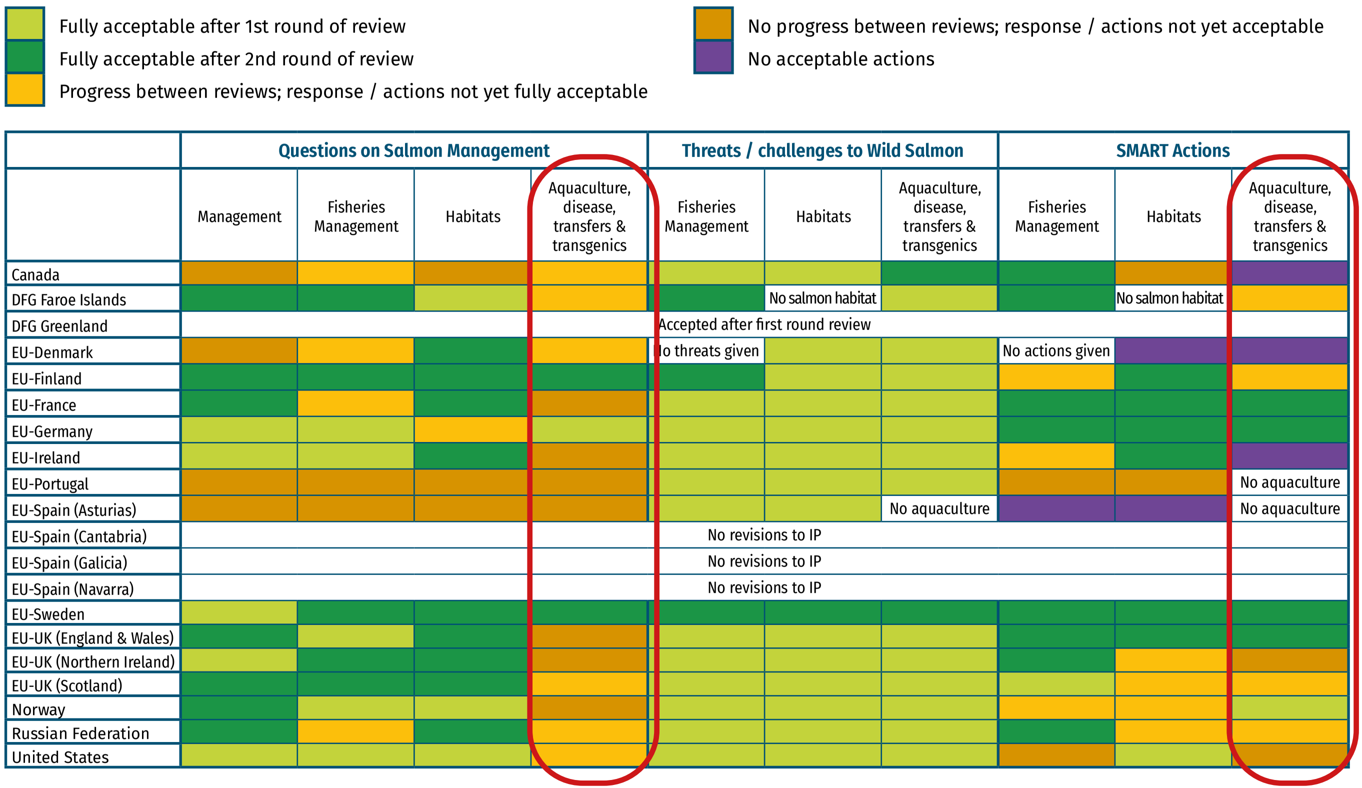
First Evaluation of IPs

- many IPs required substantial guidance from the Review Group to be brought in line with the IP Guidelines, often:
    - IP Guidelines had not been followed, especially in relation to the provision of SMART actions;
    - actions lacked clear descriptions and were combined with the expected outcome; and
    - actions were very long and difficult to interpret. In line with the IP Guidelines, the Review Group considered that SMART actions should be clear and concise.
- the Review Group developed a list of common challenges and solutions
- only one IP was deemed satisfactory

Second Evaluation of IPs

- RG assessed 16 revised IPs;
- Guidelines for the Preparation and Evaluation of NASCO IPs and for Reporting on Progress – CNL(18)49. This document stated that no Implementation Plan will be accepted until all actions are deemed satisfactory (i.e. SMART) by this Review Group;
- failure by some Parties / jurisdictions to adopt actions specifically aimed at protecting wild salmonids from the adverse impacts of aquaculture escapes and sea lice - in line with the International Goals agreed by NASCO and ISFA.

Infographic to Show the Status of the Various Sections of the Implementation Plans After Two Rounds of Review



Enhanced Guidance for Third IP Review

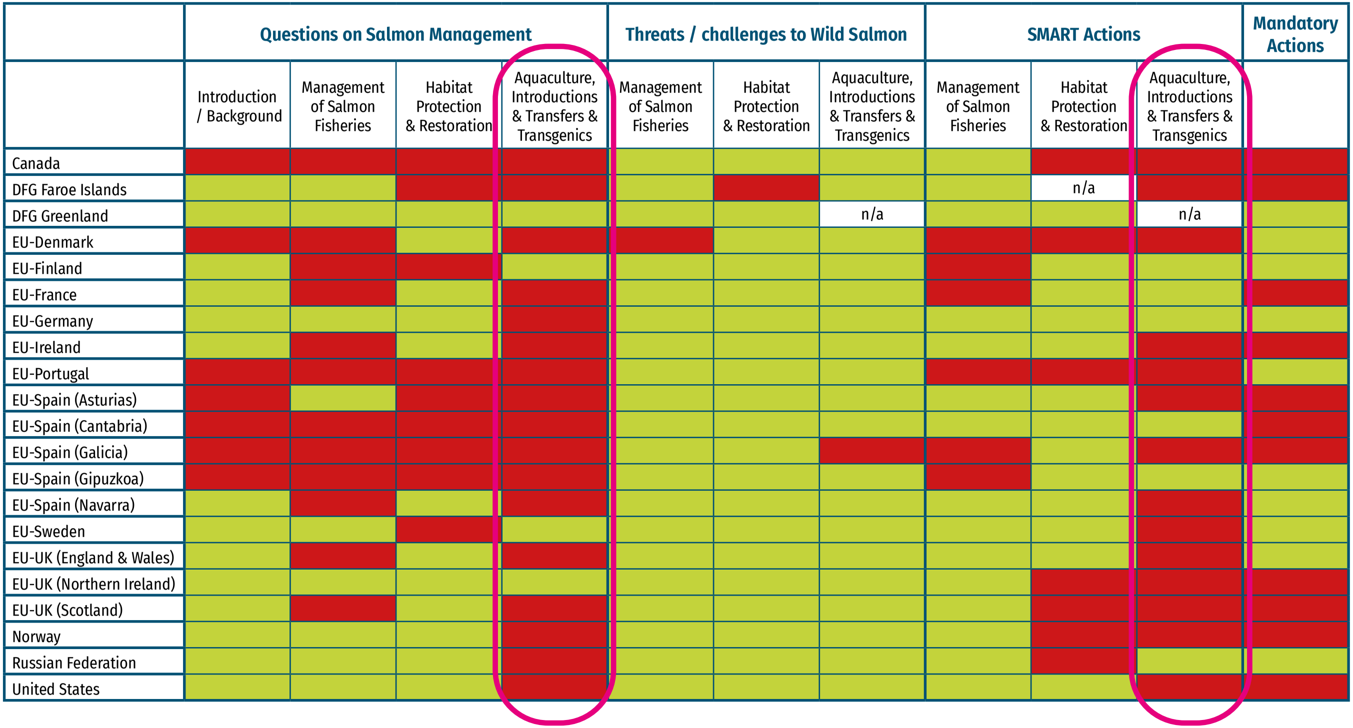
- Enhanced Guidance **CNL(20)55**:
  - there will be no overall classification of an IP as 'acceptable' or 'unacceptable'. Instead section (1), and each area of sections (2), (3) and (4), should be categorised as either 'satisfactory' or 'unsatisfactory';
  - where the Review Group considered that an action moved the Party / jurisdiction clearly towards the implementation of NASCO's Resolutions, Agreements and Guidelines even if the action was not entirely in line with the SMART criteria, the Review Group considered such an action as satisfactory; and
  - Where the action adhered to the SMART criteria, but the action was considered not to move the Party / jurisdiction towards the implementation of NASCO's Resolutions, Agreements and Guidelines, it was be deemed unsatisfactory;
- the Review Group gave a clear explanation of their assessment in their feedback and where feasible and appropriate, offered **specific suggestions / recommendations** for how it could be improved.

Overview of the Third IP Review

Infographic to Show the Status of the Various Sections of the Implementation Plans After the Third Round of Review

Section / area 'satisfactory'

Section / area 'unsatisfactory'



Impacts of sea lice and escaped farmed salmon on wild salmon stocks

	Sea Lice	Containment
	Use Williamsburg Resolution as basic guidance, supplemented as below	
Best Management Practices (BMPs)	Area management, risk-based, integrated pest management (IPM) programmes that meet jurisdictional targets for lice loads at the most vulnerable life-history stage of wild salmonids	Codes of Containment including operating protocols
	Single year-class stocking	Technical standards for equipment
	Fallowing	Verification of compliance
	Risk-based site selection	Advanced permitting to facilitate recapture and exchange of information on effectiveness of recapture efforts
	Trigger levels appropriate to effective sea lice control	Mandatory reporting of escape events and investigation of causes of loss
	Strategic timing, methods and levels of treatment to achieve the international goal and avoid lice resistance to treatment	Adaptive management in response to monitoring results to meet the goal
	A comprehensive and regulated fish health programme that includes routine sampling, monitoring and disease control	
	Lice control management programmes appropriate to the number of fish in the management area	
	Adaptive management in response to monitoring results to meet the goal	
Reporting & Tracking	Monitoring programme appropriate for the number of farmed salmon in the management area and sampling protocols effective in characterising the lice loads in the farms and wild salmonid populations.	Number of incidents of escape events and standardised descriptions of the factors giving rise to escape events
	Lice loads on wild salmonids compared to areas with no salmon farms	Number and life-stage of escaped salmon (overall number; % of farmed production)
	Lice-induced mortality of wild salmonids (e.g. as monitored using sentinel fish, fish-lift trawling, using batches of treated smolts)	Number of escaped salmon in both rivers and fisheries (overall number; % of farmed production) and relationship to reported incidents

	Monitoring to check the efficacy of lice treatments	
	Sea Lice	**Containment**
Factors Facilitating Implementation	Development of a monitoring programme appropriate for the number of farmed salmon in the management area and sampling protocols effective in characterising the lice loads in the farms	Monitoring of rivers for escaped salmon
	Access to a broad suite of therapeutants, immunostimulants and management tools	Site appropriate technology
	Collation and assessment of site selection and relocation criteria	Advanced permitting to facilitate recapture and exchange of information on effectiveness of recapture efforts
	Regulatory regimes which facilitate availability of alternative sites, as necessary, to support achievement of the goal	Technology development (e.g. cage design, counting methods for farmed salmon, methods to track origin of escaped salmon and their progeny)
	Training at all levels in support of the goal and to increase awareness of the environmental consequences of sea lice	Training at all levels in support of the goal and to increase awareness of the environmental consequences of escaped salmon
	Monitoring of lice levels: in areas with and without farms; before, during and after a farm production cycle; and in plankton samples	Assessments of the relative risks to the wild stocks from escaped salmon from freshwater compared to marine facilities and from large but infrequent escape events compared to small but frequent escape events.

Demonstrable Progress

Questions and issues found:

- National policies, based on info provided, not in line with (SLG(09)5)
- Monitoring of sea lice loads on wild salmon (SLG(09)5)
- Non demonstration of progress towards 100% effective sea lice management on farms
- Non demonstration of quantifiable progress related to specific action (containment)
- Monitoring of impact of escapes (e.g. genetic introgression) on wild salmon
- Freshwater aquaculture, non reporting (some confusion over conservation hatcheries)
- Trends in sea lice and escapes not demonstrating progress towards goals

- Non provision of information in sub-sections
- Reference to external reports/documents/links; word counts not adhered to
- Unclear as to how aquaculture facilities are located to minimise the risk to wild salmon stocks (SLG(09)5)

Good actions:

- some IPs actioned the development of new policies in line with BMP

Actions and issues found:

- Actions are just not SMART – one or more elements
- Not clear how sea lice monitoring on farms will protect wild salmon
- Not clear how new lice treatments on farms will protect wild salmon
- Some actions were more suited to qualitative reporting
- Not clear how more research on aquaculture impacts (lice and escapes) will protect wild salmon

Mandatory actions:

Mandatory action check	Is such a mandatory action required for this Party / jurisdiction? (yes / no)	Is such an action contained in the Implementation Plan? (yes / no)
Each Party / jurisdiction with salmon farming should include at least one action relating to sea lice management.		
Each Party / jurisdiction with salmon farming should include at least one action relating to containment.		

RG General Comments

- the RG request that Council consider that responses / actions in IPs that are reviewed and deemed satisfactory do not get changed over the life of the plan;
- APR reviews only to take consideration of satisfactory actions?
- cross-jurisdictional aquaculture issues need consideration
- conservation hatcheries / freshwater hatcheries be considered in the section of the IP pertaining to management of aquaculture?
- the RG has started to discuss the IP process and potential improvements.

Contributed Papers

Examining the Current State of Scientific Knowledge

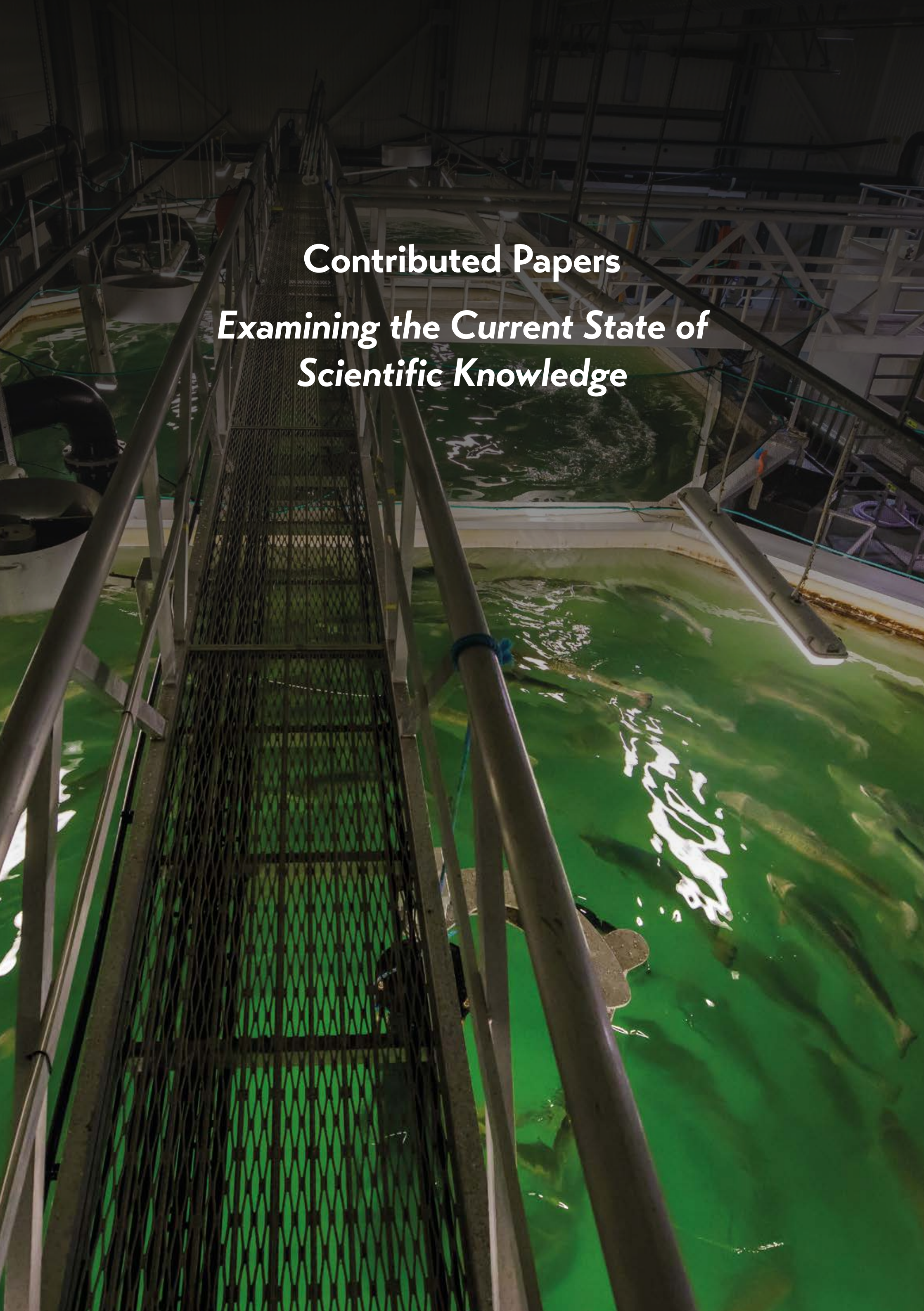


Photo: ‘Nofima Centre for Recirculation in Aquaculture’ courtesy of Terje Aamodt©Nofima

CNL(21)50

Impact of Sea Lice on Wild Atlantic Salmon

Ørjan Karlsen, Institute of Marine Research, Norway

Surveillance of Salmon Lice on Outmigrating Atlantic Salmon Post-Smolts

Three methods are used to estimate the salmon lice infestations on outmigrating Atlantic salmon in Norway; trawling using a specially designed trawl, traps adapted to catch Atlantic salmon and virtual smolt models (Kristoffersen *et al.* 2018; Johnsen *et al.* 2021) where the lice infestations are modelled. In Norway, the trawling is performed in the outer parts of fjords, usually by trawling during the day over one month each year. The start of the trawling is timed to coincide with the estimated timing of outmigration. In order to be able to determine from which river the salmon originates, salmon are assigned to home river by use of genetic tools. Consequently, lice infestation on salmon from different rivers in the fjord system being monitored may be determined. It should be noted that there are weaknesses with this method, as it assumes that there is no salmon lice related mortality (directly, or indirectly by affecting the salmon's vulnerability, e.g. to predation) before the fish reaches the trawl areas. The method also assumes that the ability to avoid the gear is unaffected by lice.

The use of specially designed traps avoids the last of the former assumptions, as this is a passive method. However, this method has shown highly variable efficiency and is at present used in only two places.

The two published models to predict salmon lice infestations on outmigrating Atlantic salmon are different. Both methods rely on the number of hatched lice released from all active salmon farms, predicted from a published formula taking into consideration the number of lice per fish, the number of fish and temperature. However, one of the models assumes a dispersion of lice decreasing in all directions from the active farms, the other uses a coupled biological-hydrodynamic model to predict the dispersion of lice. Also, the first method is calibrated (i.e. number of lice in the sea vs. infestation on fish) based on sentinel cages, while the other is calibrated against the trawl data where the fish has been assigned to a river. Finally, the assumed distribution of the timing of outmigration, migration route and migration speed are different.

The empirical trawl data and the model results do not always show the same impact. One of the reasons for this is that even though the trawling is performed in the outer parts of the fjords, the salmon still have to migrate through areas with fish farms before they reach the coast and, therefore, the empirical data will usually be underestimates. The two models shown here also give different estimates. The reasons for this are, at present, not known and are a topic of current research.

In order to predict mortality from infestations, it is assumed that if the infestation is < 0.1 lice / g fish there is no mortality, 100 % mortality if the infestation is > 0.3 lice / g fish, and 20 % and 50 % mortality if the infestation is between 0.1 – 0.2 lice / g fish or 0.2 – 0.3 lice / g fish respectively (Taranger *et al.* 2015). The smolt models assume that the fish weighs 20 g.

The Consequences of Salmon Lice on Wild Atlantic Salmon Post-Smolts

Salmon lice have the potential to negatively affect individuals and populations. The effect of salmon lice on wild Atlantic salmon depends on several factors, although none, at present, have a direct link between known infestation on wild salmon and its effect in nature.

The effects of salmon lice on individuals have been described in a series of laboratory experiments. A salmon louse feeds on its host's mucus, skin and blood. This results in increased plasma concentrations of cortisol and osmoregulatory problems and decreases the immunological capacity of the host. The damages become more severe as the lice develops from the attached to the mobile stages. Secondary effects such as reduced growth, swimming capacity and reproduction, in addition to increased mortality, have been observed (Grimnes and Jakobsen 1996). The immune system is affected (Gallardi *et al.* 2019) and lice-infected salmon appear more susceptible to viral infections (Barker *et al.* 2019). Salmon lice may affect behaviour and swimming capacity (Bui *et al.* 2016) and increase the risk of being predated (Godwin *et al.* 2015).

Assessing the effects of salmon lice on Atlantic salmon stock levels is difficult, as the number of outmigrating fish is usually unknown. To overcome this, experiments using cultivated fish protected from salmon infestations are performed. Since the duration of the protection is limited to a few weeks or months, it is assumed that survival during their seaward migration is affected by lice infestations during the first part of the migration. It is also assumed that salmon are most vulnerable shortly after they have left the rivers due to the physiological challenges with the transfer from fresh to salt water (Thorstad *et al.* 2012) and due to predation (Handeland *et al.* 1996).

The survival of salmon during their feeding migration in the sea varies between years, probably due to natural variations in the ecosystem. Norwegian data from experiments comparing fish protected from salmon lice infestations with untreated control fish has shown that the effect of the protection varies with the general survival of the groups (Vollset *et al.* 2016). In years where the general survival was high, lice protection had no statistical effect, while in years with a general low survival, the survival in the protected groups increased. Using data from releases in Daleelva in western Norway, it was calculated that lice infestations caused about 15 % mortality in the period 1997 to 2009 (Skilbrei *et al.* 2013). In a larger meta-analysis, including more data from Norway, 18 % mortality was estimated (Vollset *et al.* 2016). In nearly all years untreated smolts were found to be slightly smaller (~0.1

kg) when returning after one year in the sea, which may indicate that lice caused a growth depression even when the mortality seemed unaffected by lice. In a 26-year long time-series from the river Erriff in western Ireland, analysis indicated that after higher lice numbers in nearby farms, there were more than 50 % lower numbers of returning 1-sea-winter salmon (Shephard and Gargan 2017). In an analysis of returning salmon in Scotland and England, it was found that the condition of returning salmon was correlated to the number of lice the fish was carrying (Susdorf *et al.* 2018b) and model simulations indicated that this reduced condition could affect stock development (Susdorf *et al.* 2018a). There are obviously several differences between cultivated and wild fish, but still the results indicate that salmon lice may be an important cause of mortality for wild salmon.

Status of the Impact of Salmon Lice on Atlantic Salmon Post-Smolts in Norway

Salmon usually enter the sea during spring and salmon originating from rivers in the fjords swim through the fjords towards the open ocean. The distance and route they swim will affect their possibility of being infected. As the release of salmon lice from active salmonid farms usually increases during spring and summer due to temperature and farming practices, the later the fish leaves the fjords the higher the possibility of being infected. The actual distribution of the outmigration is highly variable and fish that leave the river early in the season are usually less likely to be infected than fish that migrate later. By using the 2017 – 2020 trawl data from the Hardangerfjord (western Norway), the estimated mortality of fish from rivers in the inner part of the fjord are higher than fish from outer rivers each year (Figure 1).

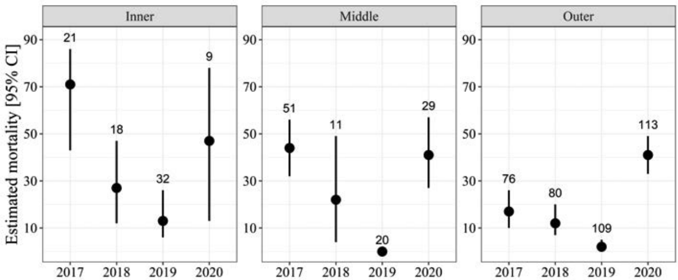


Figure 1. *Estimated mortality with confidence limits of outmigrating Atlantic salmon post-smolts caught in the outer fjord 2017 – 2020 using trawl and assigned to rivers in inner, middle or outer areas of the fjord. Numbers are shown in the figure. C.f. text for how mortality is estimated.*

Similar patterns are achieved using the virtual smolt model that the Institute of Marine Research in Norway are using (Johnsen *et al.* 2021) which combines estimated lice density with a simulated smolt migration (Figure 2). The outer rivers are less affected by lice than inner rivers.

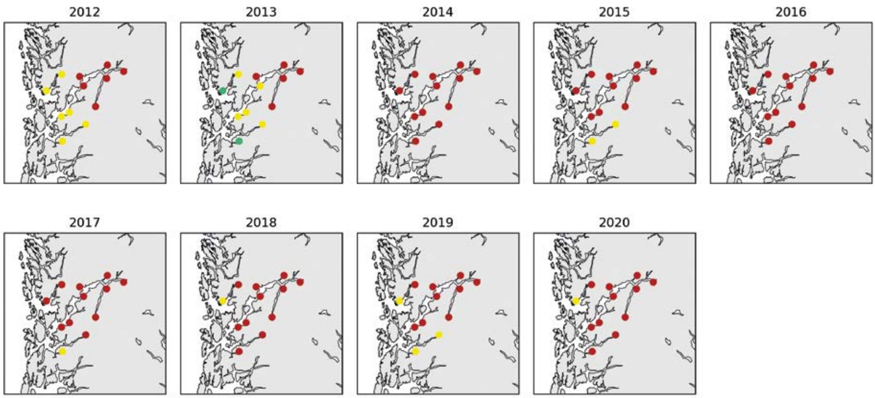


Figure 2. *Estimated mortality of outmigrating Atlantic salmon post-smolts 2012 – 2020 using a virtual smolt model. Colours indicate whether the estimates from fish from that river is <10 % (green), 10 – 30 % (yellow) or >30 % (red). C.f. Johnsen* et al. *(2021) for details about the model.*

Using these data and model results, together with other empirical data and model simulations, an expert group appointed by a steering group appointed by the Ministry of Trade, Industry and Fisheries is evaluating the effects of salmon lice separately for the 13 production areas in Norway in the nicknamed 'Traffic Light System'. The status is based on expected mortality of Atlantic salmon post-smolts.

At present, the expert group has evaluated the status yearly from 2016 – 2020 (Vollset *et al.* 2020). They conclude that the largest negative impact of salmon lice is observed in western Norway, particularly from the county of Rogaland to Møre and Romsdal. In several of these areas, the estimated mortality of outmigrating salmon post-smolts has, in one or more years, been determined to be > 30 %. It should be noted that the impact on the different rivers in each production area may vary considerably, as shown above.

The Norwegian Scientific Advisory Committee for Atlantic Salmon has used the smolt models to determine the effect of salmon lice on wild salmon populations in Norway (VRL, 2020). They conclude that salmon lice have reduced the number of returning salmon by 50,000 for the years 2012 – 2014, 29,000 in 2018 and 39,000 in 2019. The impact of salmon lice is most severe in western and middle Norway, and the advisory committee concluded that an increased number of populations are endangered by salmon lice and that there is a high risk that more populations will be endangered.

CNL(21)49

Faster Pace of Life in Wild Atlantic Salmon Following Introgression from Farmed Escapees

Geir H. Bolstad, Norwegian Institute for Nature Research (NINA), Norway

Summary

This paper outlines a talk that was held at NASCO's 2021 Annual Meeting. I argue that the effect of farmed genetic introgression on wild salmon can be better understood in light of pace-of-life theory and provide evidence that such introgression leads to a faster pace of life in the wild. From this theory, we would predict changes in suites of life-history, physiological and behavioural traits. These predictions are supported by current empirical evidence.

Introduction

Farmed Atlantic salmon *(Salmo salar)* escape from captivity and mate with their wild conspecifics, leading to high levels of farmed genetic introgression in many wild salmon populations (e.g. Karlsson *et al.* 2016; Wringe *et al.* 2018). We do know that this introgression is negative for local adaptation and therefore also fitness of wild salmon because:

1. it is theoretically improbable that the large genetic changes following selective breeding in captivity is adaptive or neutral in any wild population; and
2. we have evidence of reduced survival of genetically farmed salmon and farmed-wild hybrids in the wild environment (Fleming *et al.* 2000; McGinnity *et al.* 2003; Skaala *et al.* 2012; Skaala *et al.* 2019).

Experiments have revealed that farmed genetic introgression also leads to change in a number of other traits including growth and size, development and maturation, behaviour, plastic responses and disease susceptibility (reviewed in Glover *et al.* 2017). However, the effects of introgression have rarely been studied in wild populations (but see Bolstad *et al.* 2017).

To obtain a general understanding of the effects of farmed genetic introgression, I suggest using ecological theory on 'pace of life' and the related concept of 'pace-of-life syndromes' (POLS) (Reale *et al.* 2010). My work builds on previous attempts at getting a more general understanding through the concept of 'behavioural syndromes' (Huntingford 2004). Furthermore, I present new empirical estimates of the effect of farmed genetic introgression across 105 wild salmon populations and interpret these in light of the POLS hypothesis.

The Pace-of-Life Syndrome (POLS) Hypothesis and its Relation to Selective Breeding on Salmon

It has long been noticed that species differ systematically in their life history, from typically 'slow' (long lived and late maturing) species to 'fast' (short lived and early maturing) species (Stearns 1983; Gaillard *et al.* 1989). Evolution along the fast-slow continuum of life history has important ecological consequences, with fast species typically having higher annual fecundity and mortality and higher annual variation in these demographic rates, and therefore more fluctuating population size, compared to slow species (Sæther and Bakke 2000; Garcia *et al.* 2008; Bjørkvoll *et al.* 2012). The concept of a fast-slow continuum parallels the classic concept of *r*- and *K*-selection (MacArthur and Wilson 1967; Pianka 1970) and focus on life-history traits. The POLS hypothesis extends these concepts by recognising the close link between physiology, behaviour and life-history traits, and states that long-term selection pressures (e.g. fluctuating density-dependent selection) have integrated whole suites of traits, so that they systematically covary across the fast-slow continuum (Table 1) (Reale *et al.* 2010; Wright *et al.* 2019).

With respect to the selective breeding of salmon in aquaculture in relation to POLS, it is important to note that the main focus of the breeding programmes have been on increased growth rate (Gjedrem and Baranski 2010). From POLS theory we would then expect that genetically farmed salmon has a faster pace of life compared to wild salmon, with correlated changes in several life-history, behavioural and physiological traits (Table 1). Several other traits, such as age at maturity and disease resistance, have also been under selection (Gjedrem and Baranski 2010), in addition to selection for survival in the hatchery environment, which could lead to further evolution along the fast-slow continuum.

Table 1. *Schematic differences of slow vs. fast pace of life in life-history, behavioural and physiological traits (from Reale* et al. *2010). High growth rate is highlighted as this has been the focal trait in the selective breeding programmes of Atlantic salmon.*

Slow pace of life	Fast pace of life
Life history:	
Long life	Short life
Delayed reproduction	Precocious reproduction
Low growth rate	High growth rate
Fewer offspring of higher quality	More offspring of lower quality

Behaviour:	
Philopatry	High dispersal
High level of parental care	Low level of parental care
Low aggressiveness	High aggressiveness
Shy	Bold
Thorough exploration	Superficial explorer
Low activity	High activity
High sociability	Low sociability
Physiology:	
High HPA axis reactivity	Low HPA axis reactivity
Low sympathetic system reactivity	High sympathetic system reactivity
Low metabolism	High metabolism
Low sensitivity to oxidative stress	High sensitivity to oxidative stress
High immune response	Low immune response

The Effect of Introgression on Wild Salmon

Documenting phenotypic changes following farmed salmon introgression in wild salmon populations is difficult. Molecular markers can be used to estimate the farmed genetic relatedness of wild fish (Karlsson *et al.* 2014). However, at the individual level these estimates are imprecise due to the close relatedness between farmed and wild salmon and lead to a conservative estimate of the effect of introgression (Bolstad *et al.* 2017). Despite these challenges we have documented decreased egg size when controlling for body size (Hagen *et al.* 2019), changes in the number of years spent at sea (sea age) and increased size at maturity within sea age (Bolstad *et al.* 2017) following farmed genetic introgression. In my talk, I present a continuation of this work with a new analysis on the effect of introgression on both early and late life-history traits in wild Atlantic salmon. Here, I summarise the main points.

The new analysis is based on more than 7,000 salmon caught by anglers in 105 Norwegian salmon rivers. In addition to obtaining a scale sample, the anglers recorded mass, total length and sex. The scales were read by professional scale readers to infer freshwater age and sea age as well as back-calculated growth from the growth pattern in the scales. Genetic analysis and quantification of farmed genetic relatedness of the fish followed the method used by Bolstad *et al.* (2017). Because the escaped farmed salmon in the material was excluded based on the growth pattern in the scales, all fish included in the study were wild born but varied in their farmed genetic relatedness. All rivers in the study belonged to the Eastern Atlantic phylogenetic group (i.e. the northernmost rivers in Norway were not included) (see map in Bolstad *et al.* 2017).

The new analysis revealed that increasing farmed genetic relatedness in wild fish increased probability of smolting and migrating out to sea at age 2+, and therefore a decreased smolt age. There was no effect of introgression on size at outmigration, meaning that the body-length growth increased with increasing farmed genetic relatedness. For the later life-history traits, there was an increased probability of maturing after two sea winters (SW) for males in rivers dominated by 1SW salmon, and for females in rivers dominated by multi sea winter (MSW) salmon. For males in rivers dominated by MSW salmon and females from rivers dominated by 1SW salmon we found little effect of introgression on sea age at maturity. Combining the effect of probability of smolting and probability of maturing revealed that farmed genetic introgression reduces age at first reproduction. This was mostly due to a decreased smolt age.

Growth at sea also increased with increasing introgression. The effect of introgression on growth seemed to be largest in the first year compared to later years at sea and was particularly strong on growth during the return migration in salmon from 1SW dominated rivers.

A Faster Pace of Life Following Farmed Genetic Introgression in Wild Salmon Populations

The main conclusion of the above analysis is that wild fish with high genetic relatedness to farmed fish grow faster and mature at a younger age than genetically wild fish. This supports the prediction that selective breeding for fast growth leads to a faster pace of life following farmed genetic introgression in wild salmon populations. Our results are in general supported by the findings of the experiments of controlled releases of farmed salmon, wild salmon and their hybrid offspring in natural rivers (Fleming *et al.* 2000; McGinnity *et al.* 2003; Skaala *et al.* 2012; Skaala *et al.* 2019) and in experiments performed under hatchery conditions (Glover *et al.* 2017).

The POLS hypothesis predicts that an increased pace of life would lead to changes in suites of behavioural and physiological traits in addition to life-history traits. Experiments have shown that farmed compared to wild fish have higher levels of aggression (Einum and Fleming 1997; Fleming and Einum 1997; Houde *et al.* 2010a) more boldness in terms of shorter emergence time after exposure to an artificial predator (Einum and Fleming 1997; Fleming and Einum 1997; Houde *et al.* 2010b) and increased dispersal (Jonsson *et al.* 2003; Jonsson and Jonsson 2017), all being traits associated with the fast end of POLS. Selection for increased growth has led to a higher susceptibility to predators (Solberg *et al.* 2020), which can, at least partly, explain the observed lower juvenile survival in the wild (McGinnity *et al.* 1997; Fleming *et al.* 2000; McGinnity *et al.* 2003; Skaala *et al.* 2012; Skaala *et al.* 2019). Studies of gene transcription have shown that immune related genes are upregulated in wild compared to farmed salmon (Bicskei *et al.* 2014; Bicskei *et al.* 2016), while protein synthesis and metabolism are downregulated in wild compared to farmed salmon (Roberge *et al.* 2006; Bicskei *et al.* 2014), both supporting the POLS hypothesis. A comparison of structural genetic variation in wild and farmed Atlantic salmon have shown allele frequency changes in farmed salmon show evolution of genes underlying behavioural traits during domestication, as well as immunity and metabolism genes (Bertolotti *et al.* 2020). Taken together, the empirical evidence strongly supports our hypothesis that functional genetic differences between wild and farmed salmon can largely be explained by POLS.

The evolution towards a faster pace of life during the domestication of Atlantic salmon is not surprising because of the strong selection for faster growth. However, it could have dire consequences for the wild salmon populations strongly affected by farmed genetic introgression. We would expect changed foraging behaviour following a faster pace of life which probably has cascading effects in the river ecosystem. We would also expect demographic consequences and a more stochastic population dynamic. Increased stochasticity leads to reduced long term population growth rate (Lande *et al.* 2003) and together with increased maladaptation of life-history traits this would lead to lowered population viability.

Contributed Papers

Best Management Practices, New Technologies and Industry Implementation of New Technologies

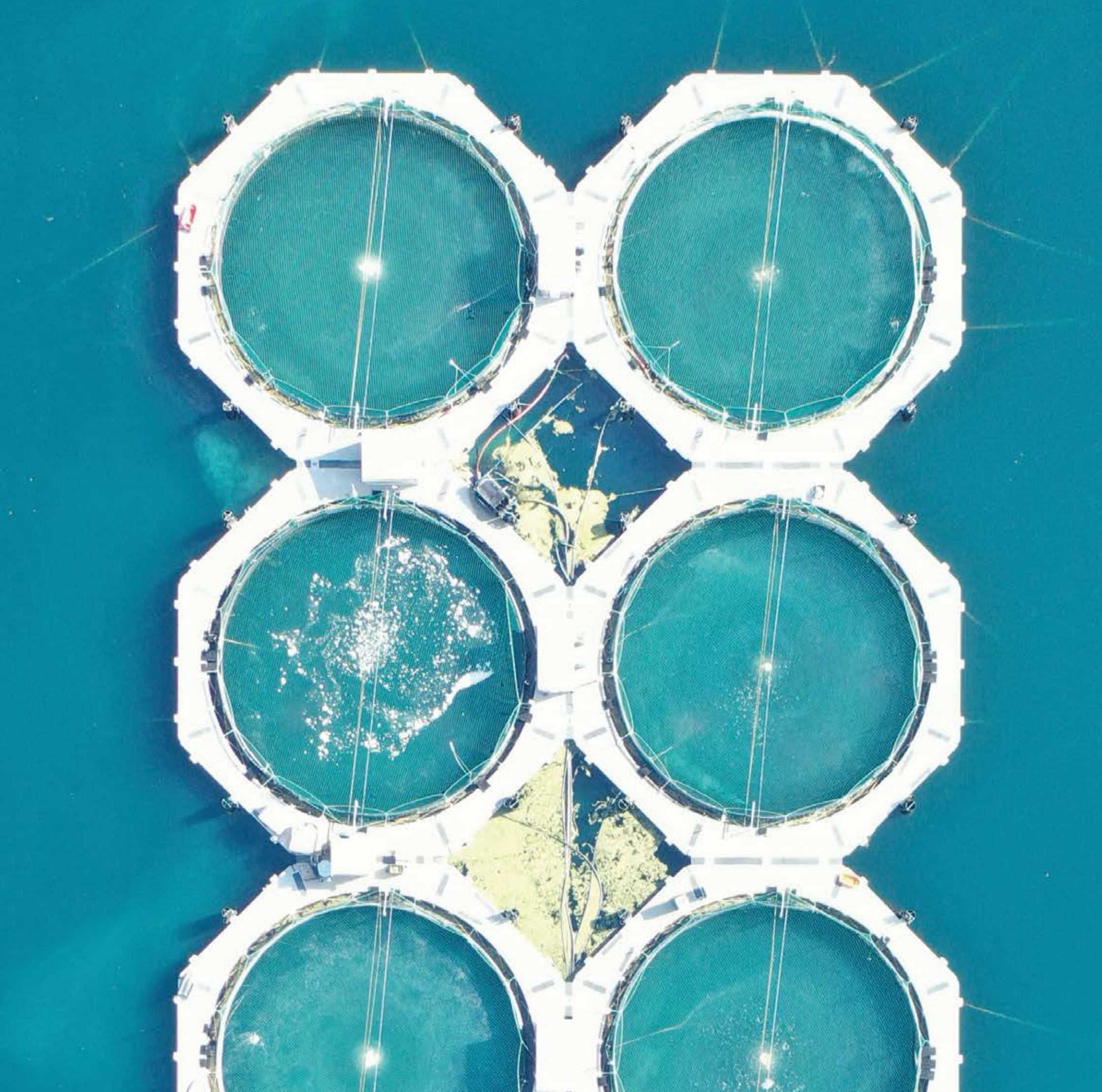


Photo: Akvafuture AS

CNL(21)52

State of Salmon Aquaculture Technologies

Alistair Struthers, Fisheries and Oceans Canada, Canada

(Paper presented by Doug Bliss, Fisheries and Oceans Canada, Canada)

In December 2018, Fisheries and Oceans Canada (DFO), in partnership with Sustainable Development Technology Canada (SDTC) and the Province of British Columbia (B.C.), commissioned and funded a study on the state of salmon aquaculture technologies to examine the risks and opportunities of the most promising emerging technologies for salmon farming in B.C. The study explored the financial, environmental and social elements of emerging aquaculture technologies and highlighted some of the ways to incent the adoption of these new technologies, including how other countries have incented adoption. The study explored four technology options: land-based closed-containment; floating closed-containment; offshore technologies; and hybrid systems which combine both land and marine-based systems. The study indicated that all four production technologies have the opportunity to reduce interactions between farmed and wild salmon compared to conventional open net pen aquaculture production, but the assessment against other environmental, economic and social elements varied.

In section 4 of the study, three tables showing the strengths, weaknesses and uncertainties for the four production technologies in relation to environmental, social and economic criteria are presented. These are reproduced below for ease of access.

The tables provide a preliminary, general assessment of these four production technologies and do not include a comparison to open net pens, the primary current production method in B.C., nor do they include the full range of aquaculture production technologies or variations on technologies being used or developed domestically and globally. Some of these technologies are at early stages and thus the tables were developed on a general understanding of how the systems are designed to operate and are not necessarily accurate predictors of how they might operate in real world settings. The State of Salmon Aquaculture Technologies report recognises that this assessment only reflects a point in time, that aquaculture technologies are developing rapidly and that information about performance and capabilities of the systems can quickly become outdated. Moreover, the impacts of each of these technologies will vary depending on various factors including their design, location and the surrounding environment.

The full study can be found at https://www.dfo-mpo.gc.ca/aquaculture/publications/ssat-ets-eng.html.

Table 5 of the State of Salmon Aquaculture Technologies Report. *Environmental strengths, weaknesses and uncertainties for the four new production technologies.*

Land RAS	Hybrid system	Floating CCS	Offshore system
Marine Escapes			
• No risk, the system is contained on land.	• No risk during land-RAS stage • Some risk at sea and during transfers, but reduced time at sea and better transfer timing is helpful	• Low risk due to solid containment, and some risk during fish transfer to/from land	• Some risk due to open containment, but built for harsh conditions • Some risk during fish transfer to/ from land • Uncertainties need more research
Wild salmon disease			
• No risk, the system is contained on land.	• No risk during land-RAS stage • Some risk at sea, but time at sea is reduced and salmon are larger and healthier	• Low risk due to solid containment, but still some risk as water filtration will not eliminate all concerns	• Some risks, but submerging capability avoids sea lice, and sites may be located away from salmon migration routes
Waste effluent			
• Waste can be composted, used in aquaponics, or to generate energy • Salt content can be a challenge	• Land-RAS waste can be composted, used in aquaponics, or to generate energy • Most waste is released to sea in grow-out, but some capture possible	• Low waste release with collection system and processing on land, but some dissolved nutrients (e.g. nitrogen, phosphorus) released	• Waste is released to sea • Location offshore in deeper high current waters will be better than inshore sites
Chemical release			
• Very low to no release outside the system • Chemicals are used for bacteria, gill diseases, and pH control	• Very low to no release from land-RAS phase • Marine phase releases chemicals to sea, but reduced use due to larger salmon	• Improved fish health will reduce chemical use, but as for waste effluent some will be released to sea	• Improved health will reduce chemical use, but released to sea • Anti-fouling agents on large metal structures are a concern, but this requires research

Wildlife interactions			
• No risk, the system is contained on land	• No risk for land-RAS phase • Some risk for marine phase, but may be improved with longer fallow periods	• Solid wall containment will eliminate risks • Mooring lines and structures may pose some risk to marine mammals	• Some risks with open containment, but integrity is expected to be very good • Mooring lines and structures may pose some risk to marine mammals • These topics require more research
Water use			
• Very low use in 99.5% recirculation systems • Use of aquifers by very large facilities is a concern	• Very low use for land-RAS phase since not used for grow-out • Marine phase only uses seawater flowing through	• The system only uses seawater flowing through, no limited freshwater resources	• The system only uses seawater flowing through, no limited freshwater resources
Energy use and GHGs			
• High energy use in system construction and operation • Grid electricity in BC has low carbon intensity • Location can minimise transport costs for feed to site and products to market	• Medium energy in grid connected land-RAS facility since not used for grow-out • Low energy use in marine phase, but petroleum products may be used for boats and feed systems • Transport to/from marine sites adds to energy use	• Medium energy use in system construction and operation • Grid electricity in BC has low carbon intensity, but some sites may not connect to grid • Transport to/from marine sites adds to energy use	• High energy use in system construction • Medium energy in operation, and petroleum products likely needed for remote operation • Transport to/from marine sites adds to energy use • Research needed on these topics

Table 6 of the State of Salmon Aquaculture Technologies Report. *Social strengths, weaknesses and uncertainties for the four new production technologies.*

Land RAS	Hybrid system	Floating CCS	Offshore system
Local support			
• Environmental strengths will earn support, but very large facilities using sensitive water resources will likely raise concerns • Economic aspects may be a concern with fewer jobs, but market access and growth potential will build support	• Environmental performance of land-RAS phase will build support, but marine phase will still be a concern • Economic performance will support local jobs, but marine concerns hampering growth may dampen local support	• Environmental performance will build support, but use of marine sites may still be a concern • Economic performance will support local jobs, while market access and growth potential will attract support	• Avoiding near-shore spatial conflicts will gain local support • Jobs will remain in coastal areas, but there may be fewer with increased automation • Growth potential will build support
Global support			
• Seafood labelling will likely support this system as a "best choice"	• Seafood labelling will likely support this system as a "good alternative" since this already applies to B.C. farmed salmon	• Seafood labelling does not cover this technology for salmon, but it should garner a "good alternative" rating or better	• Seafood labelling does not cover this technology for salmon, but it may earn a "good alternative" rating
Consumer support			
• Premium prices today are an indication of consumer support • Moves to land-RAS in key markets may mean this system is needed for access • Product quality and fish welfare may be a concern • Higher cost may be a challenge to sell into price sensitive markets	• Products will not be distinguished from conventional netpen salmon • Establishment of land-RAS in key markets may limit market access for products of this system • Product quality and cost is very good, but there may be some concerns with marine contaminants	• Products will be distinguished from those produced by open netpen systems • Product quality and fish welfare will be considered good • Higher cost may be a challenge to sell into price sensitive markets	• Products may be distinguished from those produced by near-shore open netpen systems • Product quality and fish welfare will be considered good, but there may be some concerns with marine contaminants • Research is needed to address uncertainties

Table 7 of the State of Salmon Aquaculture Technologies Report. *Economic strengths, weaknesses and uncertainties for the four new production technologies.*

Land RAS	Hybrid system	Floating CCS	Offshore system
Profitability			
• Large investments mainly by new entrants to farming are expanding this technology at large commercial scale • A couple years of commercial operations are needed to confirm profitability	• Large investments mainly by existing salmon farming companies indicate this is a profitable technology at large commercial scale	• Some investments by existing farming companies indicate this is a technology of interest at large commercial scale • A few years of commercial operations are needed to confirm profitability	• Investments mainly by new entrants to farming indicate this is a technology of interest at large commercial scale • A few years of commercial operations are needed to confirm profitability
Capital cost			
• Cost of 5,000 mt facility is \$10 to \$14 per kg of capacity • Cost of 10,000 mt facility is \$7 to \$10 per kg of capacity	• Land-RAS for post-smolt costs much less than for grow-out • Marine phase for grow-out uses very low cost netpen systems in use now	• Cost of \$5 to \$15 per kg of capacity indicates wide range of designs being evaluated	• Cost of 5,000 mt or more facility is about \$20 per kg of capacity • Other designs exist, but costs are uncertain
Operational cost			
• Cost for operations is \$5 to \$6 per kg of annual salmon produced • New sites are locating near markets to reduce transport costs	• Land-RAS for post-smolt costs much less than for grow-out • Marine phase uses very low cost netpen systems in use now • \$3.5 to \$4.5 cost per kg needs research	• Cost is lower than land-RAS, but higher than hybrid system • \$4.5 to \$5.5 cost kg needs research	• Cost may be one of the lowest amongst new technologies given high degree of automation and use of ecosystem services • Research is needed

Financial risk			
• Biological risks are mortality, high maturation rates, and growth challenges • Market risks are price drops, currency changes, lost price premiums as land-RAS market share increases	• Biological risks are very low since this is an extension of existing technologies • Market risks are those normally associated with salmon aquaculture	• Biological risks are mortality due to system failure • Market risks are price drops, currency changes, lost price premiums as new technology market share increases	• Biological risks are mortality due to high energy environment, system or component failure, growth challenges • Market risks are those normally associated with salmon aquaculture
Supply-chain			
• Feed, fish health, processing, distribution and sales are in BC, but are being developed where new sites are emerging elsewhere • There are limited expertise in BC for construction and operation of land-RAS systems so training and imports are needed	• All elements of the supply chain exist in Canada, although advanced RAS design and expertise draws from other countries • Some additional training are required to expand land-RAS workforce	• All elements of the supply chain exist in Canada including design and operational expertise • Some additional training are required to expand use of this technology	• Most elements of the supply chain exist in Canada, although offshore design and construction expertise draws from other countries • Specialized boats and training for offshore is needed • Research is needed to determine all requirements
Economy			
• Fewer jobs per mt of salmon (26 – 30 direct jobs per 1,000 mt of salmon) and not necessarily in rural areas • High average salaries due to more technical expertise required	• This system keeps most jobs (35 – 40 direct jobs per 1,000 mt of salmon) and largely where they are located now • Some more advanced expertise jobs will command higher salaries	• This system keeps most jobs (35 – 40 direct jobs per 1,000 mt of salmon) and largely where they are located now • Some more advanced expertise jobs will command higher salaries	• There are fewer jobs due to higher amount of system automation • Jobs are still located in rural areas • Some more advanced expertise jobs will command higher salaries

Expansion			
• Several large facilities could double BC salmon production • Site selection takes time to meet requirements, especially discharge permits	• Some expansion can occur at existing marine sites, but grow-out concerns must be addressed for new sites to be allocated	• Some expansion of production can occur by replacing netpens at existing marine sites, and allocation of new sites should be more acceptable due to environmental performance	• BC offers extensive opportunities for expansion once the technology is proven through test sites

CNL(21)51

Establishing Barriers Between Farmed Fish and Sea Lice – the Only Sustainable Solution?

Arve Nilsen, Norwegian Veterinary Institute, Norway

Introduction

Ectoparasitic sea lice present a major challenge to Atlantic salmon aquaculture (Coates *et al.* 2021) and a threat to fish welfare (Qviller *et al.* 2021). High infestation pressure of sea lice in the environment around commercial salmon farms has caused a critical increase in the mortality of wild salmonids (Krkosek *et al.* 2006; Ford and Myers 2008; Karlsen *et al.* 2020). Sea lice have also been described as a density-dependent constraint to salmonid farming (Jansen *et al.* 2012), where densities of farmed salmonids in an area have a strong effect on farm levels of sea lice and the efforts to control these infestations.

With widespread resistance towards all relevant delousing medications, other measures have been implemented such as mechanical and thermal delousing systems, freshwater baths (Overton *et al.* 2019) and a controversial increase in the use of cleaner fish (Overton *et al.* 2020; Sommerset 2021). Methods to prevent sea lice infestations have received little research effort, despite the many possible benefits of prevention over treatment-focused methods (Barrett *et al.* 2020). With effective prevention against salmon lice, the use of drugs which have a negative impact on non-target species around the farms (Urbina *et al.* 2019) and the ever-present challenge of drug-resistant parasites (Aaen *et al.* 2015) could be avoided. Further development of salmon farming will depend on the development and implementation of more efficient, fish-friendly and environmentally sustainable measures against salmon lice.

In this paper, I give a short presentation on semi-closed cage technology and the possible benefits and challenges of this farming technology.

What Are Semi-Closed Cages?

Semi-closed cages (SCCs) are floating, fish-farming systems with a barrier between the farmed fish inside the cage and the surrounding marine environment. Water is pumped from 20 – 35 m depth (Nilsen *et al.* 2017a; Balseiro *et al.* 2018) to create a single flow-through of sea water, with oxygen supplied through diffusers or ejector systems. In circular SCCs, water is released through a central outlet in the bottom; in some constructions, sea water is also released through several valves in the sidewall (Summerfelt *et al.* 2016). In tubular raceway systems, the water is circulated from inlet to outlet creating a constant one-way water current (Balseiro *et al.* 2018). The impermeable barriers that replace the nets used in open cages are made of flexible tarpaulin or constructions that are more rigid like composite, steel or concrete. With SCC technology, sedimentable particles can be collected and removed. So far, these systems are operated without any sophisticated cleaning or disinfection of water into or out from the cages, thus the term semi-closed or 'half'-closed.

Semi-Closed Cages – Does it Work?

In Nilsen *et al.* (2017a) and Nilsen *et al.* (2020), it was shown that effective prevention of sea lice infestation was possible with the use of semi-closed tarpaulin bags and an intake depth of 20 – 25 m. These studies were conducted between 2012 and 2017 at three different sea sites, with the same effect replicated at two new sites in the period from 2017 to 2021 (Nilsen, unpublished data). A study of semi-closed raceway systems reported similar results (Balseiro *et al.* 2018). It is also possible to reduce salmon lice infestations with other barrier technologies such as skirts, submerged cages, or 'snorkel' cages, where the infestation levels will decrease when the barrier established between the farmed fish and the sea lice contaminated surface water is strengthened (Samsing *et al.* 2016).

Closing the cages leads to other possibilities and challenges. However, studies of fish welfare in commercial-scale SCCs are few and not conclusive (Calabrese 2017) and additional longitudinal studies of fish health and welfare are necessary to compare SCCs with other production systems. The most obvious management challenge in the first circular tank-prototypes has been the relatively low water exchange rates. Retention time in such tanks has been reported to be between 50 minutes (Summerfelt *et al.* 2016) and 150 minutes (Nilsen *et al.* 2017a), while the raceway study reported a retention time of only 5 minutes (Balseiro *et al.* 2018). Low specific water consumption may lead to accumulation of particles and metabolites (Fivelstad *et al.* 1999; Thorarensen and Farrell 2011; Nilsen *et al.* 2017b), to stress and impaired skin quality (Sveen *et al.* 2016) and slower wound healing (Sveen *et al.* 2019). Reduced water exchange and the use of deep water with higher possible levels of marine pathogens as *Moritella viscosa* could increase the probability of skin and gill infections, and increased mortality caused by complex or multifactorial infections affecting the body surface or the gills have been reported (Nilsen *et al.* 2017a; Nilsen *et al.* 2020; S. Handeland, pers. comm.). It has been suggested that fish welfare and production rates could be improved in SCCs because water temperatures and oxygen levels are more stable and water velocity can be regulated (Nilsen 2019). An increase in water velocity and swimming speed has been shown to enhance the development of skeletal and heart muscle (Balseiro *et al.* 2018; Nilsen *et al.* 2019; Timmerhaus *et al.* 2021) and positive effects on a broader range of metabolic variables and welfare indicators have also been documented (Nilsen *et al.* 2019). The use of deeper water layers may also reduce the likelihood of exposure to harmful algal blooms.

With SCCs, it is possible to reduce the output of organic nutrients from marine fish farms. A considerable fraction of the settleable particles can be collected and used for production of biogas and fertilisers (Bergheim and Nilsen 2017; Nilsen unpublished data), while soluble nutrients and smaller particles are released with the discharged (and untreated) outlet water. It is possible to combine SCC farms with integrated multitrophic aquaculture (IMTA). In pilot studies with the use of dissolved nutrients and small, organic particles discharged from SCCs with Atlantic salmon (Stedt 2018), it was shown how blue mussels (*Mytilus edulis*) could remove organic particles and that sugar kelp (*Saccharina latissima*) could utilise dissolved nitrogen to increase both growth rate (75 %) and nitrogen content of the leaves (72 %).

Sea Lice Biology and Possible Prevention Strategies

Sea lice are marine copepods. In Norwegian salmonid farming the main concern is *Lepeophtheirus salmonis* (Qviller *et al.* 2021) with more sporadic problems reported with *Caligus elongatus* (Hemmingsen *et al.* 2020), whereas in Chile, the main sea lice species is *Caligus rogercresseyi* (Bravo 2003). All these have simple life cycles with juveniles, pre-adult and adult stages on the host. Gravid females release egg strings and the eggs hatch to free-living planktonic stages. The newly hatched nauplii (0.4 – 0.7 mm long) disperse in the water column and drift with the current before they reach the final copepodid stage and settle on a new host (Boxaspen 2006). Copepodids (the infective stage) aggregate towards the surface during daytime and spread out into deeper layers at night (Heuch *et al.* 1995). Copepodids show no thermal preferences, while the smaller nauplii have been shown to avoid high water temperatures (Crosbie *et al.* 2020), interpreted as a strategy to combine increased geographical dispersion of the nauplii with optimal host-finding success for the copepodids. Sea lice larvae have an affinity for high salinities, but while copepodids display a relatively wide tolerance for brackish water and some individuals occur at salinities down to 16 to 20 ppt., nauplii almost completely avoid salinities below 30 ppt. (Crosbie *et al.* 2019). Both stages aggregate at, or just below, the halocline. For nauplii, the salinity is probably an important environmental cue for optimal vertical positioning, securing largest possible dispersion patterns (Crosbie *et al.* 2019). For copepodids, vertical positioning is probably also an important host-finding mechanism.

The copepod parasite *Caligus elongatus* is less host-specific than *L. salmonis* (Hemmingsen *et al.* 2020) and not a specialised salmonid ectoparasite. Still, it has been suggested as a possible challenge with the use of depth-based strategies compared to *L. salmonis*, because *C. elongatus* is found over a greater depth range, the parasites show a different seasonal variation than *L. salmonis* and fallowing has not been confirmed effective against *C. elongatus* (Hemmingsen *et al.* 2020). *C. elongatus* is also reported as a common ectoparasite on lumpfish *(Cyclopterus lumpus)* (Heuch *et al.* 2007), the most-used cleaner fish species in Norway. In salmon lice, development on the host is divided into the attached chalimus stage, moving pre-adult and finally moving adult lice. For *C. elongatus* the development is direct from chalimii to adult (Piasecki and MacKinnon 1995). The chalimii of *C. elongatus* are hard to distinguish from *L. salmonis* during routine lice-counts, especially the first two chalimii stages (S. Dalvin, pers. comm.), while the adult stages are small and relatively easy to identify. In both species, the copepodid is the infectious stage that locates and attaches to the host (Boxaspen 2006), but for *C. elongatus* it has also been speculated that adult lice could be capable of leaving their host and attaching to a new host (Hemmingsen *et al.* 2020). The effect of skirts and different versions of submerged cages on *C. elongatus* infestations is unknown. In closed-containment systems (CCS), there have been sporadic observations with a low abundance of *C. elongatus* (Nilsen *et al.* 2017a).

With the use of deeper water, it is possible to reduce or eliminate some parasitic infestations, others will be less affected. A reduction of tapeworm (*Eubothrium* sp.) infestation in Atlantic salmon was demonstrated with the use of snorkel cages (Geitung *et al.* 2021 in press). For important gill parasites like *Paramoeba perurans* (AGD), *Parvicapsula pseudobranchicola* and *Ichthyobodo* sp., there is no evidence of preventive effects from the use of depth-based technologies (Nilsen unpublished data).

Biofouling and Biosecurity

Micro-organisms rapidly colonise all surfaces in marine waters. This formation of biofilm is important for the development and stability of marine ecosystems but is a challenge for design and management of fish farms (Dang and Lovell 2016). After the first microbiological colonisation, larger organisms like algae, hydrozoans, ascidiacea, bivalves and amphipods will settle, ending up with a complex ecosystem often referred to as biofouling. This is a perpetual process present in all fish farming units, and it comes with a significant economic impact (Fitridge *et al.* 2012). Biofilm and fouling organisms settle on all surfaces, with temporal and spatial gradients driven by variations of light and nutrients; the most rapid growth during spring and early summer and in the surface layers. Biofouling increases the weight of all underwater structures and reduces the flow of water through nets, filters and pipelines. With SCCs, the use of the copper-based antifouling chemicals that are frequently used on nets in open cages can be avoided (Grøsvik 2018); however, frequent cleaning is necessary to reduce the weight and possible negative impact on water flow from excess biofouling.

Biofilms are rich communities dominated by non-pathogenic organisms (Blancheton *et al.* 2013), however biofilms could also be reservoirs for pathogens (King *et al.* 2008), like *Aeromonas* sp. (Talagrand-Reboul *et al.* 2017) and *Paramoeba perurans* (AGD) (Tan *et al.* 2002). On the other hand, accumulations of sea lice in biofouling from salmon net pens and cleaner fish shelters have not been found (Jevne *et al.* 2020). It is also important to remember the importance of the microbiological processes in the water. In a study of land-based marine recirculating systems (RAS) and SCCs, both systems had a higher abundance of potential pathogens in the water than in the biofilm (Rud *et al.* 2016). With farming of Atlantic salmon, a significant microbiological footprint in the marine environment up to 1000 m away from the farm site was shown (Strand *et al.* 2020) and several pathogens were identified both inside the cages and in the water around the farm site.

Escaped Fish

SCCs with a commercially developed and certified technology, combined with location at more sheltered sites, could be a way to reduce the risk of escapes. However, whether introduction of more SCCs will reduce or increase the risk of escaped fish is the subject of ongoing discussion. Tarpaulin bags are flexible and supplied with an extra net to prevent fish from escaping. Other materials are rigid, like solid-wall cages of composite, steel or concrete. These constructions are less vulnerable for wear and tear, but could be at risk of critical damage when exposed to heavy weather. For all technologies, SCCs are certified for less exposed sites (lower wave height) than open cages. At least three cases of accidents caused by storms are documented and a low number of escapes were registered in one of these. For open cages, the Norwegian Directorate of Fisheries (2021) report sea lice treatments with accompanying use of boats and handling of nets as a major risk factor for tearing of nets and thus escaped fish. Other new farming technologies, such as offshore farming, are less documented, but escaped fish caused by technical or human errors have been reported (Anonymous 2020).

The Way Forward

In recent years, we have seen high profit rates in salmon farming combined with increased biological challenges and accompanying strong regulatory limitations on growth in traditional farms. The value of the existing sea-farming licenses and the very limited new license volumes has increased dramatically, creating a strong incitement for investments in land-based production (fewer regulations) or offshore farms (new areas). Semi-closed farms have, until now, been regulated with the same legislative tools as open cage farms. This may change this year, as the Ministry of Trade and Fisheries are preparing a new policy document on future growth of salmon aquaculture in Norway.

Conclusions

SCCs introduce a solid barrier between the farmed fish and the surface water. Water is pumped from 20 – 30 m depth, thus effectively avoiding the infective sea lice copepodites. If open net cages are replaced with SCCs, the negative impact on wild salmonid populations from heavy sea lice infestations will be significantly reduced. With SCCs, sedimentable particles can be collected and removed, reducing the negative impact on the local benthic environment. In addition, there will be less need for environmentally controversial therapeutic measures such as chemical treatments or the use of cleaner fish. There will also be less negative impact on the welfare of farmed fish caused by the non-medical treatments frequently used in open cages.

CNL(21)54

Recirculating Land-Based Systems – Reducing Conflicts Between Farmed and Wild Salmon

Erik Sterud, Krüger Kaldnes AS, Norway

The wild Atlantic salmon is under more pressure than ever before. Not least from the growing salmon farming industry. However, this industry is undergoing a major transition. The urge for profit, new technologies and increasing concern for environmental impacts have initiated this. We see that new technology and new production regimes erase the strict borders between smolt and salmon, between fresh water and salt water, between land and sea. The question is: can these new ways of producing salmon reduce the conflicts between farmed and wild salmon?

The Problems / Conflicts

This will be a talk about solutions and not problems, but the negative impacts of salmon farming need to be mentioned. The most serious is escaping farmed salmon. Although the modern farmed salmon is a product of good old-fashioned traditional breeding, it is a fish adapted to farming conditions. The best way to illustrate the difference between farmed and wild salmon is by asking the rhetorical question – why can fish farmers not be forced to use offspring of wild salmon in their pens? The answer is long, but the short version is that it would mean a major setback to the industry. It would simply not be possible (economically viable).

The second most serious conflict is dissemination of diseases – including parasites such as the salmon louse. It is important to stress that no disease or pathogen has spontaneously generated in a fish farm. The problem is that every pathogen specific for a host that is very scarcely distributed in the wild, has a masters' degree in finding its host. So for them a fish farm open to the environment is a never-ending party.

It is important also to mention the link or synergistic negative effects, between diseases and escaping. This especially applies to the salmon louse. To combat the lice, the farmers depend on non-medical methods as resistance to antiparasitics has evolved and spread. All non-medical methods depend on the use of cranes, well boats or barges. The combination of heavy machinery and thin vulnerable nets has shown to be bad.

Technological Paradigm Shift

For decades, 6 – 12 months production of 100 g smolts in land-based hatcheries followed by 15 – 18 months production in open net pens in coastal areas, has been the normal way of producing salmon. The increased use and rapid development of recirculating aquaculture systems – RAS – has opened up for alternative ways of farming salmon: RAS alone, such as in 100 % land-based production (Atlantic Sapphire in Miami, Florida); RAS in combination with traditional net pens (most salmon companies); offshore farming platforms (Salmar and Nordlaks, Norway); or semi-closed marine pens / tanks (several ongoing projects). All these new production regimes involving production of larger smolts (200 – 1,000 g) have in common a transfer of production time from open to closed systems and, in most cases, from the sea to land.

RAS

RAS technology is, in theory, more about water treatment than fish production. However, alongside the initial idea of saving water and energy, RAS allows us to tailor-make the water quality and control the development of the fish even more than what is possible in flow-through systems. For production of harvestable fish, the use of RAS is almost a necessity. Very few countries in the world have the Norwegian combination of a small population, available land and *ad libitum* water resources.

But the use of RAS exclusively for production of smolts (and the 'new' entity post-smolts) enables production that is not dependent on the natural annual cycle of the salmon. Today smolts are produced and stocked in the net pens every month of the year from the arctic regions to the temperate regions.

Effects of Reducing Production Time in the Sea

By moving all production on land (or in closed floating systems) and including functional water treatment (disinfection) to eliminate or significantly reduce the exchange of pathogens between wild and farmed salmon, one can obviously reduce the negative effects of salmon farming. However, even if a total transition to closed farming is not implemented, reducing the time any given farmed salmon individual spends in open net pens could have a positive effect. Exposure time is a factor in all epidemiology. The shorter you are exposed to infectious organisms, the smaller the risk of being infected. This again will reduce the total infection pressure along coast lines – for farmed salmon and for wild.

Another effect of reducing production time in the sea can be accomplished if production time is reduced from today's 15 – 18 months to 12 months or less. A synchronisation of production with the calendar will reduce the problematic effect of 'the second year in the ocean'. It will also lead to shorter intervals between fallowing, thus breaking the life cycle of infectious organisms more often.

Effects of Increased Smolt Size

Disease is a story about both the pathogens and the hosts. Robust and healthier hosts are less likely to encounter infective diseases and to spread the disease to new hosts. One of the main ideas behind increasing smolt sizes is to increase the robustness of the smolts put into net pens. This will have positive effects on the prevalence of infectious diseases. Again a benefit for both farmed and wild salmon.

Effects of New Possibilities

Governments will play an important role in this technological transition. Regulations and legislation are very often limited by the technological possibilities. They will not be put into play until the possibilities for success exist and have been proved. The mandatory (and some said premature) use of closed containment systems for sea lice treatment in Norway (executed by the former Minister of Fisheries Mrs Lisbeth Berg-Hansen) was an exception. Regulations for protecting wild salmon and ecosystems in general are more likely to be adopted by governments once the technology is there. This can be mandatory collection of wastes, mandatory use of bigger smolts, mandatory use of RAS and other closed containment systems and technologies to mention a few.

Who Should Reap the Benefit?

New production regimes can be used to increase turnover, flexibility, production and, finally, revenue for the farmers. And they can be used to reduce the conflicts and the negative impacts on wild salmon and ecosystems in general. But not necessarily both at the same time.

If reduced ecological impact of production volume X is used to allow a new production of X + x, the benefits for the wild salmon could be small. However, if X is constant the reduced ecological impact will benefit the wild salmon. This means that the technological paradigm shift occurring right now will walk hand-in-hand with governmental legislation and management regimes.

What Could Go Wrong?

Environmental awareness is a rich man’s hobby. Today’s fish farmers are rich men. Few people want to harm the environment. Thus, less negative impact from established production can probably be expected. But new technologies open the possibilities for salmon farming by new investors, new cultures, new jurisdictions. When newcomers head into new industries they often need to fight the establishment. Very seldom the environment is the winner. With new technologies salmon farming could be established in places where no wild salmon exist. But increased production in places where salmon are already under pressure can also be expected. The key is to reduce the negative impact per farmed salmon individual, without filling up the gap with new individuals and, by doing so, reducing the gain.

Conclusion

New technologies and methods for farming salmon are rapidly evolving. Land-based production (RAS or other technologies) for the whole or part of the production cycle, will be a useful tool for reducing the conflicts between farmed and wild salmon. But only if the primary goal is to reduce the conflicts and new tools are being used wisely.

CNL(21)47

Genetic and Other Innovative Strategies to Reduce Sea Lice

Michael Pietrak and Brian Peterson, U.S. Department of Agriculture, Agricultural Research Service, National Cold Water Marine Aquaculture Research Center, USA

The United States Department of Agriculture-Agricultural Research Service (USDA-ARS) National Cold Water Marine Aquaculture Center (NCWMAC) in Franklin, Maine has been supporting the United States cold water marine aquaculture industry since 2003 by developing genetically improved North American (NA) Atlantic salmon and conducting research to address industry issues. In the past six years, the NCWMAC has begun two programmes to help manage sea lice on marine net pen farms. The first programme incorporates sea lice resistance into the existing selective breeding programme and the second is the development of lumpfish culture techniques and broodstock for use as cleaner fish in marine net pens. Both selective breeding and the use of cleaner fish are management options that can be used by the domestic industry as part of their existing integrated pest management programmes (IPMP).

Breeding Programme

The NCWMAC utilises the St John River (SJR) strain because of fast growth, certification of NA origin and widespread utilisation by industry. Since 2015, the primary objectives of the salmon selection programme have been to improve commercially important traits including: carcass weight, fillet colour, fat content and sea lice resistance. Recently, the programme started to evaluate and validate the usefulness of incorporating genomic based selection techniques into the salmon breeding programme. Culture of Atlantic salmon in the breeding programme and research facility is based on life stage and separation of year class (Figure 1).

An incubation system is used for eggs and newly hatched fry before first feeding, parr tanks are used for first feeding fry to 30 – 40 g salmon, the smolt tanks are for 30 – 100 g pit-tagged salmon, on-grow tanks are for 100 g to 1.0 kg salmon in their second year, 3-yr old broodstock tanks are for 1.0 kg to 3.0 kg salmon and four 4-yr old broodstock tanks are for growing salmon 3.0 to 8.0 kg when they will be spawned. Up to 234 families of Atlantic salmon can be cultured in the breeding nucleus and approximately 250 eggs are saved from each family mating and reared. The remaining eggs are distributed to industry and used as their next generation of brood to provide eggs for commercial production. Of the fish from the 250 eggs that remain in the programme, typically 30 – 40 smolts per family are saved as the nucleus of fish (broodstock) for the breeding programme and cultured in biosecure tanks at the NCWMAC. An additional 30 – 40 smolts per family are cultured and transferred to an industry collaborator for stocking into net pens for growth performance evaluations. Additional smolts are also kept for various studies involving measurement of traits such as sea lice resistance. Selection of 4-year old fish for spawning occurs when fish are moved from 3-year old broodstock tanks into the 4-year broodstock system prior to the spawning season.

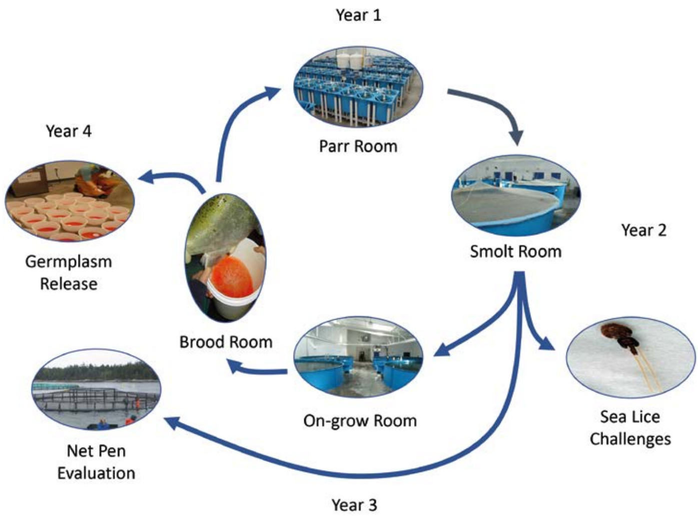


Figure 1. *Overview of the 4-year cycle for the breeding programme at the U.S. Department of Agriculture's National Cold Water Marine Aquaculture Center.*

Sea Lice Selection

Since 2015, the NCWMAC has evaluated three of the four year classes per generation and continues to evaluate and select the offspring of those year classes. The programme utilises a challenge model based on multiple small challenges to evaluate 70 – 120 families for lice resistance. Approximately 16 pit-tagged fish from each of these families are set aside for challenge trials. One fish from each family is stocked into a 1 m^3 tank, setting up a series of 16 replicate tanks.

Sea lice egg strings are collected from commercial farms and then brought back to be cultured in the laboratory to the infective copepodid stage. Challenge fish are infested via a 4-hour bath challenge as 2 – 4 day old copepodids are available. Lice are allowed to develop to the 2nd chalimus stage, approximately 10 – 14 days post infection (dpi). Fish are euthanised by an overdose of MS-222 in saltwater and then transferred to a freshwater staining bath of neutral red for 20 minutes before being individually bagged. Fish are kept on ice until the lice are counted, fish weighed, fork length measured and fin clips are preserved in 95 % Ethanol. Lice counts are standardised by lice density (LD; Gjerde *et al.* 2011) and lice per cm^2 of surface area. Surface area is calculated from the model in Frederick *et al.* (2017). Estimated breeding values for each family are generated using the programme MTDFREL.

The evaluations to date have revealed heritability values within our population of between 0.20 and 0.31 that are consistent with those published in the literature. Looking at the average lice densities for each family in each year reveals a similar pattern with a few families showing resistance and a gradual increase towards highly susceptible families (Figure 2). Efforts to date have focused on utilising the most resistant families to select a few highly resistant families, while simultaneously ensuring that most families which are selected based on growth are families not within the most susceptible 30 % of families.

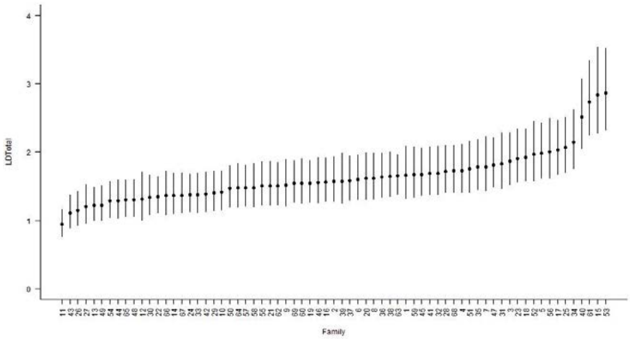


Figure 2. *Typical graph illustrating average lice density (LDTotal) per family with 95 % confidence intervals. Families exhibiting lower lice density are more resistant.*

Genomic Based Selection

Genomic based selection has made significant advances over the past 20 years since the development of the use of genome-wide dense marker maps (Meuwissen *et al.* 2001). In combination with the reduction in genotyping costs, this new technique has allowed for improved selection accuracy. This is accomplished by using a combination of traditional phenotypic based estimated breeding values (EBV) and genomic data to generate genomic estimated breeding values (gEBV) which account for within family variation in addition to between family variation. The techniques were pioneered in dairy and beef cattle and other major terrestrial livestock, but recently are more widely being used in fish for multi-locus traits such as growth and disease resistance to some pathogens (Vallejo *et al.* 2017; Garcia *et al.* 2018).

Over the past several years the programme has been collaborating with USDA-ARS scientists at the National Center for Cool and Cold Water Aquaculture (NCCCWA) in Leetown, West Virginia. These efforts have included constructing a reference genome for North American Atlantic salmon of the SJR strain and developing a publicly available 50K single nucleotide polymorphism (SNP) chip for genotyping salmon of NA origin (Gao *et al.* 2020). The goal is to implement a genomic selection programme for sea lice in November 2021. This represents a significant step forward in selective breeding for sea lice resistance.

Lumpfish

Cleaner fish have been used in European salmon farms for over 30 years (Pike 1989). However, the wrasse species that have been primarily used are not native to the western North Atlantic Ocean. More recently the lumpfish (*Cyclopterus lumpus* L.) has become a popular option for use as a cleaner fish. Lumpfish are native to the eastern coast of North America (Cox and Anderson 1918). As a result, the use of cleaner fish has only been adopted within the past 5 years or so with the commercial industry on the North American side of the Atlantic Ocean. Despite the disparate adoptions in the use of cleaner fish between the two sides of the Atlantic, the recent surge in use of lumpfish is common to both and the development of a lumpfish farming industry is rapidly developing in both locations. This rapid development presents a range of research potential and knowledge gaps for the species (Brooker *et al.* 2018; Powell *et al.* 2018).

The wide range of research coming out on lumpfish can be grouped into four broad areas. The first is the development of captive reared broodstock populations. The reliance on wild caught animals to provide eggs has been identified in several key reviews as a critical knowledge gap (Brooker *et al.* 2018; Powell *et al.* 2018). However, this situation is rapidly evolving as development of captive brood is constantly occurring in major lumpfish rearing countries. This research area is evolving to incorporate potential selective breeding, manipulation of spawning timing and improving reproduction (Imsland *et al.* 2016a; Imsland *et al.* 2019). This is one of the primary areas of focus for our lumpfish programme. In collaboration with the University of Maine, current efforts are focused on development of captive brood populations derived from local populations. Likewise, the U.S. Lumpfish Consortium spearheaded by NCWMAC, University of New Hampshire, the University of Maine and industry partners are also investigating the manipulation of spawning and interested in the potential for selective breeding.

The second broad area of research involves optimising the effective husbandry of all stages of lumpfish care both in hatcheries and in sea cages. There is a wide range of issues and topics being explored under this area. Work in this area is coming out in both peer reviewed and trade literature but is also being conducted within facilities and companies on a private basis. On the hatchery side, research into optimum water quality, temperature, nutrition and other husbandry issues are being conducted (D'Arcy *et al.* 2020; Dahle *et al.* 2020; Mortensen *et al.* 2020; Pountney *et al.* 2020). Optimising hatchery husbandry, including the maintenance and nutrition of captive broodstock populations, is the other primary focus of the NCWMAC in collaboration with the University of New Hampshire. On the net pen side, nutrition, lumpfish recapture and housing are areas of interest (Imsland *et al.* 2015a; Imsland *et al.* 2018a; Imsland *et al.* 2018b; Imsland *et al.* 2020). Feeding techniques, such as the use of gel blocks or submersible feeders to keep lumpfish from eating salmon feed are also being examined. One of the more interesting trends that has occurred with the development of lumpfish culture is that not only is there interest in optimised husbandry as demonstrated above, but there is interest in animal welfare research and how to improve this research simultaneously (Gutierrez Rabadan *et al.* 2020).

The third major area of research revolves around disease. The development of any new aquaculture species is accompanied by many new areas for disease research as it is difficult to study disease in wild populations. As might be expected, new occurrences of bacterial, viral, parasitic and mycotic pathogens are being observed (Einarsdottir *et al.* 2018; Ellul *et al.* 2018; Rouleau *et al.* 2018; Scholz *et al.* 2018; Pietrak and Rosser 2019; Stagg *et al.* 2020). Research into lumpfish immunity, pathogen treatment and other areas to improve overall health is also rapidly developing (Erkinharju *et al.* 2018; Pietrak and Backman 2018; Haugland *et al.* 2019; Jacobsen *et al.* 2019; Eggestøl *et al.* 2020; Klakegg *et al.* 2020). One new area of health research that is, and will become more, prominent is the ecology of pathogens in these polyculture systems (Murray 2017). Large scale western aquaculture has traditionally been a monospecies approach and the benefits of polyculture systems has focused on multi-trophic systems rather than multiple fish species. The increased co-culture of cleaner fish can complicate disease management on farms given the ability of some pathogens or strains to remain asymptomatic in one species cultured, but potentially cause outbreaks in the other.

Finally, the last major area of research is arguably the most important and that is documenting and optimising the efficacy of using lumpfish as cleaner fish. Early efforts focused on demonstrating the effectiveness of lumpfish by comparing sea lice levels in cages with and without lumpfish, and with varying densities of lumpfish and other factors (Imsland *et al.* 2014a; Imsland *et al.* 2014b; Imsland *et al.* 2015; Imsland *et al.* 2016b; Imsland *et al.* 2018c). However, while there is a consensus that lumpfish can help manage sea lice populations, it has been observed that not all lumpfish exhibit cleaning behaviour. A pressing topic is understanding what genetic, environmental, seasonal or life history factors are influencing cleaning behaviour (Imsland *et al.* 2016a; Imsland *et al.* 2016b; Eliasen *et al.* 2018; Leclercq *et al.* 2018). By starting to understand the various factors influencing cleaning behaviour, studies can start to help refine and optimise the most appropriate situations for utilising lumpfish (McEwan *et al.* 2019).

Summary

Significant advances are being made in the development of selective breeding for sea lice resistance and in the use of cleaner fish, especially lumpfish. However, neither of these technologies likely represents a silver bullet to managing sea lice populations on either a local or global scale. Both technologies can be important tools and components in effective IPMP as salmon farmers move from IPMP that primarily use drug-based management strategies to IPMP that use non-drug-based strategies. It is important to remember that no specific system of control strategies will fit all regions, water bodies or even companies. Rather, systems need to be individually tailored to each farm. With the proliferation of non-drug management tools in IPMP, it is critical that more research be focused on rigorously determining what strategies and technologies are effective at the local level and defining the economic costs of each strategy.

CNL(21)48

How to Protect Wild Salmon Against Sea Lice with the Use of New Technologies and Post-Smolts

Åsa Maria Espmark, Nofima, Norway

Background

Salmon lice *(Lepeophtheirus salmonis)* severely impact both wild salmon and the farmed salmon industry. In addition to the wildlife and welfare responsibility of the fish farmers, the enormous additional costs associated with lice counting and different lice combating methods are reasons for the huge interest and effort being invested to find solutions that successfully combat the parasite.

Because of the risk of resistance, the use of medical lice treatment is not preferred or common, and the different non-medical lice combating methods can roughly be divided between methods where lice are removed from the fish and methods that prevent lice from attaching to the salmon. In the first group, lice can be removed from salmon using methods involving handling the fish, such as mechanical delicing. Most of these methods include crowding and pumping of salmon that may cause severe welfare issues (Overton *et al.* 2018). Examples of methods where handling is not involved include the use of cleaner fish that eat lice and the use of lasers. Preventive methods used to various degrees include functional feed, genetic selection and vaccines. However, more successful, and common, is the use of different cage and tank systems that are constructed in such a way that lice do not enter the systems.

Semi-Closed Systems and Post-Smolts

Semi-closed systems (Figure 1) are examples of preventive methods where a physical barrier between the fish and its environment prevent lice from entering the system and fish from escaping from the system. Water is pumped into the system from depths under the lice level.

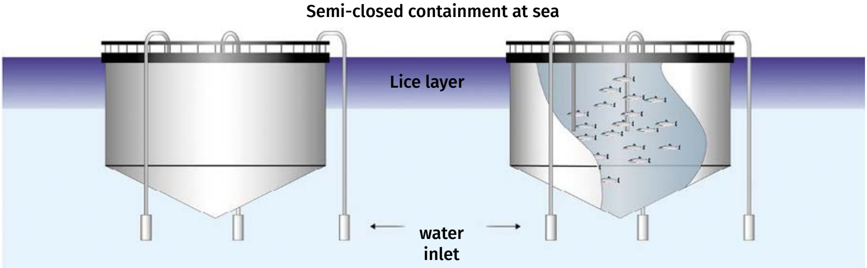


Figure 1. *Principal function of semi-closed systems.*

Semi-closed systems are so-far used for post-smolts, i.e. large smolts up to approximately 1,000 g that are already adapted to sea water. This leads to one more advantage of the systems, in that salmon are kept away from the open sea for longer, and therefore longer periods away from lice and risk of escapees. Post-smolts kept in land-based RAS (recirculation in aquaculture) facilities until they are approximately 1,000 g are also kept away from the open sea for longer. By putting large smolts of up to 1 kg into the net pens, the time spent in the open sea can be reduced from the traditional 16 – 22 months to 10 – 11 months. This way of producing fish is an alternative to the traditional method where 70 – 100 g fish are transferred to open net pens for ongrowing (Figure 2).

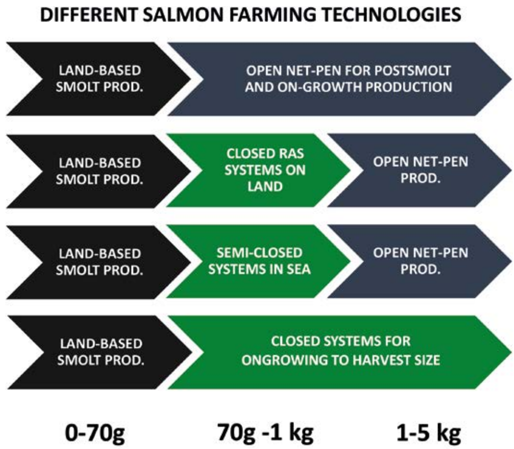


Figure 2. *Different production protocols for salmon. The upper arrow represents the traditional way where a 70 – 100 g smolt is transferred to open net pens for ongrowing. The two middle arrows represent production of post-smolts in either RAS or semi-closed systems before transfer to open net pens. The last arrow represents the system where salmon are kept on land for the whole life cycle.*

The production of post-smolts is relatively new and much research is being done to secure fish welfare and robustness in the systems and to ensure that the fish are suited to life at sea when they reach the appropriate size. Also, producing post-smolts on land means that the fish need to adapt to brackish water or salt water on land. This requires knowledge of fish biology and responses in this phase, including appropriate smoltification protocols. Also, knowledge about RAS technology to ensure fish health and welfare is required.

Cases from Research

In the presentation examples from our research concerning post-smolt welfare and performance in RAS and semi-closed systems will be shown.

Our experience with the semi-closed systems we have been investigating is that the functionality regarding lice infestation is very good. The lack of lice is also scientifically documented (Nilsen *et al*. 2017a). In a newly completed MSc thesis, where six generations of salmon were followed in one semi-closed system, it was concluded that in three out of six generations the growth was better in the semi-closed system compared to a reference cage. However, after the fish were moved out from the semi-closed system and into open net pens, fish from four out of six generations performed better when they originated from the semi-closed system than if they came from the reference net pen. The lice infestation was also lower in the fish originating from the semi-closed system, even if lice were present in the area at the time of the experiment (Øvrebø 2020).

Recently, a study was completed in which we followed a group of 200,000 smolts from a RAS facility, into a semi-closed system and finally out to an open net pen (Espmark *et al.* 2020). The main conclusions from this study were that growth (Specific Growth Rate and Thermal Growth Coefficient) was better during the time that the fish spent in the semi-closed system compared to both the RAS phase and the three months that we followed the fish in the open net pen. It was also documented that skin health improved during the stay inside the semi-closed system, shown by histology and gene expression analyses. We believe that a slight increase in temperature inside the system improved growth and that good water quality facilitated skin health and growth.

To secure survival and good welfare after sea transfer, it is important to ensure that the post-smolts are robust. Karlsen *et al.* (2018) showed that post-smolts are low in immune genes for a period of approximately one month after sea transfer (Figure 3). At the same time, skin histology and gene expressions for skin health also indicated reduced epidermis quality. Four months after sea transfer, both immune genes and skin quality improved (Karlsen *et al.* 2018). These results show that post-smolts are naturally vulnerable just after sea transfer and should thus be handled as little as possible, especially during the window of low immunity and poorer skin health.

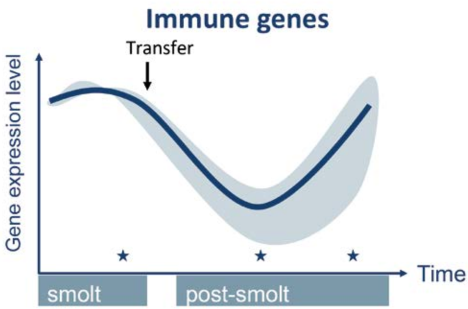


Figure 3. *Expression of group of immune genes are naturally low in the period between smolt and post-smolt (Karlsen* et al. *2018).*

Training has been proven beneficial for survival, and one way to facilitate training is with water velocity (Castro *et al.* 2011). To secure system specific recommendations for swimming speed, Timmerhaus *et al.* (2021) performed an experiment where post-smolts were exposed to velocities of 0.5, 1.0, 1.8 and 2.5 body lengths per second. It was seen that weight increased linearly with velocity. However, the fish provided with a velocity of 0.5 body lengths per second were the longest but had the lowest condition factor compared to the other test groups. There was also a linear increase in muscle cell density, indicating that the weight increase was indeed an increase in muscle mass, caused by training. The welfare of the fish at the highest velocity (2.5 body lengths per second) was not good, shown by the increased number of severe skin damages at the highest velocity. Also, shoaling was observed after a few days with the highest velocities. The reason for this behavioural change is not clear but may be because the fish tried to form a hiding place from velocities or that uneven distribution of velocities in tanks may have resulted in places with lower velocities that were preferred places for the fish compared to places with a higher velocity. From this study it was concluded that recommended swimming speed in RAS for post-smolts is 1.0 – 1.5 body lengths per second (Timmerhaus *et al.* 2021), which is the same as for earlier recommendations from flow-through.

During 'traditional' salmon production, freshwater smolts are given a winter signal with 12 hours darkness and 12 hours of light to induce smoltification that results in sea water tolerance, and the fish is ready to be transferred to sea. The transformation of aquaculture, in that the fish are kept longer on land, has also resulted in the fish being introduced to sea water or brackish water while still on land. This has led to several different smoltification protocols, varying in salinity, duration and timing of winter signal, and even the absence of winter signal. Many of the different protocols used are developed from experience and without scientific proof. During the presentation we will show an example of scientific approach where we experimented with different salinities and photoperiods and how this influenced performance and welfare.

One advantage with closed aquaculture systems is the possibility of controlling water quality and thus performance and welfare. Full control of water quality requires good skills in water quality among workers, knowledge of how to obtain and keep optimal water quality and of how to prevent failures. Recirculating water needs to be treated to remove discharges such as ammonia and carbon dioxide that may be toxic to fish. In an experiment in RAS, Mota *et al.* (2019) showed a growth penalty with CO_2 concentrations from 5 – 40 mg / l (Figure 4), without any severe welfare effects. However, the effect on growth at concentrations lower than the recommended 15 mg / l, suggests that the CO_2 levels should be kept even lower in RAS. The authors suggest 12 mg / l in RAS (Mota *et al.* 2019).

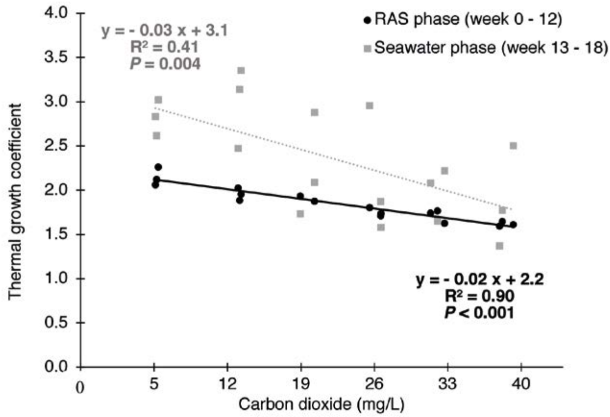


Figure 4. *Growth penalty caused by CO_2 during the RAS phase was carried over to the flow through ongrowing phase (Mota* et al. *2019).*

Many farmers prefer to treat the RAS water with ozone to reduce colouration and increase visibility in the water. However, due to the production of bromines in ozone treated saline water that may be toxic for the fish, the risk of using ozone in saline water is higher than in fresh water. In fresh water, ozone significantly improves water clarity, diminishes bacteria counts, reduces dissolved metals and leads to increased salmon growth (Davidson *et al.* 2021). Salmon is sensitive to ozone in saline water, and Stiller *et al.* (2020) demonstrated that ozone concentrations, recommended for turbot *(Scophthalmus maximus)* and sea bass *(Dicentrarchus labrax)*, turned out to be acutely lethal for salmon and was especially harmful to the gills.

To conclude, there is agreement that new technologies and production protocols are needed to prevent harmful effects on wildlife caused by aquaculture. There is a risk that new technological solutions are being developed more quickly than the research required to ensure that fish welfare is secured in the new systems. It is important that research and technological development work hand in hand so that the technologies are developed taking fish welfare into account.

Acknowledgements

Research presented is funded by CtrlAQUA (Centre for Closed-containment Aquaculture) SFI (Centre for Research Based Innovation) (RCN project #237856/O30) and FishGLOBE (RFF project #259057).

Progress by International Salmon Farmers Association (ISFA) to Promote the International Goals for Sea Lice and Containment

Presentation by Mark Lane, on behalf of ISFA, to the Theme-based Special Session

The International Salmon Farmers Association is an umbrella organization comprised of national and regional associations from around the world.

ISFA members share a common vision and dedication to helping our farmers and industry professionals produce healthy food, revitalize coastal communities and build vibrant businesses.

The farmers and industry professionals we represent produce healthy food in an economically, socially and environmentally sustainable manner. They create work in remote areas of the world and strive to be a forward looking industry, learning through research and innovation.

www.salmonfarming.org

International Goals (2009)

In 2009, 'Guidance on Best Management Practices to address impacts of sea lice and escaped farmed salmon on wild salmon stocks' (SLG(09)5), referred to as the BMP Guidance, was developed through the NASCO / International Salmon Farmers Association (ISFA) Liaison Group and adopted by both organisations.

This BMP Guidance has the following international goals:

1. ***'100% of farms to have effective sea lice management such that there is no increase in sea lice loads or lice-induced mortality of wild salmonids attributable to the farms'.***

2. ***'100% farmed fish to be retained in all production facilities'***

Guidance on Best Management Practices to address impacts of sea lice and escaped farmed salmon on wild salmon stocks (Adopted in June 2009 and Revised in June 2010)

	Sea Lice	Containment
International Goals	**100% of farms to have effective sea lice management such that there is no increase in sea lice loads or lice-induced mortality of wild salmonids attributable to the farms**	**100% farmed fish to be retained in all production facilities**
	Use Williamsburg Resolution as basic guidance, supplemented as below	
Best Management Practices (BMPs)	Area management, risk-based, integrated pest management (IPM) programmes that meet jurisdictional targets for lice loads at the most vulnerable life-history stage of wild salmonids	Codes of Containment including operating protocols
	Single year-class stocking	Technical standards for equipment
	Fallowing	Verification of compliance
	Risk-based site selection	Risk-based site selection
	Trigger levels appropriate to effective sea lice control	Mandatory reporting of escape events and investigation of causes of loss
	Strategic timing, methods and levels of treatment to achieve the international goal and avoid lice resistance to treatment	Adaptive management in response to monitoring results to meet the goal
	A comprehensive and regulated fish health programme that includes routine sampling, monitoring and disease control	
	Lice control management programmes appropriate to the number of fish in the management area	
	Adaptive management in response to monitoring results to meet the goal	

Reporting & Tracking	Monitoring programme appropriate for the number of farmed salmon in the management area and sampling protocols effective in characterising the lice loads in the farms and wild salmonid populations.	Number of incidents of escape events and standardised descriptions of the factors giving rise to escape events
	Lice loads on wild salmonids compared to areas with no salmon farms	Number and life-stage of escaped salmon (overall number; % of farmed production)
	Lice-induced mortality of wild salmonids (e.g. as monitored using sentinel fish, fish-lift trawling, using batches of treated smolts)	Number of escaped salmon in both rivers and fisheries (overall number; % of farmed production) and relationship to reported incidents
	Monitoring to check the efficacy of lice treatments	
Factors Facilitating Implementation	Development of a monitoring programme appropriate for the number of farmed salmon in the management area and sampling protocols effective in characterising the lice loads in the farms	Monitoring of rivers for escaped salmon
	Access to a broad suite of therapeutants, immunostimulants and management tools	Site appropriate technology
	Collation and assessment of site selection and relocation criteria	Advanced permitting to facilitate recapture and exchange of information on effectiveness of recapture efforts
	Regulatory regimes which facilitate availability of alternative sites, as necessary, to support achievement of the goal	Technology development (e.g. cage design, counting methods for farmed salmon, methods to track origin of escaped salmon and their progeny)
	Training at all levels in support of the goal and to increase awareness of the environmental consequences of sea lice	Training at all levels in support of the goal and to increase awareness of the environmental consequences of escaped salmon
	Monitoring of lice levels: in areas with and without farms; before, during and after a farm production cycle; and in plankton samples	Assessments of the relative risks to the wild stocks from escaped salmon from freshwater compared to marine facilities and from large but infrequent escape events compared to small but frequent escape events

Best Management Practices (BMPs) – Sea Lice

Area management, risk-based, integrated pest management (IPM) programmes that meet jurisdictional targets for lice loads at the most vulnerable life-history stage of wild salmonids	✓
Single year-class stocking	✓
Fallowing	✓
Risk-based site selection	✓
Trigger levels appropriate to effective sea lice control	✓
Strategic timing, methods and levels of treatment to achieve the international goal and avoid lice resistance to treatment	✓
A comprehensive and regulated fish health programme that includes routine sampling, monitoring and disease control	✓
Lice control management programmes appropriate to the number of fish in the management area	✓
Adaptive management in response to monitoring results to meet the goal	✓

Reporting and Tracking – Sea Lice

Monitoring programme appropriate for the number of farmed salmon in the management area and sampling protocols effective in characterising the lice loads in the farms and wild salmonid populations	✓
Lice loads on wild salmonids compared to areas with no salmon farms	✓
Lice-induced mortality of wild salmonids (e.g. as monitored using sentinel fish, fish-lift trawling, using batches of treated smolts)	✓
Monitoring efficacy of sea lice treatments	✓

Factors Affecting Implementation – Sea Lice

Development of a monitoring programme appropriate for the number of farmed salmon in the management area and sampling protocols effective in characterising the lice loads in the farms	✓
Access to a broad suite of therapeutants, immunostimulants and	✓
Site appropriate technology management tools	✓
Collation and assessment of site selection and relocation criteria	✓
Regulatory regimes which facilitate availability of alternative sites, as necessary, to support achievement of the goal	✓
Training at all levels in support of the goal and to increase awareness of the environmental consequences of sea lice	✓
Monitoring of lice levels: in areas with and without farms; before, during and after a farm production cycle; and in plankton samples	✓

Best Management Practices (BMPs) – Containment

Codes of Containment including operating protocols	✔
Technical standards for equipment	✔
Verification of Compliance	✔
Risk-based Site Selection	✔
Mandatory reporting of escape events and investigation of causes of loss	✔
Adaptive management in response to monitoring results to meet the goals	✔

Reporting and Tracking – Containment

Number of incidents of escape events and standardised descriptions of the factors giving rise to escape events	✔
Number and life-stage of escaped salmon (overall number; % of farmed production)	✔
Number of escaped salmon in both rivers and fisheries (overall number; % of farmed production) and relationship to reported incidents	✔

Factors Affecting Implementation – Containment

Monitoring Rivers for Escaped Salmon	✔
Site Appropriate Site Technology	✔
Advanced permitting to facilitate recapture and exchange of information on effectiveness of recapture efforts	✔
Technology development (e.g. cage design, counting methods for farmed salmon, methods to track origin of escaped salmon and their progeny)	✔
Training at all levels in support of the goal and to increase awareness of the environmental consequences of escaped salmon	✔
Assessments of the relative risks to the wild stocks from escaped salmon from freshwater compared to marine facilities and from large but infrequent escape events compared to small but frequent escape events	✔

'The international salmon farming industry is continually investing to discover innovative approaches and effective methods to improve the management of sea lice and containment'

Cleanerfish

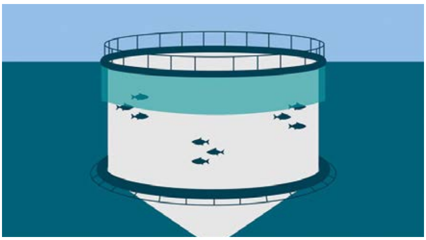
The use of cleaner fish to control sea lice as an environmentally friendly biological control is recognised as one of the key tools to control sea lice on fish farms.

Unni Austefjord

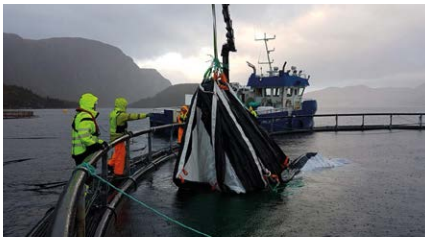
Sea Lice Skirts

Durable sheets of material that are secured to the collar of the salmon pen, extend 6-8m deep and are impervious to sea lice larvae.

Sea lice larvae generally live in the top few meters of the water column, so a skirt can act as a shield.



www.garwarefibres.com

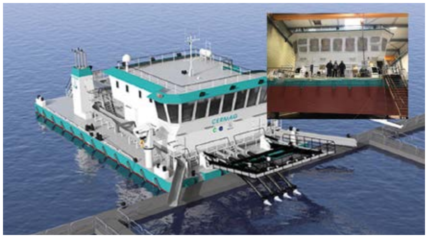


Selstad

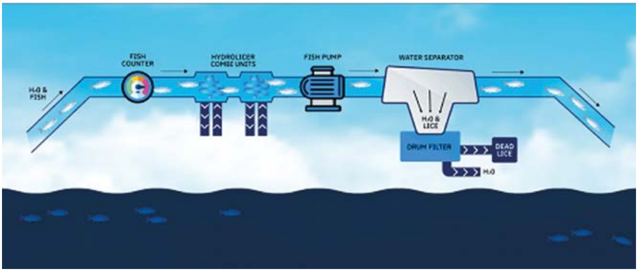
Physical Sea Lice Removal Systems

Hydrolicers and Thermolicers take advantage of parasite’s low tolerance for sudden changes in water temperature and salinity to physically remove the lice from salmon.

www.fsvgroup.com



thefishsite.com



www.aquahoy.com

Tubenet / Snorkels

Snorkels / Tubenets work by creating a physical barrier between the salmon and sea lice. A netted roof fits within the salmon pen with an enclosed ‘tube’ at the top extending to the water surface.

This technology keeps the salmon deeper in the water column and, therefore, away from sea lice larvae – which tend to be found in the first few meters of water.

As salmon need to return to the surface to take air into their swim bladders, this design enables them to easily reach the surface within a protected zone that keeps them separate from the sea lice.

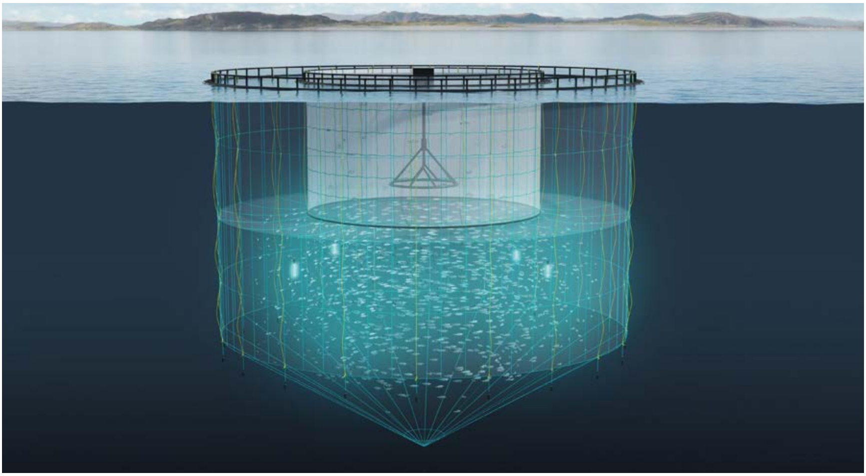
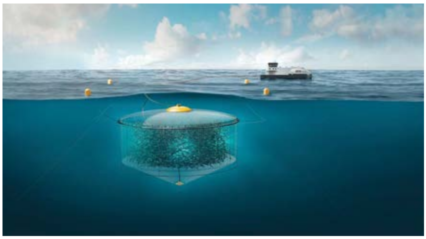


Image: AKVA www.akvagroup.com

Submersible Systems

AKVAs Atlantis



Images: AKVA www.akvagroup.com

Closed Containment Systems – Post Smolt

Image: https://www.fishglobe.no

Closed Containment Systems – Post Smolt

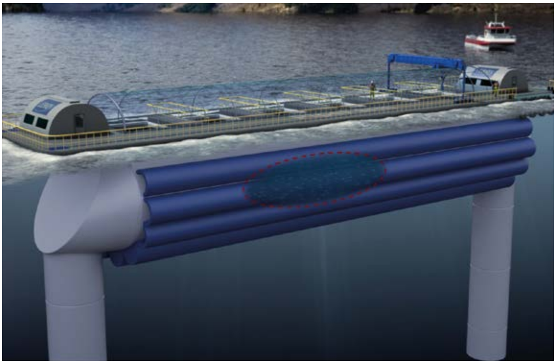


Image: https://www.leroyseafood.com

Closed Containment Systems – Post Smolt

Image: https://aquafarm.no

Physical Removal Using Lasers (Optical Delousing)

stingray Image: www.stingray.no

Closed Containment Systems – Post Smolt

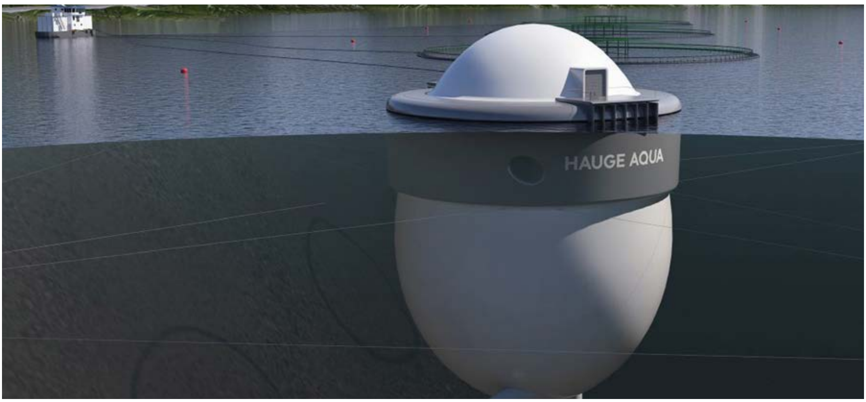


Image: https://haugeaqua.com

> *'The international salmon farming industry is continually investing to discover innovative approaches and effective methods to improve the management of sea lice and containment'*

Summary of the Discussions Held During the Theme-based Special Session

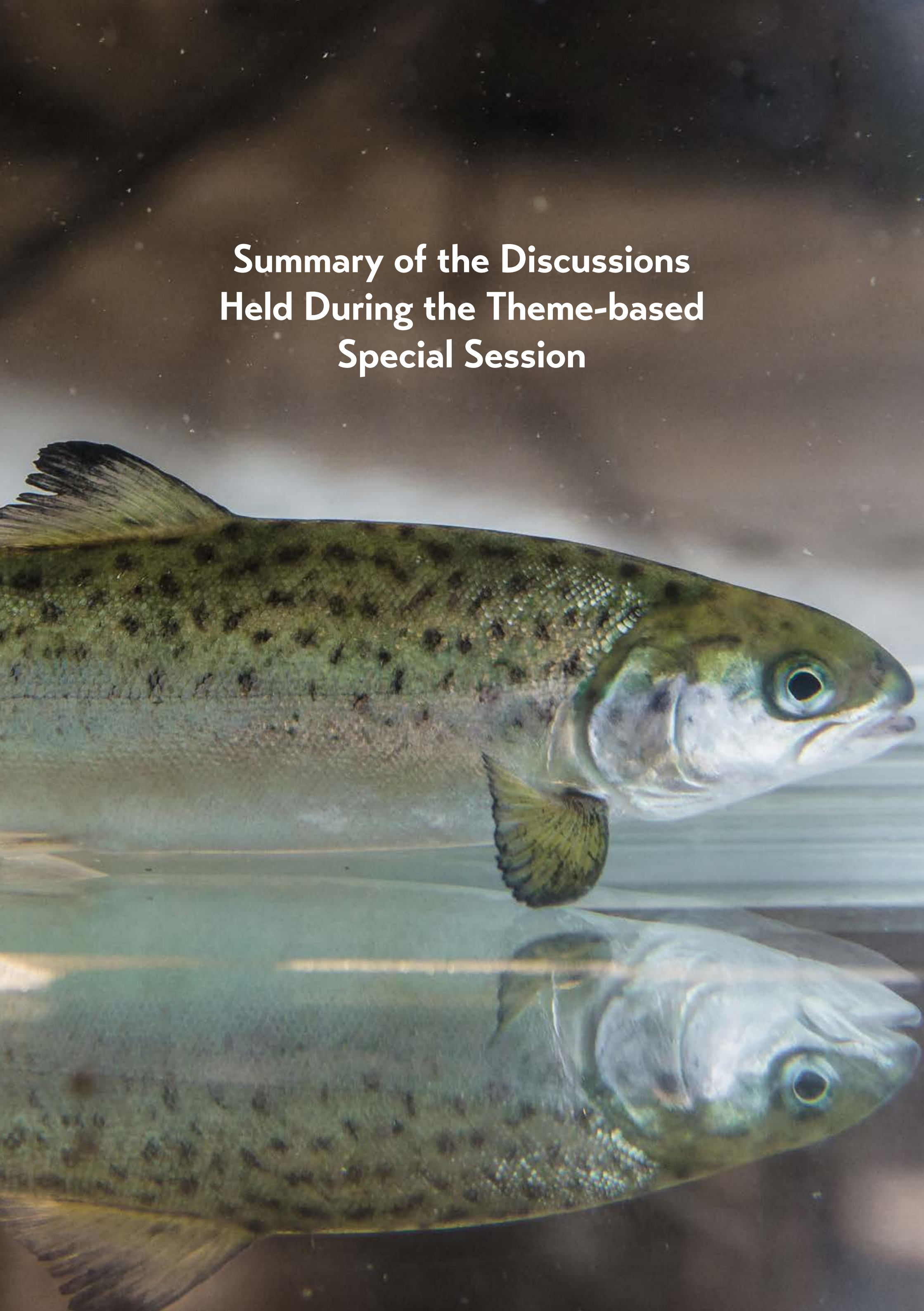


Photo: ‘Salmon post-smolt’ courtesy of Terje Aamodt©Nofima

Summary of the Discussions Held During the Theme-based Special Session

Examining the Current State of Scientific Knowledge

Raoul Bierach (Norway): thanked the speakers for their presentations. He noted that salmon need to cope with many changes, and that climate change is a very heavy burden affecting both fresh water and salt water. He asked Geir Bolstad how he expects continuing introgression to affect the salmon's ability to adapt.

Geir Bolstad (Norwegian Institute for Nature Research): indicated that the gene flow from escaped farmed fish would create difficulties for the evolution of the wild fish. He stated that continuous maladaptive gene flow from escaped farmed fish would hold the wild population back unless the farmed salmon is also selected for traits that help it to survive climate change. However, he explained that it is very difficult to select, artificially, for traits that are beneficial in the wild, as it is difficult to know what will work in the wild. He believed, therefore, that introgression would reduce the salmon's ability to evolve, but stated that it is hard to say by how much. It is likely that the most influential factor in this respect would be the level of gene flow.

Simon Dryden (Atlantic Salmon Trust): thanked the speakers for their presentations. He noted interest in the trawling Ørjan Karlsen had referred to, for the monitoring of sea lice on outmigrating smolts. He asked whether this trawling was only carried out in one area of Norway, as shown in the map in the presentation, whether it was conducted annually and whether the trawl technique perhaps underestimates the number of sea lice because some may be lost in the trawl. Finally, he asked for an indication of the cost of conducting the monitoring.

Ørjan Karlsen (Institute of Marine Research): replied that prior to 2017, trawling was carried out in two fjords each year. Since 2017, the trawling has been carried out in six fjords each year. It takes place during one month each year, and the aim is to time the monitoring to coincide with the estimated migration time of the fish, although they are not always successful in that respect. He agreed that some lice are probably lost from the fish, however, all the salmon are led into an aquarium at the end of the trawl which is designed to reduce scale and lice loss. However, this is not 100 % effective. He also reiterated that as the trawling is carried out within the fjords, before the fish have actually migrated large distances, the infestation pressure is underestimated. The cost is about one million Kroner per fjord per year.

Best Management Practices and New Technologies and Industry Implementation of New Technologies

Paddy Gargan (European Union – Ireland / Steering Committee Chair): noted his appreciation that Mark Lane had addressed the Best Management Practices, following previous concerns from the Steering Committee that the paper did not address the issues. He stated that he was glad to see that Mr Lane had indicated that he had updated the paper and had gone through all of the different goals and the Best Management Practices and set out how the industry is performing. However, Dr Gargan remained concerned that all of the Best Management Practices had been given a green or yellow score, while a lot of information contained in the Implementation Plans shows that a lot of industry is not achieving the international goals. He stated that he felt some people would have difficulties with Mr Lane's assessment of how the industry is performing, noting that there are a lot of published papers that show that there are impacts from sea lice, for instance, and that escapes are occurring that are not reported.

Mark Lane (International Salmon Farmers Association (ISFA)): acknowledged this comment.

Steve Sutton (Atlantic Salmon Federation / NGO Co-Chair): noted that the NGOs wished to follow up on Dr Gargan's comment. Dr Sutton thanked ISFA and Mr Lane for the paper and presentation and stated that the NGOs were also pleased to see some changes from the original paper submitted, including the specific mention of the international goals. Regarding the overview of the regulatory framework that was provided across the salmon farming jurisdictions, the NGOs felt that very little new information had been provided in the talk. Many of these details and regulations have appeared in Implementation Plans submitted by Parties and jurisdictions for the third reporting cycle of NASCO and many of the actions, based on that information, have been deemed unsatisfactory by the Review Group. Dr Sutton stated that the sad fact is that, despite the existence of these regulations and these regulatory frameworks, many of the key jurisdictions have not been able to demonstrate progress towards the agreed goals for sea lice and containment. He noted his belief that the regulatory frameworks within these relevant NASCO jurisdictions are not being implemented effectively and are not protecting wild Atlantic salmon from the known impacts of aquaculture. He felt that a great deal more commitment to wild fish conservation is needed from the salmon farming industry. He noted that he did not see much of a commitment in the information presented by ISFA. The NGOs called on ISFA to commit to developing genuine action plans designed to achieve the international goals and make that commitment back to NASCO.

Mark Lane (ISFA): thanked Dr Sutton for his comment and noted that he would take it back to ISFA.

Carl McLean (Canada): noted that in Canada, the provinces and the federal government have some jurisdiction around regulating the aquaculture industry. He stated that he did not think that assessing and regulating some of the projects would be a straightforward process and asked if there were any suggestions for how both the provincial and federal governments could get closer to having one kind of input and one output around regulating the aquaculture industry.

Secondly, he noted that Mr Lane had spoken about looking at risk-based site selection and asked how much priority is given to impacts on wild salmon rivers when the site selections are being undertaken.

John Campbell (Canada) (on behalf of Alistair Struthers): replied that, for the regulatory aspects, the Atlantic provinces are the lead regulators for all aquaculture on the east coast. DFO supports the provinces through its regulations as well as science work and support on issues such as siting. Other than that, there is a regular strategic committee, housed under the Canadian Council of Fisheries and Aquaculture Ministers, known as the Strategic Management Committee, where policy is discussed in Canada. The committee is a federal committee and includes all provinces, not just the Atlantic provinces. Through the Committee the relevant bodies are able to connect and discuss how to streamline and work closer together. While the provinces all have different regulatory systems, often, as one province updates its regulatory systems, so do the other provinces. Mr Campbell felt that the provinces do a great job in communicating with each other.

Mark Lane (ISFA): stated that with regards to site selection in Canada, applicants must respond to around 15 different federal and provincial departments and regulatory agencies including DFO, the Canadian Food Inspection Agency, Health Canada, Transport Canada, Environment and Climate Change, etc. All of these are involved in any process application or site selection or site approval.

In terms of site selection, he noted the aquaculture industry's concern for the environment and conservation. He indicated that he began his own career doing a salmon enhancement project on his local river. He stated that the industry always aims to reduce any type of impact on the environment or those marine organisms that live in the environment. He noted that his presentation included the amount of monetary and human resource investment that the industry has made since the last update in 2016 to achieve that. From the time a site application is made to the provincial government, for example, it must go through all those departments. It also has to go through public consultation, indigenous consultation, other stakeholder consultation, etc. He stated that he believes that the process is quite good in Canada and quite good in Newfoundland, noting that while it does take some time, it is very thorough and robust. He indicated that when a potential new site is considered, various studies are undertaken such as environmental studies, oceanographic studies and benthic observations using

Remotely Operated Vehicles and different types of technologies. The intent is to site the farms as far away as possible. Often, there is criticism of farms being, for example, in the mouths of rivers. He stated that this is not the way the industry operates; most of the farms are well away from registered or licensed salmon rivers.

He summarised by saying that for risk mitigation or risk management and site selection, the industry does a huge amount of preliminary work which is then vetted through a number of departments, upwards of 14 or 15 provincially and federally, and then goes through public consultation.

Paul Knight (Salmon and Trout Conservation UK / NGO Co-Chair): noted his support for the intervention by Dr Sutton. He expressed his concern that this Special Session could be seen as an ISFA / NASCO or NGO fight. He felt that there had been some brilliant information at the session and thanked all the speakers. He noted that he was extremely impressed by the lice dispersal model and seeing it in action, adding that it was frightening to see just how far lice could go from open net farms. He felt that the information on closed containment was very interesting, but agreed with Dr Sutton that there was nothing new from ISFA. He understood, from what had been said, that socio-economics are most important and the industry is making a lot of money out of open net farming. He noted that the information given in the session showed that there is huge potential for closed containment, whether it be in the sea or land based. He urged ISFA to forget the rhetoric and asked Mr Lane to make his Executive aware that the whole wild salmon world is looking to ISFA and the international fish farmers to really do something about protecting wild fish. He stated that while he could hear a lot of rhetoric, he could not hear anything new that gave him any great comfort.

Finally, he referred to the presentation by Dr Nilsen and the suggestion that there was a possibility that lice could get into closed containment, but the larvae would be washed out by the system. He asked Dr Nilsen whether those larvae would be dangerous to wild fish when washed out through the system and whether those closed tanks could still be repositories for breeding lice. He noted concern that the larvae may get washed out so, while they do not impact the fish welfare in the tanks, they could still impact on wild fish in the area.

Arve Nilsen (Norwegian Veterinary Institute): explained that the incidents referred to in the presentation had occurred in 2013 / 2014 at the latest. Fish with sea lice were put into the closed cages or were moved from one cage to another, and the new closed cage was accidentally filled with contaminated surface water. Very moderate-to-low levels of sea lice were found and no signs were found of reproduction inside the cages. The numbers reduced relatively rapidly towards zero. He stated that the cages are not being stocked with infested fish; they are being stocked with lice-free smolts and the lice numbers are zero. He indicated that he felt that the cages or farms are not repositories for sea lice affecting the wild fish.

Dr Nilsen then asked how the risk of microbiological impacts on the marine environment, including on wild salmonid stocks, from the marine systems should be considered and managed. He stated that within Norway and Canada, at least, the Piscine Orthoreovirus (PRV) situation is concerning and there are other pathogens too. He noted that there is a broader range of potential damage which is not limited to sea lice and escaped fish.

Åsa Maria Espmark (Nofima): replied that, with regards to the semi-closed containment systems, she could only offer a general response as there had not been any specific analysis on a lot of pathogens. However, a Professor at the University of Bergen has been following what comes into the system and from the fish for many years and, in general, the majority of the pathogens are coming from the fish, from the RAS phase, except for some parasites. She stated that, as mentioned in Dr Nilsen's presentation, this is partially linked to where the water is taken from. Normally, where issues have occurred, the inlet to the semi-closed containments is too shallow and should have been taken from deeper water where there is more control over the pathogens. It is also site specific. In some areas, different depths will have different pathogens, whereas the situation is totally different in another area.

Andrew Graham-Stewart (Salmon and Trout Conservation Scotland): stated that, reading between the lines of the ISFA presentation, it is self-evident that the salmon farmers are not going to change voluntarily; they will only change if and when new technologies become cost effective which could take years. He felt that the approach of waiting for new technologies lets governments off the hook. They have a responsibility to protect wild fish now, in line with the NASCO goals. He stated that in the short-to-medium term, there will be no progress unless the NASCO goals, particularly on sea lice, are made legally binding.

Mark Lane (ISFA): replied that, as shown in his and other presentations, there is a tremendous amount of time, effort and money being spent in all jurisdictions on RAS facilities. He indicated that currently, in Newfoundland, two of the largest RAS facilities in the world are being built with private money. Semi-closed containment, closed containment, land based, offshore are all being driven by the industry. He felt it was unfair to say that the industry has to be regulated into it. He stated that the industry knows the challenges better than anybody and invests its time and money to fix them as responsible farmers of the sea. He indicated that the industry is willing to work with others to improve the way things are done and he felt disappointed that Mr Graham-Stewart believed the industry was not committed. He assured participants at the session that the President of ISFA, himself and others, are committed to the environment, the protection of wild salmon and to producing premium seafood. He stated that there does not need to be a regulatory agency to force the industry to do so, it is done voluntarily.

Getting to Where We Want To Be

Niall Greene (Salmon Watch Ireland): congratulated the organizers of, and participants in, the session. He stated this was probably one of the best Special Sessions he had attended. He welcomed the fact that the Irish Department of Agriculture, Food and the Marine (DAFM) was present at the session. He noted that this was important because that Department is responsible not only for the development and promotion of salmon farming in Ireland, but also for the setting of standards, the licensing and the regulation of salmon farming. He hoped that DAFM would take a lot back from the session about the importance of the NASCO goals and the way in which, if an ambitious rather than defensive policy stance is taken, the tools are out there to begin to address the serious impacts of salmon farming on the wild salmonid population. He noted that the final part of the session was devoted to implementation and, in particular, asked what further steps NASCO can take to achieve the NASCO goals. Mr Greene indicated that recent statements, including at the meeting by the NGO Co-Chairs, show that the NGOs believe that NASCO needs some teeth to advance the goals which it adopts, and the policies it develops to achieve those goals. He stated that this is an issue which could not and would not be resolved at the session, but which the NGO group would be pursuing vigorously in the upcoming external review process.

He noted that, for the moment, we must rely on the IP and APR review process, revised to include the communication from the President to the political heads and individual Parties that are responsible for unsatisfactory elements. He felt it was important that this particular process gets the greatest possible transparency. While he was certain NASCO would do as much as it could, he felt that, at a national level, there must be a transparent process for highlighting those deficiencies that have been raised, and highlighting the responses that are being made to them, without the need for NGOs to undergo lengthy Freedom of Information and Environmental Information application processes. He noted that he felt, regretfully, that in the short run, the IP process is probably the main mechanism available for advancing the NASCO goals, ensuring that a bright light is shone on what is going on and that people understand the interactions between NASCO and the national governments.

Paul Knight (Salmon and Trout Conservation UK / NGO Co-Chair): noted that there had been a lot of information about new technologies at the session. He reiterated that the presentations had been terrific and positive, until the ISFA presentation. He stated that this is all new technology; closed containment is in its infancy and could take a very long time to come about. He noted that he understood that companies like Atlantic Sapphire are completely new investment rather than existing fish farming company investment. He felt that there are almost two industries involved: the closed containment industry all over the world, which seems to be new money and new investment; and the traditional industry which is more entrenched, because they are making a lot of money on open net farming, despite the fish welfare issues and impacts on wild fish.

In support of what Mr Greene said, Mr Knight believed that in the short-to-medium term, it really is down to the Parties and jurisdictions to make sure that they regulate this industry so that there is some sort of chance of achieving the NASCO goals. He indicated that he is part of the Review Group and that Group is fed up with reading Actions like ‘we have no new actions to counter fish lice’, as stated in one IP. He felt that this was not acceptable, but there is currently no comeback on those jurisdictions or Parties other than to state that this is not an acceptable action.

He stated that NASCO must have the influence to tell its Parties and jurisdictions that they really must regulate in the short-to-medium term because there is no other option. He felt the industry would sort itself out, but far into the future. Closed containment will come onboard, but he felt it necessary to find some sort of mechanism between now and then to stop this impact on wild fish because wild fish are probably at their most vulnerable for tens of thousands of years. He stated that we do not have the time to wait for new technologies; we have to act now and that is down to governments. He noted that any pressure that NASCO can bring to bear on its member governments through their representatives at the table should be embraced.

Steve Sutton (Atlantic Salmon Federation / NGO Co-Chair): noted that it is clear from Alistair Struthers’ paper, presented by Doug Bliss, that the Government of Canada is doing some significant work around exploring alternative technologies for aquaculture on the west coast of Canada. He stated that the Government of Canada has promised to transition away from open net cage aquaculture on the west coast of Canada by 2025. This is being done for the express purpose of protecting wild Pacific salmon. On the east coast, there are jurisdictional issues with the provinces being more involved. He indicated that some NGOs recently wrote to the Minister of Fisheries and Oceans, who has made the commitment on the west coast, with questions about why they are not taking the same interest on the east coast, to protect wild Atlantic salmon from aquaculture. The response from the Minister of Fisheries was that they have no evidence, or they see no evidence, that aquaculture is impacting wild Atlantic salmon on Canada's east coast. He noted that the narrative is constantly the same from the industry, including from Mark Lane, who often states on the media that the industry has no impact on wild Atlantic salmon.

Dr Sutton indicated it is, therefore, no wonder that Canada has not been able to show any progress towards meeting the international goals. He further stated that it is no wonder that Canada has no effective actions or acceptable actions to address the issues, because there is not even an acknowledgement that there is an issue to solve on the east coast. He asked what can be done about that and how we can progress if we cannot even get the people who are responsible for this industry and regulating it to even acknowledge that there is a problem. He further asked what NASCO can do to help overcome that hurdle, noting that if NASCO can do nothing, he felt that NASCO either needs to change or move on to something else.

Paddy Gargan (European Union – Ireland / Steering Committee Chair): stated that he believes that the Implementation Plan review process is there to encourage and to ask jurisdictions to put in actions and to assess whether those actions are adequate. He noted that most countries have failed on their aquaculture actions and know the process will continue and encouraged them to adopt policies so their actions are acceptable.

Andrew Graham-Stewart (Salmon and Trout Conservation Scotland): * noted that a similar problem to that mentioned by Dr Sutton exists in Scotland. Mr Graham-Stewart stated that in November 2020, a representative of the Scottish Environment Protection Agency (SEPA) was giving evidence at a parliamentary commission and was asked about the impact of sea lice on farmed fish. He stated that the representative said 'Do we think that sea lice from farmed fish are responsible for the declines that we have seen over the decades in wild fish? No'. Mr Graham-Stewart noted that this individual is from an agency that will be shortly responsible for interactions between farmed and wild fish. He felt that a losing battle was being fought because the salmon farming industry in Scotland constantly falls back upon this position of 'there is no evidence'. Mr Graham-Stewart asserted that this must change, that NASCO needs to intervene and come up with an absolutely clear set of guidelines, or similar, along the lines of 'There are impacts'. Mr Graham-Stewart stated that we cannot hide behind this 'no evidence' as it allows governments and the industry off the hook constantly.

Paddy Gargan (European Union – Ireland / Steering Committee Chair): indicated that the first recommendation of the Theme-based Special Session Steering Committee may be helpful in this respect.

*A representative of the United Kingdom raised an issue related to this intervention during the Council discussions following the Theme-based Special Session. Further information can be found in the report of the Annual Meeting of the Council (NASCO 2021).

Conclusions of, and Recommendations from, the Theme-based Special Session Steering Committee

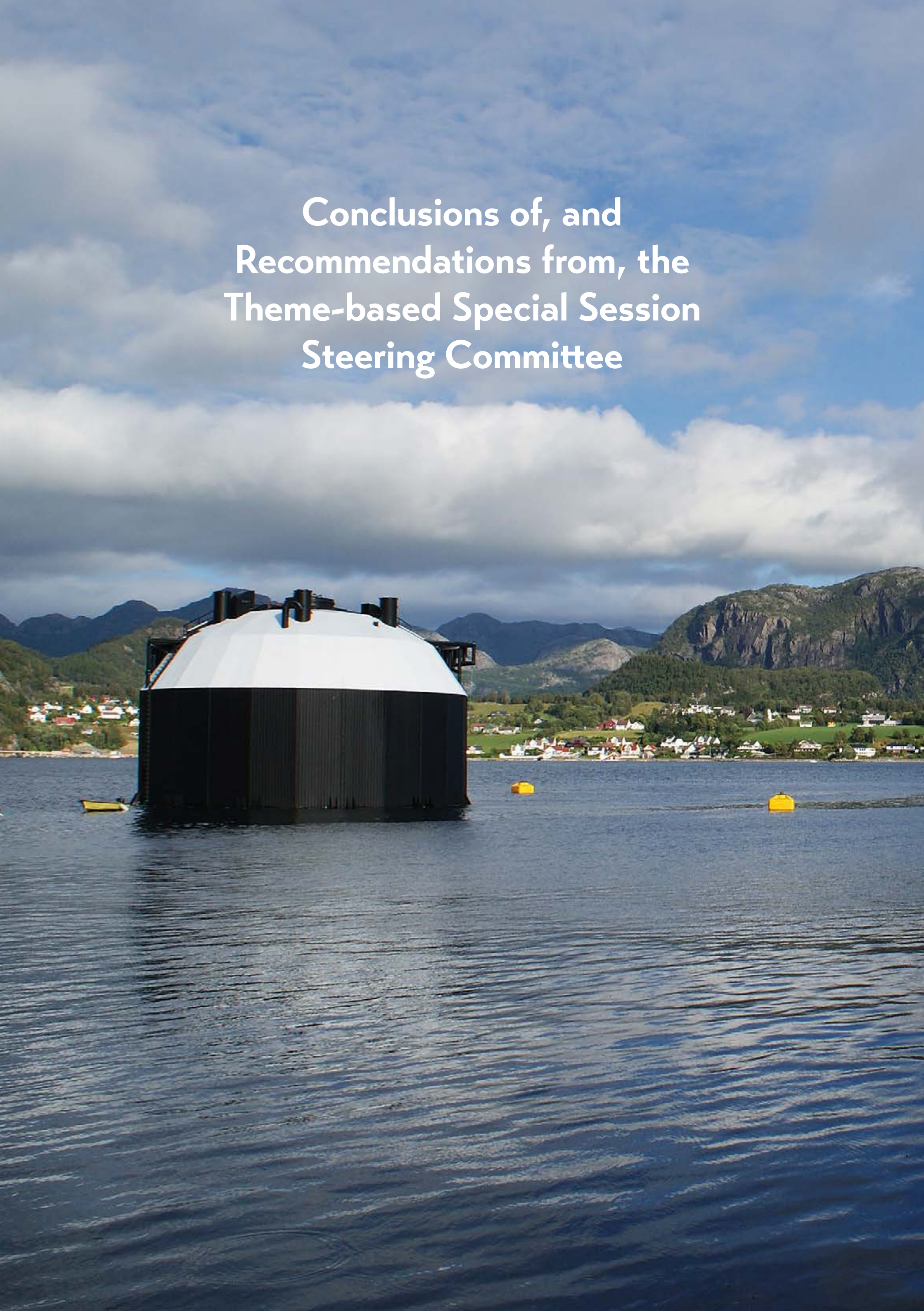


Photo: ‘FishGlobe semi-closed containment system’ ©FishGlobe

Conclusions of, and Recommendations from, the Theme-based Special Session Steering Committee

The NASCO Convention requires that, in exercising its functions, the Organization takes into account the best scientific information available to it.

In 1998, NASCO and its Parties agreed to adopt and apply a Precautionary Approach to the conservation, management and exploitation of wild Atlantic salmon to protect the resource and preserve the environments in which it lives. The Precautionary Approach requires that more caution is exercised when information is uncertain, unreliable or inadequate. The absence of adequate scientific information should not, therefore, be used as a reason for postponing conservation and management measures.

Since 1988, when the Council of NASCO first reviewed the matter, there has been mounting concern that interactions between wild and farmed salmon might prove deleterious to the wild stocks. These negative interactions include: the introduction, or enhancement, of diseases and parasites; farmed escapees leading to changes in the genetic composition of wild salmon stocks; and additional effects leading to harmful ecological consequences.

In response to these concerns, NASCO and ICES have co-convened various international meetings since 1989, the most recent of which was in 2005 (Hansen and Windsor 2006). These have reviewed the scientific understanding of interactions and provided guidance on appropriate management responses.

On the basis of the findings in the 2005 Symposium, NASCO amended its 2003 Williamsburg Resolution (NASCO 2006) and, in 2009, NASCO and the International Salmon Farmers Association (ISFA) developed jointly, and agreed, the 'Guidance on Best Management Practices to address impacts of sea lice and escaped farmed salmon on wild salmon stocks', the BMP Guidance, (NASCO 2009), which established the following international goals:

- 100 % of farms to have effective sea lice management such that there is no increase in sea lice loads or lice-induced mortality of wild salmonids attributable to the farms; and
- 100 % farmed fish to be retained in all production facilities.

In 2015, NASCO requested that ICES advise on possible effects of salmonid aquaculture on wild Atlantic salmon populations, focusing on the effects of sea lice, genetic interactions and the impact on wild salmon production and ICES reported in 2016 as part of that year's advice (ICES 2016). At that time ICES advised that:

> *'...there is substantial and growing evidence that salmon aquaculture activities can affect wild Atlantic salmon, through the impacts of sea lice as*

well as farm escapees. While both factors can reduce the productivity of wild salmon populations, there is marked temporal and spatial variability in the magnitude of reported effects'.

In 2016, NASCO convened a Theme-based Special Session on 'Addressing impacts of salmon farming on wild Atlantic salmon: Challenges to, and developments supporting, achievement of NASCO's international goals' (NASCO 2016). The conclusions from that Theme-based Special Session were:

'The Steering Committee believes that there is now sufficient evidence of significant impacts having occurred that all Parties/jurisdictions with salmon farms must implement further, more stringent measures to protect the wild stocks from the impacts of salmon farming if they are to meet their obligations under the NASCO Convention. The Williamsburg Resolution states that where significant adverse impacts on wild salmon stocks are identified, the Parties should initiate corrective measures without delay and that these should be designed to achieve their purpose promptly. New approaches that could assist in addressing impacts are at various stages of development and implementation, but there are undoubtedly substantial challenges to be addressed if the international goals for salmon farming are to be achieved. In the Steering Committee's view, there is now an urgent need for all Parties/ jurisdictions to adopt stronger measures if their international responsibilities are to be met which it believes is not currently the case'.

NASCO convened a symposium in 2019 as its major contribution to the International Year of the Salmon (IYS). The IYS Symposium, entitled 'Managing the Atlantic Salmon in a Rapidly Changing Environment – Management Challenges and Possible Responses', included several presentations on the challenges of reducing the negative impacts of aquaculture on wild Atlantic salmon. The Symposium Steering Committee concluded (NASCO 2020a) that:

'Given the continued impacts of domestic salmon farming on wild salmon, NASCO should strengthen compliance to the agreed international goals of '100% farmed fish to be retained in all production facilities and, 100% of farms to have effective sea lice management such that there is no increase in sea lice loads or lice-induced mortality of wild salmonids attributable to the farms'. This is as stated in the 2009 'Guidance on Best Management Practices to Address Impacts of Sea Lice and Escaped Farmed Salmon'.

At this juncture, it appears that many of the findings from the symposia / studies referred to above are still valid but they now have added urgency. Since 2005, production of farmed salmon in the North Atlantic has more than doubled, while in contrast, wild salmon abundance has continued to decline throughout the North Atlantic. The provisional estimate of farmed Atlantic salmon production in the North Atlantic area for 2020 was some 1.82 million tonnes (ICES 2021). Norway and UK (Scotland) continue to produce the majority of the farmed salmon in the North Atlantic (77 % and 11 %, respectively). The provisional total reported catch for wild Atlantic salmon in 2020 was 915 t. The production of farmed Atlantic salmon in the North Atlantic alone is now almost 2,000 times the reported catch of wild salmon in the North Atlantic.

Additionally, Council had expressed a wish to strengthen the Implementation Plan / Annual Progress Report (IP / APR) process through, among other things, including a greater emphasis on actions by Parties / jurisdictions working toward the achievement of the international goals for sea lice and containment by the end of the reporting period. Despite this, during its reviews of the IPs submitted under the third reporting cycle, the IP / APR Review Group has expressed concern at the failure by some Parties / jurisdictions to adopt actions in line with the international goals, specifically aimed at protecting wild salmonids. NASCO's accredited NGOs have also expressed concern about Parties' and jurisdictions' lack of commitment to the agreed international goals during the reviews of the IPs submitted under the third reporting cycle. During this period, the NGOs requested that Council consider a second Theme-based Special Session on aquaculture, given the limited progress demonstrated by many of the Parties / jurisdictions in this area.

The overarching objective for the 2021 Theme-based Special Session was to stimulate urgent action to implement further measures to protect wild salmon from the impacts of salmon farming, and to ensure demonstrable progress by Parties / jurisdictions towards achievement of the international goals for sea lice and escaped farmed salmon, taking into account the recommendations from the Steering Committees of the 2016 Theme-based Special Session (NASCO 2016) and the 2019 IYS Symposium (NASCO 2020a).

To address the agreed objective for the Theme-based Special Session, the Steering Committee's programme comprised the following four topic areas:

1. Reviewing critically the extent to which NASCO Parties / jurisdictions are meeting the international goals for sea lice and escaped farmed salmon;
2. Updating the current state of scientific knowledge of the adverse impacts of escaped farmed salmon and sea lice on wild Atlantic salmon;
3. Highlighting advances in best management practices and new technologies (infrastructure / biological etc.), their efficacy in mitigating adverse impacts on wild Atlantic salmon and challenges to their urgent implementation, and how to incentivise industry to move towards implementing these new technologies; and
4. Exploring in depth how Parties / jurisdictions can move more rapidly towards the achievement of the international goals.

The Steering Committee offers the following conclusions on each of the Special Session topic areas.

1. Reviewing Critically the Extent to Which NASCO Parties / Jurisdictions are Meeting the International Goals for Sea Lice and Escaped Farmed Salmon

The Chair of the IP / APR Review Group stated that it was clear from three rounds of review of the IPs submitted by the Parties and jurisdictions since February 2019 that many of the national policies of countries with salmon farming are not in line with NASCO's BMP Guidance (NASCO 2009), despite this being agreed jointly with the Parties and ISFA in 2009. The Review Group has determined that there is:

- little to no monitoring of sea lice loads on wild salmon;
- little progress towards 100 % effective sea lice management on farms;
- limited quantifiable progress related to actions on containment of farmed salmon;
- limited monitoring of the impact of escapes (e.g. genetic introgression) on wild salmon; and
- a lack of clarity as to how salmon farming facilities are located to minimise the risk to wild salmon stocks.

Additionally, the IP / APR Review Group Chair noted that some Parties / jurisdictions with salmon farming have made it clear that there is no intention to take mitigating steps to reduce the impact of their farming practices on wild Atlantic salmon, despite having signed up to NASCO's Resolutions, Agreements and Guidelines.

The Steering Committee considers that the current adherence to NASCO guidelines with regard to salmon aquaculture for the main salmon producing countries is unacceptable and wild salmon stocks continue to decline.

While the Steering Committee recognises that salmon farming is not wholly responsible for the overall decline of wild Atlantic salmon stocks, there is a growing body of incontrovertible evidence that sea lice and farmed salmon escapees can cause significant increased mortality and negative population effects. As signatories to the BMP Guidance (NASCO 2009), there is a responsibility on the members of ISFA to manage salmon farming to ensure adherence to the international goals for sea lice and containment. Ultimately it is the responsibility of the Parties and jurisdictions, all of whom signed up to the BMP Guidance in 2009, to regulate effectively such that the international goals on sea lice and escapes can be achieved. The evidence to date indicates that these are far from being achieved.

2. Updating the Current State of Scientific Knowledge of the Adverse Impacts of Escaped Farmed Salmon and Sea Lice on Wild Atlantic Salmon

Escaped Farmed Salmon

During the Theme-based Special Session, Dr Bolstad presented a study based on more than 7,000 salmon caught by anglers in 105 Norwegian salmon rivers in which the consequences for wild Atlantic salmon populations following introgression from farmed escapees were shown to be very negative in several ways, including:

- reducing productivity, with good evidence of reduced survival in the wild; genetic changes away from optimal life history trade-offs leading to reduced fitness; and a faster pace of life associated with more fluctuations in abundance, which further reduces long term population growth rate;
- reducing resilience to future challenges where one-way gene flow from farmed escapees is expected to erode the genetic variation of adaptively important traits in the wild; and
- altering ecosystem effects where a change in foraging behaviour and prey type that can have cascading effects in the river ecosystems is predicted, given a faster pace of life and a higher metabolism.

Additionally, one of the conclusions of the recent Sixth Assessment Report 2021 by the Intergovernmental Panel on Climate Change (IPCC 2021) is that the scale of recent changes across the climate system is unprecedented over many centuries to many thousands of years. Dr Bolstad commented in response to a question on the impacts of introgression that the gene flow from farmed escaped fish will obstruct the ability of wild salmon to respond to a changing environment.

The Steering Committee considers that introgression from escaped farmed salmon has caused unacceptable, detrimental genetic changes that are widespread in wild Atlantic salmon populations. The new research from Norway reveals that changes in life history parameters (faster growth and younger age at maturity) is one mechanism through which introgression leads to maladaptation and reduced productivity in wild salmon populations.

All of NASCO's Parties signed up to the international goal stating '100% farmed fish to be retained in all production facilities' in 2009. This international goal was developed together with ISFA. Farmed salmon producing countries need to do more to achieve the containment goal. The Steering Committee therefore considers that NASCO must increase pressure through the Implementation Plan process on those Parties / jurisdictions, to remind them of their commitment to the achievement of this international goal and to encourage strong acceptable actions through the Implementation Plan process.

Sea Lice

Several of the presenters noted that sea lice impact individual salmonids negatively in several ways, including by increasing their susceptibility to infection, reducing growth and swimming capacity, increasing predation and increasing their mortality.

In Norway, salmon usually enter the sea during spring; salmon originating from rivers flowing into fjords have to swim through the fjords to reach the open ocean. Dr Karlsen noted that the distance and route they migrate affects their possibility of being infected by sea lice. As the release of lice from active salmon farms usually increases during spring and summer due to temperature and farming practices, the later the smolts leave the fjords then the higher their possibility of being infected. Dr Karlsen presented a recent study that showed that the estimated mortality of fish from rivers in the inner part of a studied fjord is higher each year than for fish from rivers in the areas nearer the coast and, when combined with lice density, the modelling shows that smolts from rivers in the outer parts of the fjord are less affected by lice than smolts from rivers in the inner parts of the fjord.

He also stated that in terms of the impact on wild salmon populations, it has been estimated recently that, in Norway, sea lice have reduced the number of returning salmon by 50,000 for the years 2012-14, 29,000 in 2018 and 39,000 in 2019. Sea lice are regarded as an expanding threat to wild salmon populations which is affecting populations to the extent that wild salmon populations may be critically endangered or lost.

The Steering Committee considers that, without significant improvements to sea lice management, there is a high likelihood of sea lice causing even further reductions to wild salmon populations given the continuing increasing trend in farmed salmon output.

All of NASCO's Parties signed up to the international goal stating '100% of farms to have effective sea lice management such that there is no increase in sea lice loads or lice-induced mortality of wild salmonids attributable to the farms' in 2009. This international goal was developed together with ISFA. Farmed salmon producing countries need to do more to achieve the sea lice management goal. The Steering Committee therefore considers that NASCO must increase pressure through the Implementation Plan process on those Parties / jurisdictions, to remind them of their commitment to the achievement of this international goal and to encourage strong acceptable actions through the Implementation Plan process.

3. Highlighting Advances in Best Management Practices and New Technologies, their Efficacy in Mitigating Adverse Impacts on Wild Atlantic Salmon and Challenges to their Urgent Implementation, and How to Incentivise Industry to Move Towards Implementing these New Technologies

In his presentation, Dr Nilsen remarked that methods to prevent sea lice infestations have received little research effort, despite the many possible benefits of prevention over treatment-focused methods. With effective prevention against salmon lice, it could be possible to avoid the use of drugs with their negative impact on non-target species around the salmon farms and the ever-present challenge of drug-resistant parasites.

Dr Pietrak explained that two technologies that are being researched currently may help manage sea lice in open net cage salmon farms. The first incorporates sea lice resistance into the existing selective breeding programme of the farmed salmon and the second is the development of fish, such as lumpfish and wrasse, culture techniques and broodstock for use as cleaner fish in the open net cages, rather than catching and removing wild fish from stocks whose population dynamics are poorly understood.

The Steering Committee recognises that significant advances are being made in these developments, both for selective breeding for sea lice resistance and in the use of reared cleaner fish, especially lumpfish. However, neither of these technologies likely represents a silver bullet to managing sea lice populations on either a local or global scale. Both technologies can be important tools and components in effective integrated pest management programmes. However, it is important to consider that no specific system of control strategies will fit all regions, water bodies or even companies. Rather, systems would need to be individually tailored to each farm. Considerably more research is needed, including a rigorous determination of what strategies and technologies are effective at the local level and defining the economic costs of each strategy.

Other technological developments in the salmon farming industry have the ability to limit interactions between farmed salmon and the natural environment and, therefore, between farmed and wild salmon. Several of the Theme-based Special Session presenters noted that semi-closed cages are one such technology. These introduce a solid barrier between the farmed fish and the surface water. Water is pumped from 20 to 30 m depth, thus effectively avoiding the infective sea lice copepodites. If open net cages are replaced with semi-closed cages, the negative impact on wild salmonid populations from heavy sea lice infestations will be significantly reduced.

Dr Nilsen commented that for open net cages, in 2021 the Norwegian Directorate of Fisheries reported sea lice treatments with the accompanying use of boats and handling of nets as a major risk factor for tearing of nets and thus escaped farmed salmon. He noted that semi-closed cages with a commercially developed and certified technology, combined with location at more sheltered sites, could also be a way to reduce the risk of escapes. However, it is an ongoing discussion whether the introduction of more semi-closed cages will reduce or increase the risk of escaped fish. In Norway, for all technologies, semi-closed cages are certified for less exposed sites (i.e. with a lower wave height) than open net cages which is a challenge to their effective use.

In his presentation, Mr Bliss, on behalf of Mr Struthers, noted that the Canadian government has promised to have a plan to transition from open net salmon cages by 2025 in the province of British Columbia. There is, therefore, an incentive for its salmon farming industry to develop cost-effective technologies to replace open net cages. He explained that, in Canada, large integrated salmon producers have already begun investing heavily in hybrid systems to combine the benefits of both closed and open systems. Regulatory and policy frameworks, along with a familiar operating environment, already exist in Canada to accommodate this technology. A Fisheries and Oceans Canada funded study in 2018 indicated that the four production technologies studied: land-based closed-containment; floating closed-containment; offshore technologies; and hybrid systems that combine both land and marine-based systems, offer multiple improvements over the predominant conventional net cage production systems in terms of reducing interactions between farmed and wild salmon, but the assessment against other environmental, economic and social elements varied. These findings can be considered to be a challenge to their introduction and regular use when compared to open net cages.

Dr Sterud noted that, for decades, the normal way of producing farmed salmon has been 6 – 12 months' production of 100 g smolts in land-based hatcheries followed by 15 – 18 months' production in open net cages in coastal areas. The increased use and rapid development of recirculating aquaculture systems (for land-based closed containment) – RAS – has opened up alternative ways of farming salmon. Both Dr Espmark and Dr Sterud noted that the use of RAS exclusively for production of smolts (and, more recently, post-smolts) enables a production that is not dependent on the natural annual cycle of the salmon. The production of post-smolts is relatively new and much research is being done to secure fish welfare and robustness in the systems and to ensure that the fish are fit for life in the sea when they reach the appropriate size. This leads to one more advantage of the systems in that the farmed salmon are kept away from the open sea for longer, and thus longer periods away from lice.

In her presentation, Dr Espmark described a recent study in Norway that followed a group of 200,000 smolts from a RAS facility, into a semi-closed system and finally out to an open net cage. The main conclusions from this study were that growth was better during the time that the fish spent in the semi-closed system compared to both the RAS phase and the three months that the fish were followed in the open net cage. This technology enables farmed salmon to be kept in the open water for less time compared to traditional production techniques, with less opportunity for impact on wild salmon. It was also documented that skin health improved during the stay inside the semi-closed system, shown by histology and gene expression analyses. It is thought that a slight increase in temperature inside the system improved growth, and that good water quality facilitated skin health and growth.

The Steering Committee considers that such new technologies and production protocols, where growth of the farmed salmon is improved and where the necessity to mitigate sea lice infection is greatly reduced, should provide adequate incentives to the salmon farming industry to move away from the old protocols and technologies that have been in place for many years. These are useful tools to reduce the conflicts between farmed and wild salmon; they also benefit farmed salmon. Thus, the Steering Committee welcomes further development of these alternative technologies, and would like to see them promoted, supported and incentivised by the governments of the relevant jurisdictions, who will, by necessity, need to play an important role in this technological transition.

The Steering Committee notes, however, that ultimately, it is the responsibility of the Parties' governments, all of whom signed up to the 2009 NASCO / ISFA BMP Guidance, to work towards achievement of the international goals.

In terms of the contribution to the Theme-based Special Session by the salmon farming industry, the representative of ISFA explained that much of the new technology discussed is already being employed across the North Atlantic in salmon farming. Several companies are using RAS facilities in Norway, Canada and the UK to produce post-smolts to be stocked into marine cage sites at sizes between 500 and 1,200 g and virtually all other jurisdictions have plans for, or are in construction of, post-smolt facilities. Closed-containment systems are either in the design, testing or pre-commercial phases of development. The reporting of escapes is mandatory in many jurisdictions.

The Steering Committee recognises that across the North Atlantic the proportion of escapes is in decline due to improved farm management practices. Nevertheless, significant escapes continue to occur and, due to the size of the industry, even a small proportion of escapes can equate to large numbers of farmed salmon that can, and demonstrably do, overwhelm the local wild salmon populations. The Steering Committee also notes that many salmon farming regulations have appeared in Implementation Plans submitted by Parties and jurisdictions for the third reporting cycle of NASCO. However, despite the existence of these regulations and these regulatory frameworks, many of the key jurisdictions have not been able to demonstrate progress towards the agreed international goals for sea lice and containment.

The Steering Committee considers that a great deal more commitment to wild fish conservation is required from the salmon farming industry.

The Steering Committee calls upon ISFA to commit to developing meaningful action plans designed to achieve the international goals, agreed in 2009, and to make that commitment back to NASCO. The Steering Committee considers that the lack of meaningful actions by the industry to demonstrate progress is a major impediment to the urgent implementation of the international goals, and in mitigating the adverse impacts of salmon farming on wild Atlantic salmon.

4. Exploring In Depth How Parties / Jurisdictions Can Move More Rapidly Towards the Achievement of the International Goals

The overarching objective for the 2021 Theme-based Special Session was to stimulate urgent action to implement further measures to protect wild salmon from the impacts of salmon farming, and to ensure demonstrable progress by Parties / jurisdictions towards achievement of the international goals for sea lice and escaped farmed salmon, taking into account the recommendations from the Steering Committees of the 2016 Theme-based Special Session (NASCO 2016) and the 2019 IYS Symposium (NASCO 2020a).

There are clearly new technologies in the pipeline to mitigate the negative impacts of salmon farming on wild Atlantic salmon. However, much of the salmon cage technology appears to be in its infancy when comparing the output from the new closed and semi-closed cages with that from the traditionally used open net cages. It has been reported in this Theme-based Special Session (see paper by Dr Nilsen) that sea lice treatments with the accompanying use of boats and handling of nets, the traditional method, is a major risk factor for tearing of nets leading to escape of farmed salmon. The release of sea lice nauplii from open net cages to the wider environment continues to be a major threat to wild salmon. It is the view of the Steering Committee that traditional cage technology will ultimately need to be replaced with alternative technologies to reduce the impacts on wild salmon.

The industry has stated that it is committed to the protection of wild salmon as well as the production of premium seafood and that a regulatory regime is not required to achieve these commitments. However, in the farmed salmon producing countries across the North Atlantic, the Implementation Plans are demonstrating a distinct lack of progress towards protecting wild salmon from the consequences of salmon farming. The Steering Committee considers that if an ambitious policy stance is taken in these jurisdictions, the tools are already available to begin to address the serious impacts of salmon farming on the wild salmonid population.

The Steering Committee is of the strong opinion that the Parties / jurisdictions with salmon farming have not made adequate progress with minimising impacts on wild salmon since 2016, when the last Theme-based Special Session on aquaculture was held, despite Council's wish to strengthen the third Implementation Plan reporting cycle, from 2019 – 2024. Council's guidance to Parties / jurisdictions mandated the addition of actions on sea lice and containment for those Parties / jurisdictions with salmon farming, an emphasis on SMART actions, and opportunities to demonstrate commitment to NASCO's Resolutions, Agreements and Guidelines. After two rounds of review, Council produced further guidance in 2020 with, among other issues, the introduction of a letter from the NASCO President to high-level officials in each Party / jurisdiction after the review of their Implementation Plans. These letters noted the deficiencies in their Plans and requested a response to include how the Party / jurisdiction will demonstrate progress towards the attainment of NASCO's Resolutions, Agreements and Guidelines in areas where deficiencies have been identified. All of this correspondence is publicly available on the NASCO website.

The Steering Committee considers that there is now a transparent process in NASCO for highlighting those deficiencies that have been raised and highlighting the responses that are being made to them. The Implementation Plans and their reviews (visible to any interested party on NASCO's website) that present who is doing what and where will, hopefully, encourage peer-pressure such that more jurisdictions with salmon farming will be able to learn from the best practices of others.

Concluding Remarks

The Steering Committee considers that there is now overwhelming evidence across the Northern Hemisphere of the adverse impact of traditional salmon farming methods on wild salmon populations.

However, the Committee also considers that a lack of such evidence in a particular jurisdiction should not be used to continue with salmon farming practices that have been shown to be deleterious elsewhere. This is in line with the Precautionary Approach that NASCO adopted in 1998.

The Steering Committee recognises that any action to ensure adherence to NASCO's Resolutions, Agreements and Guidelines is the responsibility of the governments of NASCO's Parties / jurisdictions. They alone have the authority to implement further measures to protect wild salmon from the negative impacts of salmon farming demonstrated so well in this Theme-based Special Session.

The Steering Committee seeks, therefore, to galvanise the pressure that NASCO can bring to bear on its member governments through their representatives in the NASCO Council through the following recommendations[1]:

1. **Council should 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 (State of Knowledge Report on lice and escaped farmed salmon). The Secretariat should explore if this report could be a NASCO / ICES joint venture.**

[1] N.B. The draft versions of these recommendations were presented to the Council during the 2021 Annual Meeting of NASCO and discussed. They can be found in the Council report (NASCO 2021).

2. **A NASCO statement should be issued to:**
   - **promote adoption of innovative and alternative technologies, at sea and on land, to help achieve 100 % containment of farmed fish and for 100 % of farms to have effective sea lice management such that there is no increase in sea lice loads, or lice-induced mortality attributed to the farms, for the protection of wild salmon and sea trout; and**
   - **state that any increase in sea lice loads or lice-induced mortality on wild salmon smolts or genetic introgression of salmon stocks caused by salmon farming is unacceptable when referenced as part of an Implementation Plan action and cannot be considered, under the review process, as progressing the relevant party or jurisdiction towards achieving the international goals.**
3. **A renewed request should be made from the NASCO Council that all Parties and jurisdictions with salmon farming produce SMART actions in their revised Implementation Plans for the management of lice and escapes. These actions should reflect strong and sustained progress towards meeting the goals of 100 % containment of farmed fish, and for 100 % of farms to have effective sea lice management. Monitoring of sea lice and escapes should only be a secondary activity to research or assess the effectiveness of the main action.**
4. **Parties / jurisdictions should consider adopting a policy of phasing out open net cage salmon aquaculture over a specified period or licence term and restrict any new licences to those utilising alternative technologies in order to make significant progress towards achievement of the international goals for sea lice and containment. This policy should be prioritised in sensitive areas such as the estuaries of NASCO Class I salmon rivers, as defined in the Williamsburg Resolution, or salmon rivers in Special Areas of Conservation and other protected areas and along salmon migration routes.**

   (Please note that this recommendation was made following the Theme-based Special Session. During the TBSS Steering Committee discussions to agree the conclusions and recommendations, unanimous agreement to include this text was not achieved. Therefore, the Steering Committee has opted by rule of majority to include this recommendation).

References

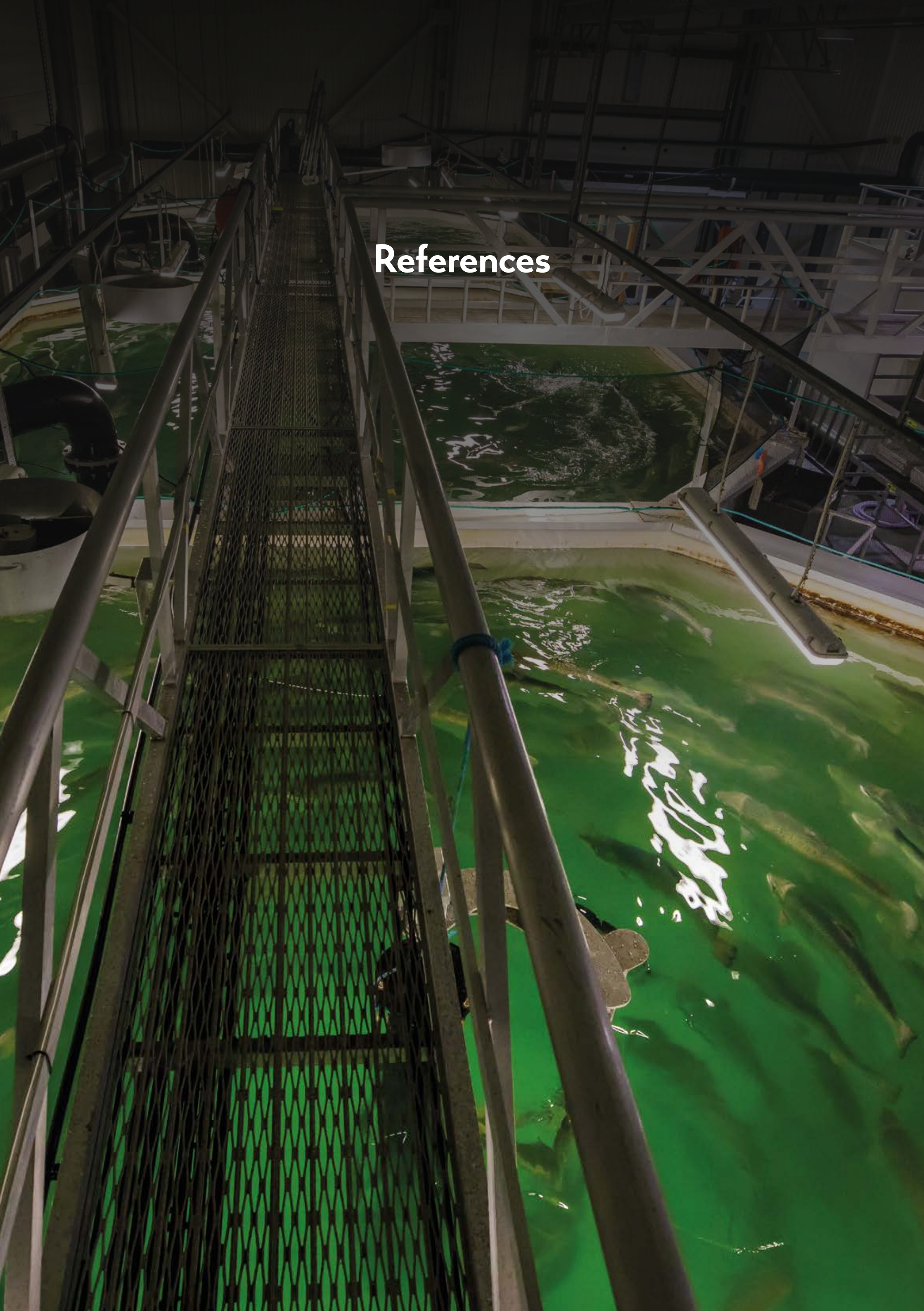


Photo: 'Nofima Centre for Recirculation in Aquaculture' courtesy of Terje Aamodt©Nofima

References

Aaen, S.M., Helgesen, K.O., Bakke, M.J., Kaur, K., and Horsberg, T.E. 2015. Drug resistance in sea lice: a threat to salmonid aquaculture. Trends in Parasitology, 31(2), 72-81. doi: 10.1016/j.pt.2014.12.006.

Anonymous 2020. Sluttrapport Prosjekt Ocean Farm 1. Website: https://www.fiskeridir.no/Akvakultur/Tildeling-og-tillatelser/Saertillatelser/Utviklingstillatelser/Kunnskap-fra-utviklingsprosjektene (In Norwegian). Retrieved 2021 04 14.

Balseiro, P., Moe, O., Gamlem, I., Shimizu, M., Sveier, H., Nilsen, T.O., Kaneko, N. *et al.* 2018. Comparison between Atlantic salmon *Salmo salar* post-smolts reared in open sea cages and in the Preline raceway semi-closed containment aquaculture system. Journal of Fish Biology, 93(3), 567-579. doi: 10.1111/jfb.13659.

Barker, S.E., Bricknell, I.R., Covello, J., Purcell, S., Fast, M.D., Wolters, W. and Bouchard, D.A. 2019. Sea lice, *Lepeophtheirus salmonis* (Krøyer 1837), infected Atlantic salmon (*Salmo salar* L.) are more susceptible to infectious salmon anemia virus. PLOS One, 14, e0209178.

Barrett, L.T., Oppedal, F., Robinson, N. and Dempster, T. 2020. Prevention not cure: a review of methods to avoid sea lice infestations. Reviews in Aquaculture, 12, 2527-2543. doi.org/10.1111/raq.12456.

Bergheim, A. and Nilsen, A. 2017. Slamproduksjon ved mekanisk behandling av avløp fra lukkede merder, Akva Future AS, avd. Sæterosen, 2017 (in Norwegian). Report IRIS – 2017/060.

Bertolotti, A.C., Layer, R.M., Gundappa, M.K., Gallagher, M.D., Pehlivanoglu, E., Nome, T., Robledo, D., *et al.* 2020. The structural variation landscape in 492 Atlantic salmon genomes. Nature Communications, 11, 5176.

Bicskei, B., Bron, J.E., Glover, K.A., and Taggart, J.B. 2014. A comparison of gene transcription profiles of domesticated and wild Atlantic salmon (*Salmo salar* L.) at early life stages, reared under controlled conditions. BMC Genomics, 15, 884.

Bicskei, B., Taggart, J.B., Glover, K.A., and Bron, J.E. 2016. Comparing the transcriptomes of embryos from domesticated and wild Atlantic salmon (*Salmo salar* L.) stocks and examining factors that influence heritability of gene expression. Genetics Selection Evolution, 48, 20.

Bjørkvoll, E., Grøtan, V., Aanes, S., Sæther, B.-E., Engen, S., and Aanes, R. 2012. Stochastic population dynamics and life-history variation in marine fish species. American Naturalist, 180, 372-387.

Blancheton, J.P., Attramadal, K.J.K., Michaud, L., d´Orbcastel, E.R., Vadstein, O. 2013. Insight into bacterial population in aquaculture systems and its implication. Aquaculture, 53, 30-39.

Bolstad, G.H., Hindar, K., Robertsen, G., Jonsson, B., Sægrov, H., Diserud, O.H., Fiske, P., *et al.* 2017. Gene flow from domesticated escapes alters the life history of wild Atlantic salmon. Nature Ecology & Evolution, 1, 0124.

Boxaspen, K. 2006. A review of the biology and genetics of sea lice. ICES Journal of Marine Science, 63, 1304-1316.

Bravo, S. 2003. Sea lice in Chilean salmon farms. Bulletin of the European Association of Fish Pathologists, 23(4), 197-200.

Brooker, A.J., Papadopoulou, A., Gutierrez, C., Rey, S., Davie, A. and Migaud, H. 2018. Sustainable production and use of cleaner fish for the biological control of sea lice: recent advances and current challenges. Veterinary Record, 183, 383.

Bui, S., Dempster, T., Remen, M. and Oppedal, F. 2016. Effect of ectoparasite infestation density and life-history stages on the swimming performance of Atlantic salmon *Salmo salar.* Aquaculture Environment Interactions, 8, 387-395.

Calabrese, S. 2017. Environmental and biological requirements of post-smolt Atlantic salmon (*Salmo salar* L.) in closed-containment aquaculture systems. (Doctoral dissertation), University of Bergen, Bergen, Norway. 80 pp.

Castro, V., Grisdale-Helland, B., Helland, S.J., Kristensen, T., Jorgensen, S.M., Helgerud, J., Claireaux, G., *et al.* 2011. Aerobic training stimulates growth and promotes disease resistance in Atlantic salmon (*Salmo salar*). Comparative Biochemistry and Physiology A-Molecular & Integrative Physiology, 160 (2), 278-290.

Coates, A., Philips, B.L., Bui, S., Oppedal, F., Robinson, N.A., Dempster, T. 2021. Evolution of salmon lice in response to management strategies: a review. Reviews in Aquaculture, 1-26. doi: 10.1111/raq.12528.

Crosbie, T., Wright, D.W., Oppedal, F., Dalvin, S., Myksvoll, M.S., Dempster, T. 2020. Impact of thermoclines on the vertical distribution of salmon lice larvae. Aquaculture Environment Interactions, 12, 1-10. doi 10.3354/aei00344.

Crosbie, T., Wright, D.W., Oppedal, F., Johnsen, I.A., Samsing, F., Dempster, T. 2019. Effects of step salinity on salmon lice larvae behaviour and dispersal. Aquaculture Environment Interactions, 11, 181-190. doi 10.3354/aei00303.

Dahle, S.W., Bakke, I., Birkeland, M., Nordøy, K., Dalum, A.S. and Attramadal, K.J.K. 2020. Production of lumpfish (*Cyclopterus lumpus* L.) in RAS with distinct water treatments: Effects on fish survival, growth, gill health and microbial communities in rearing water and biofilm. Aquaculture, 522, 735097.

Dang, H. and Lovell, C.R. 2016. Microbial surface colonization and biofilm development in marine environments. Microbiology and Molecular Biology Reviews, 80, 91–138.

Davidson, J., Summerfelt, S., Mota, V., Espmark, A.M.O. and Good, C. 2021. Effects of ozone on post-smolt Atlantic salmon *Salmo salar* performance, health, and maturation in freshwater recirculation aquaculture systems. Aquaculture, 533, 736208.

D'Arcy, J., Kelly, S., McDermott, T., Hyland, J., Jackson, D. and Bolton-Warberg, M. 2020. Assessment of PIT tag retention, growth and post-tagging survival in juvenile lumpfish, *Cyclopterus lumpus*. Animal Biotelemetry, 8, 1.

Eggestøl, H.Ø., Lunde, H.S. and Haugland, G.T. 2020. The proinflammatory cytokines TNF-α and IL-6 in lumpfish (*Cyclopterus lumpus* L.) – identification, molecular characterization, phylogeny and gene expression analyses. Developmental & Comparative Immunology, 105, 103608.

Einarsdottir, T., Sigurdardottir, H., Bjornsdottir, T.S. and Einarsdottir, E. 2018. Moritella viscosa in lumpfish (*Cyclopterus lumpus*) and Atlantic salmon (*Salmo salar*). Journal of Fish Diseases, 41, 1751-1758.

Einum, S. and Fleming, I.A. 1997. Genetic divergence and interactions in the wild among native, farmed and hybrid Atlantic salmon. Journal of Fish Biology, 50, 634-651.

Eliasen, K., Danielsen, E., Johannesen, Á., Joensen, L.L. and Patursson, E.J. 2018. The cleaning efficacy of lumpfish (*Cyclopterus lumpus* L.) in Faroese salmon (*Salmo salar* L.) farming pens in relation to lumpfish size and seasonality. Aquaculture, 488, 61-65.

Ellul, R.M., Walde, C., Haugland, G.T., Wergeland, H. and Ronneseth, A. 2018. Pathogenicity of Pasteurella sp. in lumpsuckers (*Cyclopterus lumpus* L.). Journal of Fish Diseases.

Erkinharju, T., Dalmo, R.A., Vågsnes, Ø., Hordvik, I. and Seternes, T. 2018. Vaccination of Atlantic lumpfish (*Cyclopterus lumpus* L.) at a low temperature leads to a low antibody response against *Aeromonas salmonicida*. Journal of Fish Diseases, 41, 613-623.

Espmark, Å.M., Stiller, K., Shahzad, K., Reiten, B.G., Marchenko, Y., Gerwins, J., Radonjic, F.S., *et al.* 2020. Nytt S-CCS konsept for oppdrett av laks - Postsmoltproduksjon i FishGLOBE. Nofima rapport 42/2020 (In Norwegian). 41 pp.

Fitridge, I., Dempster, T., Guenther, J. and de Nys, R. 2012. The impact and control of biofouling in marine aquaculture. Biofouling, 28(7), 649-669.

Fivelstad, S., Bergheim, A., Kloften, H., Haugen, R., Lohne, T. and Olsen, A.B. 1999. Water flow requirements in the intensive production of Atlantic salmon (*Salmo salar* L.) fry: growth and oxygen consumption. Aquacultural Engineering, 20(1), 1-15. doi: Doi 10.1016/S0144-8609(99)00002-3.

Fleming, I.A. and Einum, S. 1997. Experimental tests of genetic divergence of farmed from wild Atlantic salmon due to domestication. ICES Journal of Marine Science, 54, 1051-1063.

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 B-Biological Sciences, 267, 1517-1523.

Ford, J.S. and Myers, R.A. 2008. A global assessment of salmon aquaculture impacts on wild salmonids. PLOS Biology, 6(2):e33, doi 10.1371/journal.pbio.0060033.

Frederick, C., Brady, D.C. and Bricknell, I. 2017. Landing strips: Model development for estimating body surface area of farmed Atlantic salmon (*Salmo salar*). Aquaculture, 473, 299-302.

Gaillard, J.M., Pontier, D., Allainé, D., Lebreton, J.D., Trouvilliez, J., Clobert, J. and Allaine, D. 1989. An analysis of demographic tactics in birds and mammals. Oikos, 56, 59-76.

Gallardi, D., Xue, X., Hamoutene, D., Lush, L. and Rise, M.L. 2019. Impact of origin (wild vs. farmed) and sea lice (*Lepeophtheirus salmonis*) infestation on expression of immune-relevant genes in Atlantic salmon (*Salmo salar* L.) skin. *Aquaculture* 499, 306-315.

Gao, G., Pietrak, M.R., Burr, G.S., Rexroad, C.E., Peterson, B.C. and Palti, Y. 2020. A New Single Nucleotide Polymorphism Database for North American Atlantic Salmon Generated Through Whole Genome Resequencing. Frontiers in Genetics, 11: 85. doi.org/10.3389/fgene.2020.00085.

Garcia, M.B., Pico, F.X. and Ehrlen, J. 2008. Life span correlates with population dynamics in perennial herbaceous plants. American Journal of Botany, 95, 258-262.

Garcia, A.L.S., Bosworth, B., Waldbieser, G., Misztal, I., Tsuruta, S. and Lourenco, D.A.L. 2018. Development of genomic predictions for harvest and carcass weight in channel catfish. Genetics Selection Evolution, 50, 66. doi.org/10.1186/s12711-018-0435-5.

Geitung, L., Wright, D.W., Stien, L.H., Oppedal, F. and Karlsbakk, E. 2021 (In press). Tapeworm (*Eubothrium* sp.) infestation in sea caged Atlantic salmon decreased by lice barrier snorkels during a commercial-scale study. Aquaculture, online 17 April 2021, doi: 10.1016/j.aquaculture.2021.736774.

Gjedrem, T. and Baranski, M. 2010. Selective breeding in aquaculture: an introduction. Springer Science & Business Media.

Gjerde, B., Odegard, J. and Thorland, I. 2011. Estimates of genetic variation in the susceptibility of Atlantic salmon (*Salmo salar*) to the salmon louse *Lepeophtheirus salmonis*. Aquaculture, 314, 66-72.

Glover, K.A., Solberg, M.F., McGinnity, P., Hindar, K., Verspoor, E., Coulson, M.W., Hansen, M.M., *et al.* 2017. Half a century of genetic interaction between farmed and wild Atlantic salmon: status of knowledge and unanswered questions. Fish and Fisheries, 18, 890-927.

Godwin, S.C., Dill, L.M., Reynolds, J.D. and Krkošek, M. 2015. Sea lice, sockeye salmon, and foraging competition: lousy fish are lousy competitors. Canadian Journal of Fisheries and Aquatic Sciences, 72, 1113-1120.

Grimnes, A. and Jakobsen, P.J. 1996. The physiological effects of salmon lice infection on post-smolt of Atlantic salmon. Journal of Fish Biology. 48, 1179-1194.

Grøsvik, B.E. 2018. Fremmedstoff. *In Risikorapport norsk fiskeoppdrett (In Norwegian)*, pp 132-140. E.S. Grefsrud, K. Glover, B.E. Grøsvik, V. Husa, Ø. Karlsen, T. Kristiansen, B.O. Kvamme *et al.* (Eds). Norwegian Institute of Marine Research, Fisken og havet, Særnummer 1-2018. 184 pp.

Gutierrez Rabadan, C., Spreadbury, C., Consuegra, S. and Garcia de Leaniz, C. 2020. Development, validation and testing of an Operational Welfare Score Index for farmed lumpfish *Cyclopterus lumpus* L. Aquaculture, 531. doi.org/10.1016/j.aquaculture.2020.735777.

Hagen, I.J., Jensen, A.J., Bolstad, G.H., Diserud, O.H., Hindar, K., Lo, H. and Karlsson, S. 2019. Supplementary stocking selects for domesticated genotypes. Nature Communications, 10, 199.

Handeland, S.O., Järvi, T., Fernø, A. and Stefansson, S.O. 1996. Osmotic stress, antipredator behaviour, and mortality of Atlantic salmon smolts. Canadian Journal of Fisheries and Aquatic Sciences, 53, 2673-2680.

Hansen, L.P. and Windsor, M. 2006. Interactions between aquaculture and wild stocks of Atlantic salmon and other diadromous fish species: science and management, challenges and solutions. NINA Special Report 34. Trondheim, Norway, October 2006. 74 pp.

Haugland, G.T., Kverme, K.O., Hannisdal, R., Kallekleiv, M., Colquhoun, D.J., Lunestad, B.T., Wergeland, H.I., *et al.* 2019. Pharmacokinetic Data Show That Oxolinic Acid and Flumequine Are Absorbed and Excreted Rapidly From Plasma and Tissues of Lumpfish. Frontiers in Veterinary Science, 6, 394.

Hemmingsen, W., MacKenzie, K., Sagerup, K., Remen, M., Bloch-Hansen, K. and Imsland, A.L.D. 2020. *Caligus elongatus* and other sea lice of the genus *Caligus* as parasites of farmed salmonids: A review. Aquaculture, 522, 735160, doi: 10.1016/j.aquaculture.2020.735160.

Heuch, P.A., Øines, Ø., Knutsen, J.A. and Schram, T.A. 2007. Infection of wild fishes by the parasitic copepod *Caligus elongatus* on the south east coast of Norway. Diseases of Aquatic Organisms, 77, 149-158. doi: 10.3354/dao01833.

Heuch, P.A., Parsons, A. and Boxaspen, K. 1995. Diel Vertical Migration – a Possible Host-Finding Mechanism in Salmon Louse (*Lepeophtheirus-Salmonis*) Copepodids. Canadian Journal of Fisheries and Aquatic Sciences, 52(4), 681-689.

Houde, A.L.S., Fraser, D.J. and Hutchings, J.A. 2010a. Fitness-related consequences of competitive interactions between farmed and wild Atlantic salmon at different proportional representations of wild-farmed hybrids. ICES Journal of Marine Science, 67, 657-667.

Houde, A.L.S., Fraser, D.J. and Hutchings, J.A. 2010b. Reduced anti-predator responses in multi-generational hybrids of farmed and wild Atlantic salmon (*Salmo salar* L.). Conservation Genetics, 11, 785-794.

Huntingford, F.A. 2004. Implications of domestication and rearing conditions for the behaviour of cultivated fishes. Journal of Fish Biology, 65, 122-142.

ICES. 2016. North Atlantic Salmon Stocks. ICES Advice on fishing opportunities, catch and effort. Book 10. 68 pp.

ICES. 2021. North Atlantic Salmon Stocks. ICES Advice 2021 – sal.oth.nasco – https://doi.org/10.17895/ices.advice.8110.

Imsland, A., Hanssen, A., Nytro, A.V., Reynolds, P., Jonassen, T.M., Hangstad, T.A., Elvegard, T.A., *et al.* 2018c. It works! Lumpfish can significantly lower sea lice infestation in large-scale salmon farming. Biology Open, 7. doi.org/10.1242/bio.036301.

Imsland, A.K., Hangstad, T.A., Jonassen, T.M., Stefansson, S.O., Nilsen, T.O., Hovgaard, P., Elvegard, T.A., *et al.* 2019. The use of photoperiods to provide year round spawning in lumpfish *Cyclopterus lumpus*. Comparative Biochemistry and Physiology - Part A: Molecular & Integrative Physiology, 228, 62-70.

Imsland, A.K., Reynolds, P., Eliassen, G., Hangstad, T.A., Foss, A., Vikingstad, E. and Elvegård, T.A. 2014a. The use of lumpfish (*Cyclopterus lumpus* L.) to control sea lice (*Lepeophtheirus salmonis* Krøyer) infestations in intensively farmed Atlantic salmon (*Salmo salar* L.). Aquaculture, 424-425, 18-23.

Imsland, A.K., Reynolds, P., Eliassen, G., Hangstad, T.A., Nytrø, A.V., Foss, A., Vikingstad, E., *et al.* 2014b. Assessment of growth and sea lice infection levels in Atlantic salmon stocked in small-scale cages with lumpfish. Aquaculture, 433, 137-142.

Imsland, A.K., Reynolds, P., Eliassen, G., Hangstad, T., Nytrø, A., Foss, A., Vikingstad, E., *et al.* 2015a. Assessment of suitable substrates for lumpfish in sea pens. Aquaculture International, 23, 639-645.

Imsland, A.K., Reynolds, P., Eliassen, G., Hangstad, T.A., Nytro, A.V., Foss, A., Vikingstad, E., *et al.* 2015b. Feeding preferences of lumpfish (*Cyclopterus lumpus* L.) maintained in open net pens with Atlantic salmon (*Salmo salar* L.). Aquaculture, 436, 47-51.

Imsland, A.K., Reynolds, P., Eliassen, G., Mortensen, A., Hansen, Ø.J., Puvanendran, V., Hangstad, T.A., *et al.* 2016a. Is cleaning behaviour in lumpfish (*Cyclopterus lumpus*) parentally controlled? Aquaculture, 459, 156-165.

Imsland, A.K., Reynolds, P., Hangstad, T.A., Jónsdóttir, Ó.D.B., Noble, T., Wilson, M., Mackie, J.A., *et al.* 2018a. Feeding behaviour and growth of lumpfish (*Cyclopterus lumpus* L.) fed with feed blocks. Aquaculture Research, 49, 2006-2012.

Imsland, A.K., Reynolds, P., Nytrø, A.V., Eliassen, G., Hangstad, T.A., Jónsdóttir, Ó.D.B., Emaus, P.-A., *et al.* 2016b. Effects of lumpfish size on foraging behaviour and co-existence with sea lice infected Atlantic salmon in sea cages. Aquaculture, 465, 19-27.

Imsland, A.K.D., Reynolds, P., Jonassen, T.M., Hangstad, T.A., Elvegård, T.A., Urskog, T.C. and Mikalsen, B. 2018b. Effects of three commercial diets on growth, cataract development and histopathology of lumpfish (*Cyclopterus lumpus* L.). Aquaculture Research, 49, 3131-3141.

Imsland, A.K.D., Reynolds, P., Lorentzen, M., Eilertsen, R.A., Micallef, G. and Tvenning, R. 2020. Improving survival and health of lumpfish (*Cyclopterus lumpus* L.) by the use of feed blocks and operational welfare indicators (OWIs) in commercial Atlantic salmon cages. Aquaculture, 527, 735476.

IPCC. 2021. 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, *et al.* (Eds.). Cambridge University Press. In Press. 3949 pp.

Jacobsen, J.V., Steen, K. and Nilssen, K.J. 2019. Anaesthetic efficacy of Aqui-S, Benzoak, and MS-222 on lumpfish (*Cyclopterus lumpus*) fries. Impact from temperature, salinity, and fasting. PLOS One, 14, e0211080.

Jansen, P.A., Kristoffersen, A.B., Viljugrein, H., Jimenez, D., Aldrin, M. and Stien, A. 2012. Sea lice as a density-dependent constraint to salmonid farming. Proceedings of the Royal Society B-Biological Sciences, 279(1737), 2330-2338. doi: 10.1098/rspb.2012.0084.

Jevne, L.S., Øvrelid, M.S., Hagemann, A., Bloecher, N., Steinhovden, K.B., Båtnes, A.S., Olsen, Y., Reitan, K.I. 2020. Biofouling on Salmon Net Pens and Cleaner Fish Shelters Does Not Harbor Planktonic Stages of Sea Lice. Frontiers in Marine Science, 7, 727.

Johnsen, I.A., Harvey, A., Sævik, P.N., Sandvik, A.D., Ugedal, O., Ådlandsvik, B., Wennevik, V., *et al.* 2021. Salmon lice-induced mortality of Atlantic salmon during post-smolt migration in Norway. ICES Journal of Marine Science, 78, 142-154.

Jonsson, B. and Jonsson, N. 2017. Maternal inheritance influences homing and growth of hybrid offspring between wild and farmed Atlantic salmon. Aquaculture Environment Interactions, 9, 231-238.

Jonsson, B., Jonsson, N. and Hansen, L.P. 2003. Atlantic salmon straying from the River Imsa. Journal of Fish Biology, 62, 641-657.

Karlsen, C., Ytteborg, E., Timmerhaus, G., Høst, V., Handeland, S., Jørgensen, S.M. and Krasnov, A. 2018. Atlantic salmon skin barrier functions gradually enhance after seawater transfer. Scientific Reports, 8, 9510.

Karlsen, Ø., Dalvin, S., Johnsen, I.A., Sandvik, A.D. and Serra-Llinares, R.M. 2020. Risiko knyttet til dødelighet hos utvandrende postsmolt laks som følge av utslipp av lakselus fra fiskeoppdrett, pp. 9-29. *In Risikorapport norsk fiskeoppdrett. 2020 (in Norwegian).* E.S. Grefsrud., Ø. Karlsen., T. Svåsand. (Eds.). Norwegian Institute of Marine Research, Report. 2020-4. 30 pp.

Karlsson, S., Diserud, O.H., Fiske, P. and Hindar, K. 2016. Widespread genetic introgression of escaped farmed Atlantic salmon in wild salmon populations. ICES Journal of Marine Science, 73, 2488-2498.

Karlsson, S., Diserud, O.H., Moen, T. and Hindar, K. 2014. A standardized method for quantifying unidirectional genetic introgression. Ecology and Evolution, 4, 3256-3263.

King, R.K., Flick Jr., G.J., Pierson, D., Smith, S.A., Boardman, G.D. and Coale Jr., C.W. 2008. Identification of Bacterial Pathogens in Biofilms of Recirculating Aquaculture Systems. Journal of Aquatic Food Product Technology, 13(1), 125-133.

Klakegg, Ø., Myhren, S., Juell, R.A., Aase, M., Salonius, K. and Sørum, H. 2020. Improved health and better survival of farmed lumpfish (*Cyclopterus lumpus*) after a probiotic bath with two probiotic strains of *Aliivibrio*. Aquaculture, 518, 734810.

Kristoffersen, A.B., Qviller, L., Helgesen, K.O., Vollset, K.W., Viljugrein, H. and Jansen, P.A. 2018. Quantitative risk assessment of salmon louse-induced mortality of seaward-migrating post-smolt Atlantic salmon. Epidemics 23, 19-33.

Krkosek, M., Lewis, M.A., Morton, A., Frazer, L.N. and Volpe, J.P. 2006. Epizootics of wild fish induced by farm fish. Proceedings of the National Academy of Sciences, 103(42), 15506-15510, doi: 10.1073/pnas.0603525103.

Lande, R., Engen, S. and Sæther, B.-E. 2003. Stochastic population dynamics in ecology and conservation. Oxford University Press, Oxford.

Leclercq, E., Zerafa, B., Brooker, A.J., Davie, A. and Migaud, H. 2018. Application of passive-acoustic telemetry to explore the behaviour of ballan wrasse (*Labrus bergylta*) and lumpfish (*Cyclopterus lumpus*) in commercial Scottish salmon sea-pens. Aquaculture, 495, 1-12.

MacArthur, R.H. and Wilson, E.O. 1967. Theory of island biogeography. Princeton University Press.

McEwan, G.F., Groner, M.L., Cohen, A.A.B., Imsland, A.K.D. and Revie, C.W. 2019. Modelling sea lice control by lumpfish on Atlantic salmon farms: interactions with mate limitation, temperature and treatment rules. Diseases of Aquatic Organisms, 133, 69-82.

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 B-Biological Sciences, 270, 2443-2450.

McGinnity, P., Stone, C., Taggart, J.B., Cooke, D., Cotter, D., Hynes, R., McCamley, C., *et al.* 1997. Genetic impact of escaped farmed Atlantic salmon (*Salmo salar* L.) on native populations: use of DNA profiling to assess freshwater performance of wild, farmed, and hybrid progeny in a natural river environment. ICES Journal of Marine Science, 54, 998-1008.

Meuwissen, T.H.E., Hayes, B.J. and Goddard, M.E. 2001. Prediction of Total Genetic Value Using Genome-Wide Dense Marker Maps. Genetics, 157, 1819-1829.

Mortensen, A., Johansen, R.B., Hansen, Ø.J. and Puvanendran, V. 2020. Temperature preference of juvenile lumpfish (*Cyclopterus lumpus*) originating from the southern and northern parts of Norway. Journal of Thermal Biology, 89, 102562.

Mota, V., Nilsen, T.O., Gerwins, J., Gallo, M., Ytteborg, E., Baeverfjord, G., Kolarevic, J., *et al.* 2019. The effects of carbon dioxide on growth performance, welfare, and health of Atlantic salmon post-smolt (*Salmo salar*) in recirculating aquaculture systems. Aquaculture, 498, 578 – 586.

Murray, A.G. 2017. A model of the process of spillover and adaption leading to potential emergence of disease in salmon held with cleaner fish used to control lice. Aquaculture, 473, 283-290.

NASCO. 1988. Report of the Fifth Annual Meeting of the Council, CNL(88)44. 95 pp.

NASCO. 1994. Resolution by the Parties to the Convention for the Conservation of Salmon in the North Atlantic Ocean to Minimise Impacts from Salmon Aquaculture on the Wild Salmon Stocks, pp. 181-188. *In Report of the Eleventh Annual Meeting of the Council, CNL(94)55*. 203 pp.

NASCO. 2006. Resolution by the Parties to the Convention for the Conservation of Salmon in the North Atlantic Ocean to Minimise Impacts from Aquaculture, Introductions and Transfers, and Transgenics on the Wild Salmon Stocks – The Williamsburg Resolution, CNL(06)48. 43 pp.

NASCO. 2009. Guidance on Best Management Practices to address impacts of sea lice and escaped farmed salmon on wild salmon stocks, SLG(09)5. 3 pp.

NASCO. 2013. Action Plan for taking forward the recommendations of the External Performance Review and the review of the 'Next Steps' for NASCO, CNL(13)38. 16 pp.

NASCO. 2016. Addressing impacts of salmon farming on wild Atlantic salmon: Challenges to, and developments supporting, achievement of NASCO's international goals. W. Cowan, K. Damon-Randall, P. Gargan, H. Hansen, P. Knight, P. Hutchinson and S.L. Forero Segovia. (Eds.). Report of a Theme-based Special Session of the Council of NASCO, CNL(16)60. 196 pp.

NASCO. 2018. Guidelines for the Preparation and Evaluation of NASCO Implementation Plans and for Reporting on Progress, CNL(18)49. 13 pp.

NASCO. 2020a. Report from the Tromsø Symposium on the Recommendations to Address Future Management Challenges, CNL(19)16. *In Managing the Atlantic Salmon in a Rapidly Changing Environment – Management Challenges and Possible Responses,* pp. 3-16. E.B Thorstad, D. Bliss, K. Damon-Randall, H. Hansen, G. Horsburgh, N.Ó. Maoiléidigh, S.G. Sutton, V. Newton and E.M.C. Hatfield. (Eds.). Report of the IYS Symposium held in Tromsø, Norway, 3 – 4 June 2019. 176 pp.

NASCO. 2020b. Report of the Thirty-Seventh Annual Meeting of the Council, CNL(20)51rev. 94 pp.

NASCO. 2021. Report of the Thirty-Eighth Annual Meeting of the Council, CNL(21)62. 128 pp.

Nilsen, A. 2019. Production of Atlantic salmon (*Salmo salar*) in closed confinement systems (CCS) – salmon lice, growth rates, mortality and fish welfare. Norwegian University of Life Sciences, Doctoral thesis 2019:48. 234 pp.

Nilsen, A., Nielsen, K.V. and Bergheim, A. 2017b. The impact of production intensity on water quality in oxygen enriched, floating enclosures for post-smolt salmon culture. Aquacultural engineering 78, 221-227. doi: 10.1016/j.aquaeng.2017.06.001.

Nilsen, A., Nielsen, K.V. and Bergheim, A., 2020. A closer look at closed cages: Growth and mortality rates during production of post-smolt Atlantic salmon in marine closed confinement systems. Aquacultural Engineering 91. doi: 10.1016/j.aquaeng.2020.102124.

Nilsen, A., Nielsen, K.V., Biering, E. and Bergheim, A. 2017a. Effective protection against sea lice during the production of Atlantic salmon in floating enclosures. Aquaculture 466, 41-50. doi: 10.1016/j.aquaculture.2016.09.009.

Nilsen, A., Hagen, Ø., Johnsen, C.A., Prytz, H., Zhou, B., Nielsen, K.V. and Bjørnevik, M. 2019. The importance of exercise: Increased water velocity improves growth of Atlantic salmon in closed cages. Aquacultural Engineering 78, 221-227. doi: 10.1016 / j.aquaculture.2018.09.057.

Norwegian Directorate of Fisheries. 2021. Website: https://www.fiskeridir.no/Akvakultur/Tall-og-analyse/Roemmingsstatistikk. Retrieved 2021 04 14.

Overton, K., Barrett, L.T., Oppedal, F., Kristiansen, T.S. and Dempster, T. 2020. Sea lice removal by cleaner fish in salmon aquaculture: a review of the evidence base. Aquaculture environment interactions, 12, 31-44. doi: 10.3354/aei00345.

Overton, K., Dempster, T., Oppedal, F., Kristiansen, T.S., Gismervik, K. and Stien, L.H. 2019. Salmon lice treatments and salmon mortality in Norwegian aquaculture: a review. Reviews in Aquaculture, 11, 1398-1417. doi: 10.1111/raq.12299.

Øvrebø, T.K. 2020. Growth performance and welfare of post-smolt (*Salmo salar* L.) reared in semi closed containment systems (S-CCS) – a comparative study. Master of Science thesis, Department of Biology, University of Bergen, Norway, 144 pp.

Pianka, E.R. 1970. On r- and K-selection. The American Naturalist, 104, 592-597.

Piasecki, W. and Mackinnon, B.M. 1995. Life-Cycle of a Sea Louse, *Caligus elongatus* Von nordmann, 1832 (Copepoda, Siphonostomatoida, Caligidae). Canadian Journal of Zoology-Revue Canadienne De Zoologie, 73(1), 74-82. doi: Doi 10.1139/Z95-009.

Pietrak, M. and Backman, S. 2018. Treatment of lumpfish (*Cyclopterus lumpus* L.) infected with *Gyrodactylus cyclopteri* (Scyborskaya 1948). Journal of Fish Diseases, 41, 721-723.

Pietrak, M. and Rosser, T.G. 2019. Morphologic and molecular characterization of *Gyrodactylus cyclopteri* Scyborskaja, 1948, from *Cyclopterus lumpus* L., 1758. Parasitology Research, 119, 879-884.

Pike, A.W. 1989. Sea lice — Major pathogens of farmed Atlantic salmon. Parasitology Today, 5, 291-297.

Pountney, S.M., Lein, I., Migaud, H. and Davie, A. 2020. High temperature is detrimental to captive lumpfish (*Cyclopterus lumpus* L) reproductive performance. Aquaculture, 522, 735121.

Powell, A., Treasurer, J.W., Pooley, C.L., Keay, A.J., Lloyd, R., Imsland, A.K. and Garcia de Leaniz, C. 2018. Use of lumpfish for sea-lice control in salmon farming: challenges and opportunities. Reviews in Aquaculture, 10, 683-702.

Reale, D., Garant, D., Humphries, M.M., Bergeron, P., Careau, V., and Montiglio, P.O. 2010. Personality and the emergence of the pace-of-life syndrome concept at the population level. Philosophical transactions of the Royal Society of London. Series B, Biological sciences, 365, 4051-4063.

Roberge, C., Einum, S., Guderley, H. and Bernatchez, L. 2006. Rapid parallel evolutionary changes of gene transcription profiles in farmed Atlantic salmon. Molecular Ecology, 15, 9-20.

Rouleau, F.D., Vincent, A.T. and Charette, S.J. 2018. Genomic and phenotypic characterization of an atypical Aeromonas salmonicida strain isolated from a lumpfish and producing unusual granular structures. Journal of Fish Diseases, 41, 673-681.

Rud, I., Kolarevic, J., Holan, A.B., Berget, I., Calabrese, S. and Terjesen, B. F. 2017. Deep-sequencing of the bacterial microbiota in commercial-scale recirculating and semi-closed aquaculture systems for Atlantic salmon post-smolt production. Aquacultural Engineering, 78, 50-62. doi: 10.1016/j.aquaeng.2016.10.003.

Sæther, B.-E. and Bakke, O. 2000. Avian life history variation and contribution of demographic traits to the population growth rate. Ecology, 81, 642-653.

Samsing, F., Johnsen, I., Stien, L.H., Oppedal, F., Albretsen, J., Asplin, L. and Dempster, T. 2016. Predicting the effectiveness of depth-based technologies to prevent salmon lice infection using a dispersal model. Preventive Veterinary Medicine, 129, 48-57. doi:10.1016/j.prevetmed.2016.05.010.

Scholz, F., Ruane, N., Marcos-López, M., Mitchell, S., Bolton-Warberg, M., O'Connor, I., Mirimin, L., *et al.* 2018. Systemic mycoses in lumpfish (*Cyclopterus lumpus* L.) in Ireland: aetiology and clinical presentation. Bulletin of the European Association of Fish Pathologists, 35, 202-212.

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., Glover, K.A., Barlaup, B.T., Svåsand, T., Besnier, F., Hansen, M.M. and Borgstrøm, R. 2012. Performance of farmed, hybrid, and wild Atlantic salmon (*Salmo salar*) families in a natural river environment. Canadian Journal of Fisheries and Aquatic Sciences, 69, 1994-2006.

Skaala, Ø., Besnier, F., Borgstrøm, R., Barlaup, B., 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.

Skilbrei, O.T., Finstad, B., Urdal, K., Bakke, G., Kroglund, F. and Strand, R. 2013. Impact of early salmon louse, *L. salmonis*, infestation and differences in survival and marine growth of sea-ranched Atlantic salmon, *Salmo salar* L., smolts 1997–2009. Journal of Fish Diseases, 36, 249-260.

Solberg, M.F., Robertsen, G., Sundt-Hansen, L.E., Hindar, K. and Glover, K.A. 2020. Domestication leads to increased predation susceptibility. Scientific Reports, 10, 1929.

Sommerset, I. 2021. *In Fish Health Report from the Norwegian Veterinary Institute (in Norwegian)*. I. Sommerset, B. Bang Jensen, B. Bornø, A. Haukaas and E. Brun (Eds.). Report 41a/2021. 184 pp.

Stagg, H.E.B., Guðmundsdóttir, S., Vendramin, N., Ruane, N.M., Sigurðardóttir, H., Christiansen, D.H., Cuenca, A., *et al.* 2020. Characterization of ranaviruses isolated from lumpfish *Cyclopterus lumpus* L. in the North Atlantic area: proposal for a new ranavirus species (European North Atlantic Ranavirus). Journal of General Virology, 101, 1298-207.

Stedt, K. 2018. Integrated multi-trophic aquaculture: The Potential of Using *Saccharina latissima* and *Mytilus edulis* as Bioremediative Species in Sea-Based Aquaculture Systems. (Masters thesis), University of Gothenburg. 29 pp.

Strand, D., Sørum, H., Nielsen, K.V., Næss, A., Johnsen, T.O., Singdahlsen, J.O., Fjelldalselv, B. *et al.* 2020. Fiskehelse og mikrobielt miljø a lukkede merder (In Norwegian). Presentation at Norwegian Research Council annual meeting, HAVBRUK, June 12th 2020.

Stearns, S.C. 1983. The influence of size and phylogeny on patterns of covariation among life-history traits in the mammals. Oikos, 41, 173-187.

Stiller K.T. Kolarevic J., Lazado C.C., Gerwins G., Good C., Summerfelt S.T., Mota V.C. and Espmark Å.M.O. 2020. The Effects of Ozone on Atlantic Salmon Post-Smolt in Brackish Water – Establishing Welfare Indicators and Thresholds. International Journal of Molecular Sciences, 21, 5109; doi:10.3390/ijms21145109.

Summerfelt, S.T., Mathisen, F., Holan, A.B. and Terjesen, B.F. 2016. Survey of large circular and octagonal tanks operated at Norwegian commercial smolt and post-smolt sites. Aquacultural Engineering, 74, 105-110. doi: 10.1016/j.aquaeng.2016.07.004.

Susdorf, R., Salama, N.K.G. and Lusseau, D. 2018a. Influence of body condition on the population dynamics of Atlantic salmon with consideration of the potential impact of sea lice. Journal of Fish Diseases, 41, 941-951.

Susdorf, R., Salama, N.K.G., Todd, C.D., Hillman, R.J., Elsmere, P. and Lusseau, D. 2018b. Context-dependent reduction in somatic condition of wild Atlantic salmon infested with sea lice. Marine Ecology Progress Series, 606, 91-104.

Sveen, L.R., Timmerhaus, G., Krasnov, A., Takle, H., Handeland, S. and Ytteborg, E. 2019. Wound Healing in post-smolt Atlantic salmon (*Salmo salar* L.). Scientific Reports, 9. doi: Artn 356510.1038/S41598-019-39080-X.

Sveen, L.R., Timmerhaus, G., Torgersen, J.S., Ytteborg, E., Jorgensen, S.M., Handeland, S. Stefansson, S.O., *et al.* 2016. Impact of fish density and specific water flow on skin properties in Atlantic salmon (*Salmo salar* L.) post-smolts. Aquaculture, 464, 629-637. doi: 10.1016 / j.aquaculture.2016.08.012.

Talagrand-Reboul, E., Jumas-Bilak, E. and Lamy, B. 2017. The Social Life of *Aeromonas* through Biofilm and Quorum Sensing Systems. Frontiers in Microbiology, 8, 37.

Tan, C.K.F., Nowak, B.F. and Hodson, S.L. 2002. Biofouling as a reservoir of *Neoparamoeba pemaquidensis* (Page, 1970), the causative agent of amoebic gill disease in Atlantic salmon. Aquaculture, 210, 49-58.

Taranger, G.L., Karlsen, Ø., Bannister, R.J., Glover, K. A., *et al.* 2015. Risk assessment of the environmental impact of Norwegian Atlantic salmon farming. ICES Journal of Marine Science, 72, 997-1021.

Thorarensen, H. and Farrell, A.P. 2011. The biological requirements for post-smolt Atlantic salmon in closed-containment systems. Aquaculture, 312(1-4), 1-14. doi: 10.1016 / j.aquaculture.2010.11.043.

Thorstad, E.B., Whoriskey, F., Uglem, I., Moore, A., Rikardsen, A.H. and Finstad, B. 2012. A critical life stage of the Atlantic salmon *Salmo salar*: behaviour and survival during the smolt and initial post-smolt migration. Journal of Fish Biology, 81, 500-542.

Timmerhaus, G., Lazado, C.C., Cabillon, N.A.R., Reiten, B.K.M. and Johansen, L.H. 2021. The optimum velocity for Atlantic salmon post-smolts in RAS is a compromise between muscle growth and fish welfare. Aquaculture, 532, doi: 10.1016/j.aquaculture.2020.736076.

Qviller, L., Helgesen, K.O. and Stige, L.C. 2021. Lakselus – *Lepeophtheirus salmonis*, pp 107-113. I*n Fish Health Report from the Norwegian Veterinary Institute (in Norwegian).* I. Sommerset and E. Brun (Eds.). Report 41a/2021. 184 pp.

Urbina, M.A., Cumillaf, J.P., Paschke, K. and Gebauer, P. 2019. Effects of pharmaceuticals used to treat salmon lice on non-target species: Evidence from a systematic review. Science of the Total Environment, 649, 1124-1136. doi: 10.1016/j.scitotenv.2018.08.334.

Vallejo, R.L., Leeds, T.D., Gao, G., Parsons, J.E., Martin, K.E., Evenhuis, J.P., Fragomeni, B.O., *et al.* 2017. Genomic selection models double the accuracy of predicted breeding values for bacterial cold water disease resistance compared to a traditional pedigree-based model in rainbow trout aquaculture. Genetics Selection Evolution, 49, 17.

Vollset, K.W., Krontveit, R.I., Jansen, P.A., Finstad, B., *et al.* 2016. Impacts of parasites on marine survival of Atlantic salmon: a meta-analysis. Fish and Fisheries, 17, 714-730.

Vollset, K.W., Nilsen, F., Ellingsen, I.H., Finstad, B., Karlsen, Ø., Myksvoll, M.S., Stige, L.C., *et al.* 2020. Vurdering av lakselusindusert villfiskdødelighet per produksjonsområde i 2020. Rapport fra ekspertgruppe for vurdering av lusepåvirkning. 107 pp.

VRL (2020). Status for norske laksebestander i 2020. Vitenskapelig råd for lakseforvaltning, 147 pp.

Wright, J., Bolstad, G.H., Araya-Ajoy, Y.G. and Dingemanse, N.J. 2019. Life-history evolution under fluctuating density-dependent selection and the adaptive alignment of pace-of-life syndromes. Biological Reviews, 94, 230-247.

Wringe, B.F., Jeffery, N.W., Stanley, R.R.E., Hamilton, L.C., Anderson, E.C., Fleming, I.A., Grant, C., *et al.* 2018. Extensive hybridization following a large escape of domesticated Atlantic salmon in the Northwest Atlantic. Communications Biology, 1, 108.

For bibliographic purposes, this publication may be cited as follows:

NASCO. 2021. 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. J. Campbell, J. Crocker, P. Gargan, H. Hansen, P. Knight, S.G. Sutton, S.L. Forero Segovia, W. Kenyon, V. Newton and E.M.C. Hatfield. (Eds.). Report of a Theme-based Special Session of the Council of NASCO, CNL(21)65. 124 pp.

Design, layout and printing: shaw-online.com

Publisher: North Atlantic Salmon Conservation Organization (NASCO), 11 Rutland Square, Edinburgh EH1 2AS, UK. email: hq@nasco.int

ISBN: 978-1-7398364-0-5

Date of Publication: December 2021

Contact: The Secretary, NASCO, 11 Rutland Square, Edinburgh EH1 2AS, UK

Cover photograph courtesy of Akvafuture AS