EXHIBIT 069

NSARB-2023-001-AFF-003

RECEIVED February 20, 2024

NSARB 2023-001

NOVA SCOTIA AQUACULTURE REVIEW BOARD

Applications by KELLY COVE SALMON LTD. for a BOUNDARY AMENDMENT and TWO NEW MARINE FINFISH AQUACULTURE LICENSES and LEASES for the cultivation of ATLANTIC SALMON (Salmo salar) - AQ#1205x, AQ#1432, AQ#1433 in LIVERPOOL BAY, QUEENS COUNTY.

Supplementary Affidavit of Jonathan W. Carr

I, Jonathan Weldon Carr, of the Town of St. Andrews, in the Province of New Brunswick, affirm as follows:

1. I have been asked to review and provide an expert opinion regarding impacts to wild Atlantic salmon that are likely to result from the approval of the applications by Kelly Cove Salmon Ltd. ("**KCS**") for a boundary amendment to marine finfish licence and lease AQ#1205, and for new marine finfish licences and leases AQ#1432 and AQ#1433 (the "**Applications**") on behalf of the intervenor Protect Liverpool Bay Association.

2. Following receipt of the evidence of KCS and the Department of Fisheries and Aquaculture ("**DFA**"), I have co-authored a supplementary report along with Dr. Stephen Sutton and Heather Perry, which is attached to my affidavit as **Exhibit "A".** The Supplementary Report is limited to addressing new information arising from the evidence filed on January 22, 2024. The Supplementary Report represents my objective opinion with respect to the accuracy, reliability, and completeness of the evidence filed by KCS and DFA about the likely impacts of the Applications on the survival, conservation, and recovery of wild Atlantic salmon. I have exercised my professional judgment to the best of my training, knowledge and ability regarding the data, analysis and conclusions set out in the Supplementary Report.

3. My qualifications as a subject matter expert on the protection, conservation and recovery of wild Atlantic salmon are set out in my Curriculum Vitae, which is attached as **Exhibit "B"** to my affidavit affirmed January 19, 2024. Dr. Stephen Sutton and Heather Perry's qualifications are set out in their CVs, attached as **Exhibits "C"** and **"D"**, respectively, to my affidavit affirmed January 19, 2024.

4. I affirm this affidavit in support of the Report and in support of Protect Liverpool Bay Association's intervention before the Aquaculture Review Board and for no other or improper purpose.

Affirmed before me on this)
16 day of February, 2024)
at St. Andrews, New Brunswick)

[redacted]

A Commissioner of Oaths in and for the)
Province of New Brunswick)
David R. Ames K.C.

[redacted]

Jonathan W. Carr

This is **Exhibit "A"** referred to in the affidavit
of **Jonathan W. Carr**, affirmed before me

[redacted]

A Commissioner of Oaths in
and for the Province of New
Brunswick

David R. Ames K.C.

Supplementary Report for the Aquaculture Review Board

Respecting an application by Kelly Cove Salmon Ltd. for an amendment to finfish licence and lease AQ #1205x and for new licences and leases #AQ 1432 and #AQ 1433 in Liverpool Bay, Nova Scotia

Jonathan Carr, M. Sc.

Stephen Sutton, Ph. D.

Heather Perry, B. Sc.

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Scope of the Report

We have been asked by the intervenor Protect Liverpool Bay Association to provide an expert opinion regarding impacts on wild salmon resulting from Kelly Cove Salmon Ltd.'s applications for an expansion to existing salmon farming site AQ#1205, and for new sites AQ#1432 and AQ#1433, all located in Liverpool Bay, NS.

In this supplementary report, we limited our opinion to addressing new information arising from the evidence filed on January 22, 2024. In particular, we address evidence contained in the report prepared by Dr. Kurt Samways (the "**Samways Report**"), exhibited to his affidavit affirmed January 19, 2024, and the affidavit of Jessica Feindel, affirmed January 19, 2024.

Affidavit and report of Dr. Kurt Samways

The conclusion of the Samways Report that "the proposed Liverpool Bay finfish marine aquaculture Development Plans pose a very low risk to wild Atlantic salmon in the Liverpool Bay region" is unfounded. In support of this, we make the following points:

1. The Samways Report minimizes the intensification of impacts of the proposed farms on endangered wild Atlantic salmon by overstating the protection afforded by the distance between the Medway River and Liverpool Bay (21km), and by ignoring the rest of the sub-populations from the Southern Uplands as well as the outer Bay of Fundy and Gulf of Maine populations. The scientific literature demonstrates that impacts from salmon farms on wild

salmon can extend over much greater distances than the 21km between the Medway and Liverpool Bay. Sea lice can disperse tens of kilometres in the ocean (Harrington et al. 2023) and elevated sea lice levels on wild salmonids have been demonstrated at 30km from salmon farms (Thorstad et al. 2015). Farmed salmon can travel hundreds of kilometres when released into the ocean (Hansen 2006). Wringe et al. (2018) found interbreeding between wild and farmed salmon in rivers 100km from an escape site in Newfoundland. This evidence suggests that impacts on wild salmon from the Liverpool Bay proposal could extend several hundred kilometres along the coast, putting all populations of wild salmon south of the Sackville River at risk.

2. In our original submission we reviewed the scientific literature on the impacts of salmon farming on wild Atlantic salmon. As we demonstrated, the scientific evidence is voluminous and clear: there are at least 5 ways in which salmon farming can impact wild salmon, and the impacts from sea lice and escapes are particularly well documented. The Samways Report has failed to consider most of this literature.

3. Much of the scientific literature used in the Samways Report in paragraphs 15-19 to support the argument that sea lice from the proposed expansion of salmon farming in Liverpool Bay will not pose a risk to wild salmon has been cited incorrectly or inappropriately. Consequently, in terms of sea lice, the Samways Report offers little scientific evidence to support the conclusion in paragraph 29 that "Based on the available evidence, it is reasonable to conclude that the proposed Liverpool Bay finfish marine aquaculture Development Plans pose a very low risk to wild Atlantic salmon in the Liverpool Bay region." We detail these incorrect citations in the following points:
    a) At paragraph 19, the Samways Report cites Carr and Whoriskey (2004) to support the statement that "where post-smolts (if present) can rapidly migrate to sea, the potential for sea-lice infestations to negatively impact post-smolt survival, is absent or negligible." However that study only examined sea lice on returning adults whereas juveniles migrating from the river at the smolt stage are the most vulnerable to sea lice, given lower load thresholds for lethal and sublethal effects as well as osmotic stress during acclimation to salt water (Shephard and Gargan 2021; Moriarty et al. 2023, **Tab 2**). Carr and Whoriskey (2004) provides no support for Dr. Samways' conclusion that sea lice from farms in Liverpool Bay pose no threat to wild Atlantic salmon.

    b) At paragraph 18, the Samways Report cites Forseth et al. (2017) and Otero et al. (2011) to say that "Despite having many farms situated in very narrow fjords, Norway is among the countries with the smallest decline in adult abundance." Neither paper says anything about the number of farms, the shape of the bays they are in, or the magnitude of the salmon declines in Norway or how they compare to declines in other areas and therefore provide no support for the statement that sea lice from salmon farms in Liverpool Bay pose no threat to wild Atlantic salmon. In fact, Forseth et al. (2017) develops a ranking system for threats to wild salmon and ranks escapes and sea lice from salmon farming as the top two anthropogenic threats to wild salmon in Norway. Furthermore, Forseth et al. (2017) provides a robust review of the literature on the impacts of sea lice (and escapes) on wild salmon which directly contradicts the statement made at paragraph 20 of the Samways Report that "modern salmon farming practices are not negatively impacting wild salmon populations regarding sea lice."

c) At paragraph 18, the Samways Report cites Butler and Watt (2003) and Greaker et al. (2020) to say that sea lice affecting post-smolt ability to successfully return as adults appears to only occur in regions where post-smolts must navigate a complex of multiple farms, situated in narrow passageways. Neither paper discusses the effect of bay type/shape or number of farms on sea lice impacts on wild salmon and therefore provide no support for the Samways Report's conclusion that sea lice from salmon farms in Liverpool Bay pose no risk to wild Atlantic salmon.

d) At paragraph 21 the Samways Report states "according to DFO (DFO 2014) there have been no proven cases of the transmission of sea lice or ISA disease to wild populations from aquaculture sites." This is inaccurate and misrepresents the content of the cited DFO report. The report is focused on "(1) ensuring that transmission of sea lice from farms to wild populations does not negatively impact the latter and (2) ensuring the health of fish on farms." That sea lice can be transmitted from farmed to wild fish is acknowledged in the first Summary bullet on page 2 of the DFO report: "Transmission of sea lice between and within wild fish populations and salmon farms is known to occur," which directly contradicts the statement from the Samways Report referenced above.

   Additionally, the report does not contain any reference to ISA disease either in salmon farms or wild salmon and therefore provides no support for the statement that transmission of ISA disease from farmed to wild salmon has not been proven.

4. At paragraph 20 the Samways Report cites a recent investigation by DFO (2023) that found no statistical association between sea lice numbers found on Atlantic salmon farms and those found on wild juvenile Pacific salmon. However, the Samways Report failed to note that the methods and results of the study have been heavily criticized by 16 scientific experts including from the University of British Columbia (UBC), Simon Fraser University (SFU), the University of Victoria and the University of Toronto (Bateman et al 2023, **Tab 1**). In fact, when these scientists reanalyzed the data using appropriate statistical methods there was a clear association between sea lice numbers in salmon farms and lice numbers on wild salmon (Bateman et al. 2023, **Tab 1**). We agree with the critique provided by Bateman et al. (2023, **Tab 1**) and therefore consider the conclusions of the DFO (2023) report to be invalid. The DFO (2023) report therefore provides no support for the conclusion that "modern salmon farming practices are not negatively impacting wild salmon populations regarding sea lice." Furthermore, the Samways Report fails to acknowledge the large body of scientific literature demonstrating impacts of sea lice from salmon farming on wild Atlantic salmon, which several of the peer-reviewed papers cited in the Samways Report describe and discuss (e.g., Butler and Watt (2003); Forseth et al. (2017); Fleming et al. (2000); Glover et al. (2017); McGinnity et al. (2003)).

5. At paragraph 19, the Samways Report concludes that "in regions such as Liverpool Bay, where post-smolts (if present) can rapidly migrate to sea, the potential for sea-lice infestations to negatively impact post-smolt survival, is absent or negligible." In addition to

the problems with the literature used to support this conclusion as noted above, no information has been provided to enable an understanding of how fast post-smolts actually migrate through Liverpool Bay or how long they must remain in the vicinity of salmon farms before they pick up sea lice. Unpublished research on smolt migration in the Bay of Fundy cited in paragraph 15 of the Samways Report provides no insight into the migratory behaviour of smolts in Liverpool Bay. Furthermore, one of the references cited in the Samways Report (Butler and Watt (2003)) directly contradicts the implied conclusion that post-smolts must spend an unspecified 'extended' period in contact with salmon farms to be infected with sea lice. They report that significant sea lice transmission occurs in Norway and Scotland despite smolts departing local bays within a few hours of leaving their natal rivers (Butler and Watt, 2003, p108).

6. At paragraph 18, the Samways Report states "Nova Scotia farms tend to have very low lice loads usually not requiring treatment". However, no data are provided on lice loads, how often outbreaks occur, or at what level treatment is typically initiated. Unlike other jurisdictions, Nova Scotia has no regulations to ensure lice levels in salmon farms are kept at levels intended to minimize impacts on wild Atlantic salmon (e.g., Norway requires that farms have no more than 0.2 female lice/fish during the spring when wild salmon smolts are migrating past the farms (Vormedal (2023), **Tab 3**). Thus, it is left to operators to decide when to treat farms for sea lice. Absent data on lice loads, outbreaks, and treatment levels the statement cited above is meaningless because lice loads necessary to protect wild salmon can be different from those at which operators choose to apply treatment. Low reported levels of sea lice in Nova Scotia have been attributed to the limited scale and wider distribution of the open net pen ("**ONP**") industry in Nova Scotia (Doelle and Lahey 2014). The Canadian Science Advisory Secretariat (CSAS) and Doelle-Lahey reports note that sea lice levels at the sites are unknown and density-dependent transmission of sea lice on salmonid farms will increase as production increases (Doelle and Lahey 2014; DFO 2021), suggesting that lice levels in Liverpool Bay farms will likely rise if KCS's proposed expansion is approved.

7. At paragraph 10, the Samways Report states that the Liverpool Bay proposal poses "low to medium risk to nearby salmon rivers" in terms of escapes and interbreeding. No scientific evidence is cited to support this conclusion. The report does however state that the conclusion of low to medium risk is because "only 12 to 15% of returning Atlantic salmon typically stray to other rivers." Straying rates of wild salmon are irrelevant because farmed salmon do not behave like wild salmon. Farmed salmon can travel hundreds of kilometers when released into the wild and they do not appear to demonstrate the same homing behaviour as wild salmon (Hansen 2006).

   Analyses presented in the CSAS report demonstrate that the proposed expansion will substantially increase the impacts of escapees on wild Atlantic salmon in most rivers within 200km to either side of the proposed farms, including all those in the genetically distinct Southern Uplands population (DFO 2021).

Propagule pressure, or the intensity of human-mediated ‘species introductions’, is expected to increase by an average of 17% for rivers within 100km of the proposed sites (19% for the LaHave population), 55% for rivers within 50km of proposed sites (including the Petite, Broad and Medway Rivers), and 107% for the Mersey River (DFO 2021).

Their models indicated that invasions of 2.5% or more of the wild population size reduced the number of returning spawners, and invasions above 5% of the population size are likely to have lasting genetic impacts that would reduce fitness of the wild populations. Therefore, the small size of the Medway River spawning population, for example, would render it even more vulnerable to genetic introgression by escapees (DFO 2021).

Activities that threaten the genetic integrity of the SU population, an entire genetically distinct and endangered population of Atlantic salmon, cannot be considered ‘low to medium risk’. Based on the information presented above and in our original submission, we believe the Samways Report has significantly underestimated the risk posed by escapes and genetic introgression from the existing and proposed sites at Liverpool Bay to wild Atlantic salmon in Nova Scotia.

8. In paragraphs 8, 9, and 11, the Samways Report disregards the role of expanding ONP operations in preventing the recovery of wild Atlantic Salmon in the Southern Uplands region by diverting the focus to other threats. The Report acknowledges the complex suite of threats to wild Atlantic salmon supported by substantive peer reviewed research and dismisses them based on one paper’s hypothesis (Samways Report, para. 9). The paper referenced, Dadswell et al. (2021) contends that no single threat can explain the magnitude and the ubiquity of salmon declines and presents the hypothesis that Illegal Unreported Unauthorized fishing may explain some of the losses in the marine environment.

   Despite uncertainties about specific dynamics in the marine environment and their variable impacts on different populations and lifestages, the peer-reviewed literature clearly demonstrates significant impairments to the recovery of sustainable wild Atlantic salmon populations. Gibson and Bowlby (2013) assert that small changes in marine survival could dramatically increase the viability of the SU population. The Doelle Lahey panel and CSAS report emphasize that the need for better management of other threats does not justify developing or conducting aquaculture on the basis that the relative impact is small or unimportant (Doelle & Lahey 2014; DFO 2021). The myriad of threats identified for wild Atlantic salmon act cumulatively on their survival, therefore any reductions to fitness and sublethal effects from genetic introgression and elevated levels of sea lice exacerbates mortalities as other stressors are encountered throughout their migration (Finstad et al. 2007; Shephard and Gargan 2021; Moriarty et al. 2023, **Tab 2**). It is imperative to do everything in our power to minimize anthropogenic impacts to promote the sustainability of wild Atlantic salmon populations.

Affidavit of Jessica Feindel

The enhanced river monitoring program that may be developed by the NSDFA described in Exhibit ‘E’ of Jessica Feindel’s Affidavit (the Department of Fisheries and Aquaculture’s “Containment Management Framework”) would not effectively or efficiently prevent interactions between farmed escapees and wild salmon. The frequency of containment breaches is estimated to be substantially higher than what is reported (Doelle and Lahey 2014; DFO 2021), therefore monitoring efforts triggered by detected breaches would likely be ineffective to identify and recapture the majority of escaped salmon. Though monitoring can be used to assess the impacts and is essential to adaptive management, the only way to prevent interactions between wild Atlantic salmon and farmed salmon is by ensuring that they do not share water using closed containment aquaculture systems or locating sea cages very far from wild fish (Harrington et al. 2006; Frazer 2009).

References

Bateman et al. 2023. Academic scientists' critique of DFO Science Response Report 2022/045. https://krkosek.eeb.utoronto.ca/files/2023/02/Scientists-critique-of-DFO-CSAS-Response-Report-2022_045.pdf (**Tab 1**)

DFO. 2021. DFO Maritimes Region Science Review of the Proposed Marine FinFish Aquaculture Boundary Amendment and New Sites, Liverpool Bay, Queens County, Nova Scotia. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2021/nnn

Doelle, M. and Lahey, W. 2014. A New Regulatory Framework for Low-Impact/High Value Aquaculture in Nova Scotia. Available at SSRN: https://ssrn.com/abstract=2463759 or http://dx.doi.org/10.2139/ssrn.2463759.

Finstad, B., Kroglund, F., Strand, R., Stefansson, S.O., Bjorn, P.A., Rosselund, B. O., Nilsen, T.O., Salbu, B. 2007. Salmon lice or suboptimal water quality — Reasons for reduced postsmolt survival? Aquaculture (273): 374-383.

Frazer L. 2009. Sea-cage aquaculture, sea lice, and declines of wild fish. Conservation Biology, 23: 599–607.

Gibson, A.J.F., Bowlby, H.D., Hardie, D.C, O'Reilly, P.T. 2011. Populations on the Brink: Low Abundance of Southern Upland Atlantic Salmon in Nova Scotia, Canada. North American Journal of Fisheries Management, 31(4):733-741

Hansen. 2006. Migration and survival of farmed Atlantic salmon (Salmo salar L.) released from two Norwegian fish farms, ICES Journal of Marine Science, Volume 63, Issue 7, Pages 1211–1217

Harrington, P. D. , Cantrell, D. L., Foreman, M. G., M. Guo, and Lewis, M. A. 2023. Timing and probability of arrival for sea lice dispersing between salmon farms, Royal Society Open Science, vol. 10, no. 2.

Moriarty, M., Ives, S., Murphy, J., Murray, A. 2023. Modelling parasite impacts of aquaculture on wild fish: The case of the salmon louse (Lepeophtheirus salmonis) on out-migrating wild Atlantic salmon (Salmo salar) smolt. Preventative Veterinary Medicine 214:105888 (**Tab 2**)

Shephard, S., and Gargan, P. 2021. 'Wild Atlantic Salmon Exposed to Sea Lice from Aquaculture Show Reduced Marine Survival and Modified Response to Ocean Climate'. Edited by Howard Browman. ICES Journal of Marine Science 78, 1: 368–76

Thorstad, E.B. et al. 2015. Effects of salmon lice Lepeophtheirus salmonis on wild sea trout Salmo trutta a literature review. Aquaculture Environment Interactions 7: 91–113.

Vormedal, I. 2023. Sea-lice regulation in salmon-farming countries: how science shape policies for protecting wild salmon. Aquaculture Interactions (**Tab 3**)

Wringe, B.F., Jeffery, N.W., Stanley, R.R.E. *et al.* 2018. Extensive hybridization following a large escape of domesticated Atlantic salmon in the Northwest Atlantic. *Commun Biol* **1,** 108

January 30, 2023

The Honourable Joyce Murray
Minister of Fisheries, Oceans and the Canadian Coast Guard
House of Commons
Ottawa, Ontario,
Canada K1A0A6

Academic scientists’ critique of DFO Science Response Report 2022/045

Dear Minister,

We are a group of 16 professors and research scientists who, collectively, have extensive research expertise in fisheries, epidemiology, and the environmental consequences of aquaculture. We write to express our professional dismay at serious scientific failings in a recently published DFO Science Response Report (#2022/045) about sea lice on salmon farms and wild salmon in BC. We are deeply concerned with the report's flaws and its main, unsupported conclusion: that the presence of parasitic sea lice on wild juvenile salmon is not significantly associated with sea lice from nearby salmon farms.

In fact, a simple analysis of the report’s own results indicates an *overall significant association between infestation pressure attributable to Atlantic Salmon farms and the probability of L. salmonis infestations on wild juvenile chum and pink salmon* (details below).

We, the undersigned, have cumulatively published over 1500 peer-reviewed scientific papers, serve or have served on over 30 editorial boards of scientific journals, include five Fellows of the Royal Society of Canada, and have many decades of experience in science advice processes across levels of government. We note this so that it will not be taken lightly when we say that this report falls *far* short of the standards of credible independent peer review and publishable science.

In addition to technical flaws, we have serious concerns about the processes that generated this report. The report was written by employees of DFO Aquaculture Management and Aquaculture Science and was externally reviewed by one industry-associated professor. This does not constitute independent peer review. Furthermore, the report appears to rely on selective reporting of non-significant statistical results (see below). Finally, there are over 30 peer-reviewed scientific papers from BC that link sea lice on wild juvenile salmon with salmon farms, and many more papers internationally. Despite some of these being cited in the report, none were integrated into the report’s conclusions.

Yet, the report will be — and has been — taken to imply that sea lice from salmon farms are not a problem for wild salmon. This is not a credible conclusion. The Science Response Report in no way overturns the accumulated scientific evidence that salmon farms are one of the primary drivers of sea louse infestations on nearby wild juvenile salmon.

The research topic that this report seeks to address is fundamental to the precautionary management of salmon farming in BC, and has long deserved a peer-reviewed analysis by DFO that is much more rigorous than the one carried out for this report. Given the report's major flaws, its findings are not suitable to feed into the upcoming CSAS "risk assessment of sea lice in BC" or policy decisions concerning BC salmon farms.

The key flaws of the Science Response Report are:

1. the reporting of methods and results appears to be selective, according to ATIP records (Appendix B), such that not all analyses were reported and statistically significant results were omitted;
2. the contributors to the report are almost all Aquaculture-focused DFO staff with the mandate to "support aquaculture development," and no external, industry-unaffiliated scientists were involved, such that the report's approval via a "National Peer Review Process" clearly violated any reasonable standards of independent peer review;
3. the report downplays a large body of peer-reviewed research — both BC-focussed and international — that has repeatedly demonstrated the relationship between salmon farms and sea lice on wild juvenile salmon;
4. the report lacks a power analysis to place in context the real possibility that negative results in each region resulted from weak analysis, even if effects of salmon farms truly exist;
5. the analyses cannot be validated, because the underlying data were not provided.
6. the claims rely on an unvalidated infestation model that is inconsistent with the state of scientific knowledge on the topic; and
7. the statistical analyses were inappropriate (in terms of data manipulation, analysis type, and underlying assumptions), and analysis of the results *in the report* produces the opposite conclusions.

We have included further details regarding these seven issues in the attached "Appendix A."

In conclusion, this report fails to meet widely accepted scientific standards on numerous fronts, and therefore falls well short of the quality of science advice that you need to make informed decisions on the future of salmon aquaculture in Canada. Wild salmon deserve better.

We hope that this letter is received as it is intended: to be constructive, and to help improve the quality of science advice that reaches you, Minister, and other decision makers at DFO. Ultimately, promoting a system of evidence-based science advice that attains the highest standards of impartiality and transparency, underscored by a rigorous and independent peer review process, will build Canadians' trust in The Department and decisions surrounding controversial files, such as salmon aquaculture. The scientific community is ready to contribute.

Signed,

Prof. (Adjunct) Andrew Bateman, University of Toronto
& Salmon Health Manager, Pacific Salmon Foundation
Prof. Chris Darimont, University of Victoria
Prof. (Emeritus) Lawrence Dill, Simon Fraser University, FRSC
Prof. Andrea Frommel, University of British Columbia
Prof. (Retired) Neil Frazer, University of Hawaii
Prof. (Incoming) Sean Godwin, University of California, Davis
Prof. Scott Hinch, University of British Columbia, FRSC
Prof. Martin Krkosek, University of Toronto
Prof. Mark Lewis, University of Victoria, FRSC
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Prof. Sarah Otto, University of British Columbia, FRSC
Dr. Stephanie Peacock, Analyst, Pacific Salmon Foundation
Dr. Michael Price, Simon Fraser University
Prof. John Reynolds, Simon Fraser University, FRSC
Prof. (Emeritus) Rick Routledge, Simon Fraser University

Appendixes for "Open Letter: Academic scientists' critique of DFO Science Response Report 2022/045"

Appendix A – Details of the issues with the Science Response Report 2022/045

1. **The reporting of methods and results appears to be selective, according to ATIP records (Appendix B), such that not all analyses were reported and statistically significant results were omitted.**
    - ATIP documents (Appendix B) show that a variety of statistical analyses were employed by the authors, and that some of these found a statistically significant association between sea louse numbers on farms and on wild salmon. The documents show that the various analyses were distributed among the contributors, but only analyses that found no significant associations were included in the final report.
    - Selective reporting of analysis runs counter to basic statistical practice and scientific integrity, and thus the failure to report on all the analytical approaches attempted invalidates the statistical results that were finally made public ("p-values" are meaningless if an analysis is performed over and over and over again, until a palatable version emerges).
    - In combination with the excessive reliance on statistical significance testing, the decisions to not include 'positive' findings suggest that the authors have engineered the results to suit their initial bias.

2. **The contributors to the report are almost all Aquaculture-focused DFO staff with the mandate to "support aquaculture development," and no external, industry-unaffiliated scientists were involved, such that the report's approval via a "National Peer Review Process" clearly violated any reasonable standards of independent peer review.**
    - For this report, with one exception, participation of scientists was limited to Aquaculture Management and Aquaculture Regulatory Science, who have the mandate to "support aquaculture development".
    - The remaining participant, who acted as the sole external reviewer of the report (as confirmed by ATIP documents; Appendix C), is an industry-associated professor who regularly advises BC salmon-farming companies.
    - This process not only fails to meet the minimum standard of independent peer review, but also does not reflect DFO's SAGE principles, which dictate that "advice should be drawn from a variety of scientific sources and from experts" in order to achieve "sound science advice by reducing the impacts of conflicts of interest or biases that may exist".

3. **The report downplays a large body of peer-reviewed research — both BC-focussed and international — that has repeatedly demonstrated the relationship between salmon farms and sea lice on wild juvenile salmon.**

- A plethora of industry-unaffiliated peer-reviewed research in BC (e.g., [1:4]) and around the world (e.g., [5,6]) has found statistical associations between sea louse numbers on farmed and wild salmon. None of this research was given weight in interpretation of the results or in the conclusions.
- The report frames the analysis with the phrase “what is still debated is the effect of sea lice infestations on wild salmon populations”, but it fails to acknowledge the peer-reviewed, industry-unaffiliated research suggesting exactly these effects. This body of literature has repeatedly shown that sea lice are associated with population-level impacts on some wild salmon populations in BC (e.g., [3,7,8]) and in Europe, where a causal link between the two has been established (e.g., [9,10]). In the report, however, the only BC-focussed publications on the topic of population-level effects that were cited were those associated with industry and with negative results (e.g., [2], which was later discredited and the data re-analysed in [8], which found an effect).

4. **The report lacks a power analysis to place in context the real possibility that negative results in each region resulted from weak analysis, even if effects of salmon farms truly exist.**
    - Given the shortcomings of the statistical analysis (see point 7), the potential to reveal any connection between the modelled infestation pressure and empirical sea louse data was likely greatly reduced, and the authors should have evaluated their chosen analytical approach.
    - Underpowered studies are, in effect, unable to answer the research question they pose. Without an analysis that quantifies statistical power there is a serious risk of drawing conclusions based on a false negative result - failing to find an effect due to statistical shortcomings rather than a bonafide absence of effect.
    - For this reason, it is **standard** practice when reporting negative results — especially in such a policy-relevant context — to perform a statistical power analysis to understand the approach’s chances of detecting an effect *if it were really there*. The non-significant results reported may be due to low statistical power more so than an absence of a biological effect.

5. **The analyses cannot be validated, because the underlying data were not provided.**
    - In stark contrast to modern standards of data sharing (as demonstrated by the open-data policies of granting agencies, journals, the Government of Canada, and DFO itself), this report does not provide the data it analyses.
    - This lack of data sharing prevents any independent assessment of the results or conclusions.
    - We have sent an urgent data request to DFO in hopes that scientists external to DFO will be able to redo the analysis using more appropriate methods.

6. **The claims rely on an unvalidated infestation model that is inconsistent with the state of scientific knowledge on the topic.**

- The complex predictive infestation-pressure modelling draws from multiple sources in a way that is, overall, unvalidated (i.e. not tested with empirical data); therefore, any lack of statistical association with sea louse counts on wild salmon could be interpreted as a failure of this initial modelling step, just as much as a lack of association between farm infection pressure and sea lice on wild salmon.
- The infestation-pressure model makes no attempt to incorporate the known temporal and spatial infection dynamics that have been extensively covered in the peer-reviewed literature, and which are necessary for describing the spillover of sea lice from farmed to wild salmon. A key example of this is the lack of acknowledgement that wild juvenile salmon pick up sea lice as they migrate past farms. Instead, "distance from farm" is applied. This is a fundamentally inappropriate measure of exposure, since it treats migrating fish caught 30 km before and 30 km after a farm as the same, even though (simplistically) the first fish has not yet been exposed and the second fish will have already swum through the full 60 km of farm-derived infestation pressure.
- The infestation-pressure model, against all the evidence from a well-established body of peer-reviewed research, assumes that larval sea-louse dispersal is a symmetric process and does not rely on ocean conditions or hydrodynamics.
- In addition, the infestation-pressure model assumes, with no justification, that a model of development from Atlantic sea lice is appropriate for Pacific sea lice, when DFO scientists regularly make the point that sea lice from the two oceans are distinct evolutionary units and likely separate species.
- Regardless, the report provides insufficient detail to evaluate — or reproduce — the infestation model, even if the data had been made available (see point 7).

7. **The statistical analyses were inappropriate (in terms of data manipulation, analysis type, and underlying assumptions), and analysis of the results *in the report* produces the opposite conclusions.**
    - Critically, the analysis relies on the inappropriate assumption that observed copepodid and chalimus lice (which could be well over a week old, depending on the month) on wild salmon were all the result of infestation pressure at the *point and time* of capture (rather than from earlier in the salmon's migration).
        - This is like developing a complex model of COVID-19 transmission, then assuming that all recent cases were acquired at testing sites (e.g. hospital parking lots & airports).
        - An obvious "fix" would have been to consider only very recently attached (copepodid) lice, but this would still ignore a large fraction of the sea louse data from wild salmon, which other analyses (e.g., [1]) have directly incorporated in an appropriate manner.
    - Decisions in the analysis undermined its ability to detect any true effects of sea lice on salmon farms. Rather than directly analysing *prevalence of infection* within a sample (the standard approach to dealing with the number of infested individuals out of a given total number), the authors analyse *prevalence of nonzero sea louse prevalence* within a sample. This results in an inappropriate

aggregation/muddying of the data and, ultimately, an analysis that is most likely underpowered to detect an effect (see point 4).

  - ○ The appropriate analysis of all of the prevalence data (which should have been done but was not) would have been a generalised linear model of presence/absence, i.e. “binomial regression” (with appropriate random effects).
  - ○ The appropriate analysis of all the louse *abundance* data (which should have been done, but was not) would have been a negative binomial regression (with appropriate random effects).
- Consistency across regions was ignored. The report found that all regions displayed the same statistical trend, and two of the regions narrowly missed the arbitrary 5% p-value cut off for significance (by 1 percent). If these data were re-analysed in a more suitable and powerful analytical framework (see point 4) that combined all four regions together in an appropriate manner, the authors’ results would have been much more likely to be “significant,” but no discussion of this was presented.
- In fact, a simple analysis, using “Fisher’s method” (a standard statistical approach) to combine the results across regions, yields an *overall* statistically significant p-value of 0.032. That is, based solely on the evidence presented in the Science Response Report, we can say that:

  Coastwide, a significant association was observed between infestation pressure attributable to Atlantic Salmon farms and the probability of L. salmonis infestations on wild juvenile chum and pink salmon

References

[1] Krkosek, M., M.A. Lewis, and J.P. Volpe, Transmission dynamics of parasitic sea lice from farm to wild salmon. Proceedings of the Royal Society B: Biological Sciences, 2005. 272(1564): p. 689-696.
[2] Marty, G.D., S.M. Saksida, and T.J. Quinn, Relationship of farm salmon, sea lice, and wild salmon populations. Proceedings of the National Academy of Sciences, 2010. 107(52): p. 22599-22604.
[3] Peacock, S.J., et al., Cessation of a salmon decline with control of parasites. Ecological Applications, 2013. 23(3): p. 606-620.
[4] Price, M.H.H., et al., Sea louse infection of juvenile sockeye salmon in relation to marine salmon farms on Canada's west coast. PLOS ONE, 2011. 6(2): p. e16851.
[5] Kristoffersen, A.B., et al., Large scale modelling of salmon lice (*L. salmonis*) infection pressure based on lice monitoring data from Norwegian salmonid farms. Epidemics, 2014. 9: p. 31-39.
[6] Middlemas, S., et al., Relationship between sea lice levels on sea trout and fish farm activity in western Scotland. Fisheries Management and Ecology, 2013. 20(1): p. 68-74.
[7] Connors, B.M., et al., Coho salmon productivity in relation to salmon lice from infected prey and salmon farms. Journal of Applied Ecology, 2010. 47(6): p. 1372-1377.
[8] Krkosek, M., et al., Effects of parasites from salmon farms on productivity of wild salmon. Proceedings of the National Academy of Sciences, 2011. 108(35): p. 14700-14704.
[9] Krkosek, M., et al., Impact of parasites on salmon recruitment in the Northeast Atlantic Ocean. Proceedings of the Royal Society B: Biological Sciences, 2013. 280(1750): p. 20122359.
[10] Vollset, K.W., et al., Impacts of parasites on marine survival of Atlantic salmon: a meta‐analysis. Fish and Fisheries, 2016. 17(3): p. 714-730.

Appendix B – Supporting ATIP documents for selective reporting

The following pages provide email exchanges among DFO participants, in which the main analyst for the Science Response Report sent summarized results and draft documents that fed into the final report. These messages show that a variety of statistical analyses were employed by the authors, and that some of these found a statistically significant association between sea louse numbers on farms and on wild salmon. This selective reporting runs counter to basic statistical practice and scientific integrity, and thus the failure to ultimately report on all the analytical approaches attempted invalidates the statistical results that were finally made public ("p-values" are meaningless if an analysis is performed over and over and over again, until a palatable version emerges). The documents show that the various analyses were distributed among the contributors, but only analyses that found no significant associations were included in the final report. These documents were obtained under the Access to Information and Privacy (ATIP) request #A-2022-00378. Our annotations to the original documents are in **red.**

From: Jeong, Jaewoon
Sent: Tuesday, March 29, 2022 5:39 PM
To: Mimeault, Caroline; Siemens, Lisa; Price, Derek; Johnson, Stewart; Jones, Simon; Parsons, Jay
Subject: Document for the sea lice update meeting (this Thursday)
Attachments: effect of excluding mature sea lice.docx

Hello all,

I share this document that includes the results from models evaluating the association between the overall output pressure of lice from Atlantic salmon farms in four areas of British Columbia with and without mature sea lice. I am also currently working on the segmented regression to model to evaluate the association between the overall output pressure of lice from Atlantic salmon farms and sea lice density on wild fish.

Jaewoon

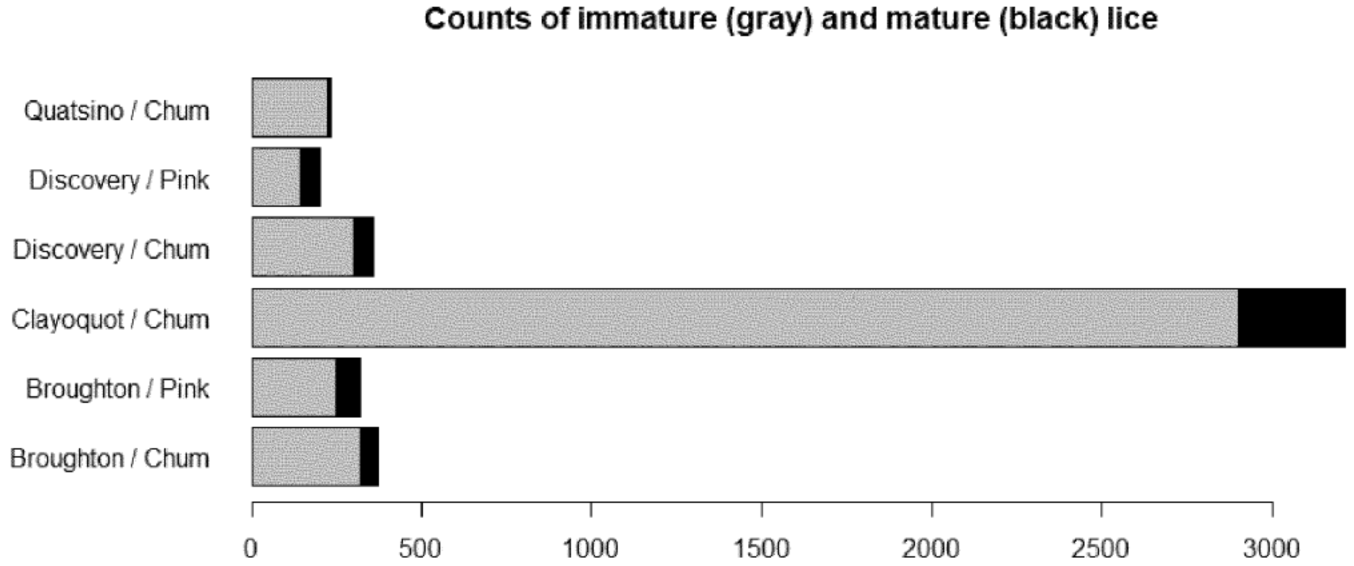
Table 1. The results from models evaluating the association between the overall output pressure of lice from Atlantic salmon farms in four areas of British Columbia and the log-odds of the presence of an infestation (logistic regression model) and the prevalence of infestation with lice (linear regression model).

		Region	**Broughton**	**Broughton**	**Clayoquot**	**Discovery**	**Discovery**	**Quatsino**
		Fish species	**Chum**	**Pink**	**Chum**	**Chum**	**Pink**	**Chum**
Without mature lice (copepodid + chalimus)	Logistic regression	**Log-Odds**	0.09	0.14	0.36	0.51	0.32	0.31
		CI	-0.09 – 0.26	-0.03 – 0.30	0.24 – 0.49	0.36 – 0.66	0.21 – 0.43	0.14 – 0.48
		p-value	0.343	0.105	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	Linear regression	**Estimates**	0.04	0.11	0.23	0.07	0.05	-0.04
		CI	-0.07 – 0.16	0.02 – 0.21	0.16 – 0.30	0.01 – 0.14	0.01 – 0.09	-0.15 – 0.07
		p-value	0.431	**0.021**	**<0.001**	**0.033**	**0.019**	0.483
With mature lice (copepodid + chalimus + preadult + adult)	Logistic regression	**Log-Odds**	0.09	0.09	0.39	0.57	0.28	0.29
		CI	-0.08 – 0.27	-0.07 – 0.26	0.26 – 0.51	0.42 – 0.72	0.18 – 0.39	0.13 – 0.45
		p-value	0.309	0.249	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	Linear regression	**Estimates**	0.01	0.12	0.21	0.07	0.07	-0.03
		CI	-0.11 – 0.13	0.03 – 0.21	0.14 – 0.28	0.01 – 0.14	0.02 – 0.11	-0.13 – 0.07
		p-value	0.857	**0.009**	**<0.001**	**0.025**	**0.006**	0.561

Initial analyses by species showed "significant" results for multiple species and regions.

Table 2. counts of immature, mature lice and number of sampled fish by regions and fish species.

Region	**Broughton**	**Broughton**	**Clayoquot**	**Discovery**	**Discovery**	**Quatsino**
Fish species	**Chum**	**Pink**	**Chum**	**Chum**	**Pink**	**Chum**
Immature lice	321	246	2901	300	144	222
Mature lice	52	71	316	59	58	11
Total lice	373	317	3217	359	202	233
Number of sampled fish	2347	2138	4701	3745	2744	2199



From: Jeong, Jaewoon
Sent: Thursday, May 19, 2022 10:18 AM
To: Mimeault, Caroline; Parsons, Jay; Price, Derek; Siemens, Lisa; Johnson, Stewart; Jones, Simon
Subject: sea lice document for today meeting
Attachments: Analyses by area (chum and pink combined).docx

Hello all,

I share this document for the sea lice update meeting later today.

Jaewoon

Amalgamated analyses

Table. The number of unique combination of sampling site – week – year.

	Logistic regression	Linear regression
Clayoquot Sound	185	153
Quatsino Sound	73	43
Discovery Islands	223	122
Broughton Archipelago	169	121

Table. The number of unique combination of sampling site – week – year.

	Discovery Islands		Broughton Archipelago	
Fish species	Zero prevalence	Non-zero prevalence	Zero prevalence	Non-zero prevalence
Chum	59	66	25	62
Pink	42	56	23	59

Logistic regression analysis

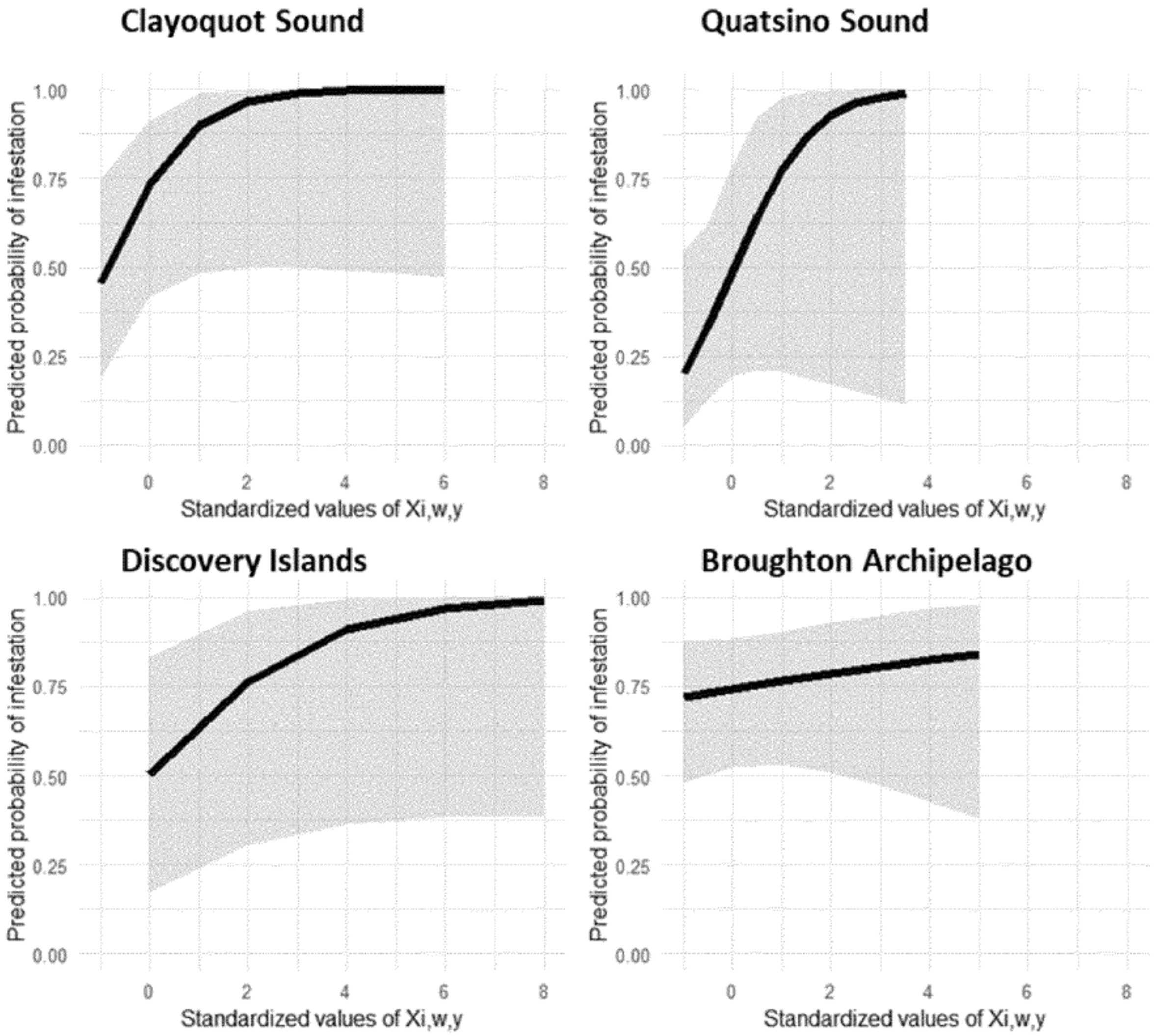


Figure. Margins plots based on logistic regression illustrating the relationship between the standardized *L. salmonis* output pressure (the main predictor of interest, Xi,w,y) from the study farms (X-axis) on the predicted probability of infestation on out-migrating wild juvenile salmon (Y-axis). The grey area represents 95% confidence interval about the prediction line (black).

Table. Results for the logistic regression evaluating the effect of fish species on the log-odds of the presence of infestation with lice on out-migrating salmon (Y). Fish [Pink] means that Pink Salmon contributes to the outcome (Prevalence) as much as the coefficient compared to Chum Salmon.

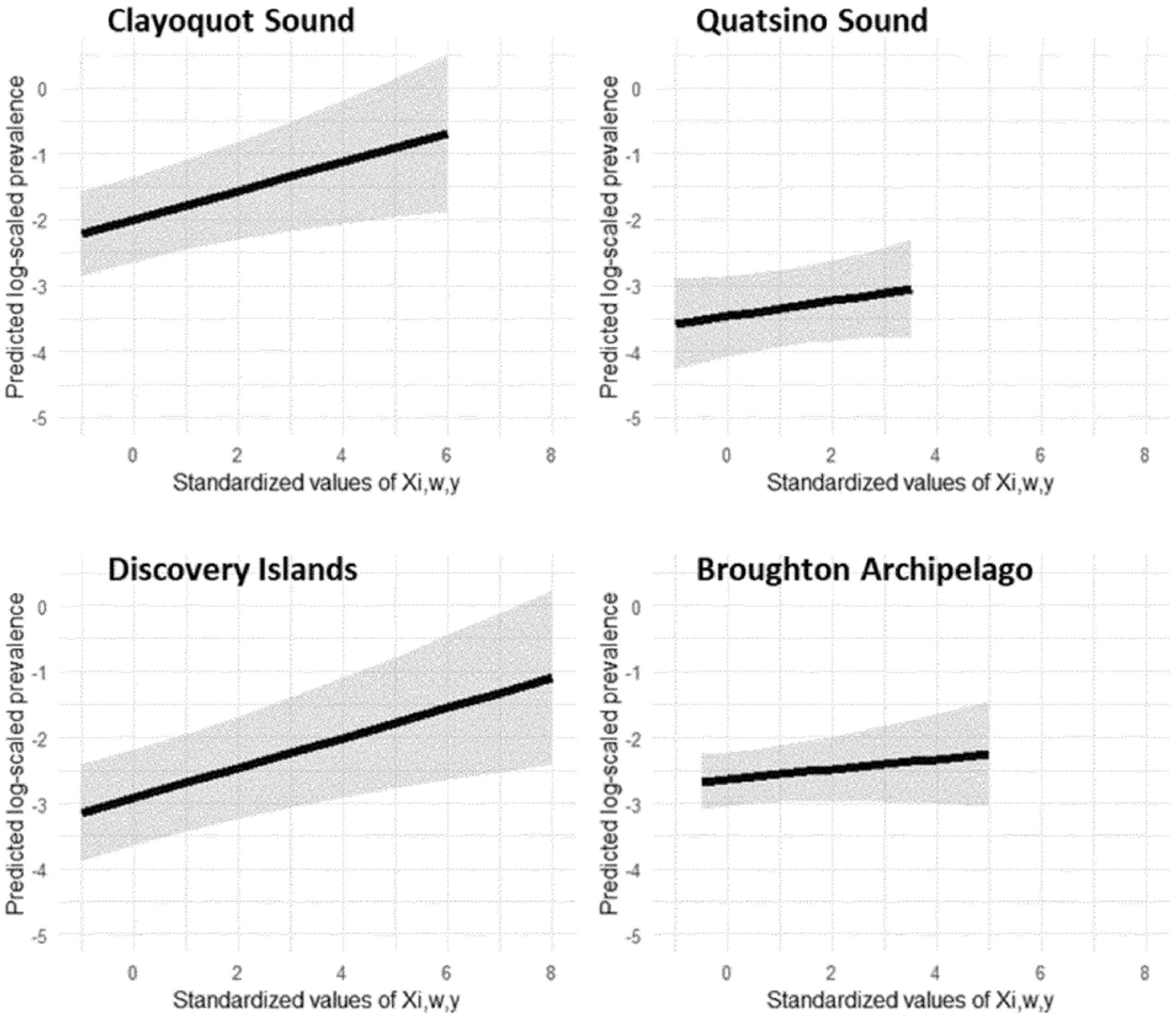
Region	Variable	Coefficient	95% CI	P-value
Discovery Islands	Fish [Pink]	0.06	-0.52 ~ 0.65	0.83
Broughton Archipelago	Fish [Pink]	0.03	-0.66 ~ 0.71	0.94

Overall, it is difficult to say that there is an effect of fish species on prevalence, because the direction of coefficient and p-value vary massively. Therefore, it is appropriate to analyze the data without separating by fish species.

Table. Results for the logistic regression evaluating the effect of L. salmonis output pressure (Xi,w,y) from the study farms on the log-odds of the presence of infestation with lice on out-migrating salmon (Y).

Region	Coefficient	95% CI	P-value
Clayoquot Sound	1.19	- 0.06 ~ 2.43	0.06
Quatsino Sound	1.3	- 0.34 ~ 2.95	0.12
Discovery Islands	0.57	- 0.03 ~ 1.17	0.06
Broughton Archipelago	0.12	- 0.25 ~ 0.50	0.52

Linear regression analysis



Clayoquot Sound

Quatsino Sound

Discovery Islands

Broughton Archipelago

Figure. Margins plots based on linear regression illustrating the relationship between the standardized *L. salmonis* output pressure (the main predictor of interest, Xi,w,y) from the study farms (X-axis) on the predicted log-scaled prevalence of lice on out-migrating wild juvenile salmon (Y-axis). The grey area represents 95% confidence interval about the prediction line (black).

Table. Results for the linear regression evaluating the effect of fish species on the log-prevalence of the infestation on out-migrating juvenile salmon (Y). Fish [Pink] means that Pink Salmon contributes to the outcome (Prevalence) as much as the coefficient compared to Chum Salmon.

Region	Variable	Coefficient	95% CI	P-value
Discovery Islands	Fish [Pink]	-0.32	-0.59 ~ -0.05	0.02
Broughton Archipelago	Fish [Pink]	-0.15	-0.39 ~ 0.09	0.21

Overall, it is difficult to say that there is an effect of fish species on prevalence, because the direction of coefficient and p-value vary massively. Therefore, it is appropriate to analyze the data without separating by fish species.

Table. Results for the linear regression evaluating the effect of L. salmonis output pressure (Xi,w,y) from study farms on the log-prevalence of the infestation on out-migrating juvenile salmon (Y).

Region	Coefficient	95% CI	P-value
Clayoquot Sound	0.22	0.06 ~ 0.38	0.01
Quatsino Sound	0.12	- 0.08 ~ 0.31	0.22
Discovery Islands	0.23	0.09 ~ 0.36	<0.01
Broughton Archipelago	0.08	- 0.06 ~ 0.21	0.28

Initial analyses showed "significant" results for two regions.

MODELING THE ASSOCIATION OF S~~EA~~ALMON LOUSE, *Lepeophtheirus salmonis*, INFECTIONS BETWEEN FARMED ATLANTIC SALMON (*Salmo salar*) AND JUVENILE PACIFIC SALMON IN COASTAL BRITISH COLUMBIA

Jaewoon Jeong, Derek Price, Stewart C. Johnson, Caroline Mimeault, Lisa Siemens, G. Jay Parsons, Simon R. M. Jones*

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The salmon louse (*Lepeophtheirus salmonis*) is an important pest of marine-reared Atlantic salmon. In British Columbia, conservation of wild salmon is a primary driver for salmon louse management as a condition of license for farmed Atlantic salmon. To minimize risk to juvenile wild salmon, an average of three~~3~~ motile sea lice per fish must not be exceeded ~~during pre-migration and outmigration~~immediately prior to and during the period of ~~wild~~ Pacific salmon outmigration. ~~seasons.~~ Compliance with this threshold is established through systematic ~~parasite~~ sea lice counts conducted by industry and through audits conducted by F~~f~~isheries and Oceans Canada's ~~(DFO)~~'s Aquaculture Management Division. In addition, sea lice data on juvenile wild salmon are collected by industry. The goal of this research was to define the strength of association between sea lice levels on farmed and wild salmon through the analysis of ~~public~~ sea lice counts on Atlantic salmon farms and on juvenile wild salmon~~data~~.

The study focused on
~~Data from~~ four coastal regions (Broughton Archipelago, Clayoquot Sound, Quatsino Sound, Discovery ~~(Vancouver~~ Islands)~~,~~ ~~collected~~ between 201~~6~~3 and 2021, and weekly ~~which included sea lice counts from 14 farm~~observations~~s~~ from between 54 and 70 farms per year and from ~~18~~ wild salmon collected~~ion~~ during out migrations ~~sites~~between 2016 and 2021.~~, and the seaway distances between farms and sampling sites wereas used in our analysis.~~ ~~The number f~~Farm level output of ~~infective~~ copepodids ~~released at the farm level~~ was estimated from numbers of adult female lice ~~sea lice~~ by ~~sequential~~ application of previously published ~~temperature or and salinity dependent~~ models. Standardized infection pressure values derived from copepodid numbers and connectivity of farms were ~~These estimates were~~ used in a mixed-effects logistic regression model ~~and a mixed-effects linear regression model~~, ~~each~~ with~~used~~ a seven~~7~~-day time lag to test the probability of occurrence of infection ~~(model 1) and of non-zero prevalence (model 2)~~ on juvenile pink or chum salmon. In all regions ~~The~~ the ~~logistic~~ model revealed a statistically insignificant ~~n initial~~ increase in the probability of infection on wild salmon with increasing infection pressure ~~copepodid output which plateaued at intermediate to high farm output levels~~ (Fig. 1a). ~~The linear model showed a direct relationship between farm output and prevalence on chum salmon (Fig. 1b).~~

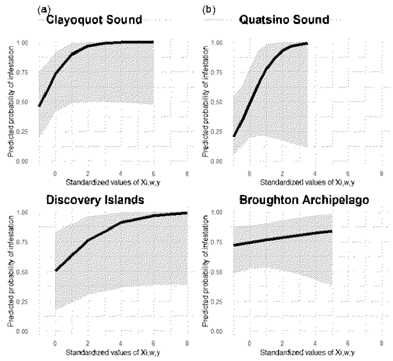

Figure 1. For BC coastal regions ~~Clayoquot Sound~~ between 2016 and 2021, the relationships between the standardized *L. salmonis* farm output pressure (Xi,ws,y) on ~~(a)~~ the predicted probability of infestation on chum salmon (Clayoquot, Quatsino) or pink salmon and chum salmon (Discovery, Broughton)~~, and (b) the predicted probability of non-zero prevalence on chum salmon~~. Grey areas represent 95% CI about the prediction line (black).

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The analysis ~~The models~~ suggests~~ed~~ that ~~in Clayoquot Sound between 2016 and 2021, both~~ the occurrence ~~and prevalence~~ of *L. salmonis* infection on wild migrating juvenile pink or chum ~~chum~~ salmon could not be explained by infection pressure of farm-sourced copepodids. This work, including refinements to the present model, will inform efforts to manage farm-based sea lice to minimize risks to migrating juvenile wild salmon in BC. ~~is influenced by only sufficiently high copepodid infection pressures derived from farmed Atlantic salmon. The absence of hydrodynamic and wild salmon migratory data confers some uncertainty to model outputs, and suggests directions for further model refinement.~~

Commented [JS1]: This isn't clear to me maybe Derick can help?

Commented [PJ2]: Do we want to say anything about management implications - ...these findings will provide insight to management measure to limit sea lice during out migration...or these findings support efforts to reduce sea lice numbers during the outmigration period to minimise risk to wild salmon.

This edit completely changes the meanings of the report's initial findings.

Analysis and Response

This section addresses the main objectives of this advice: (1) estimates number of sea lice copepodids (infective sea lice larval stage) produced by Atlantic Salmon farms in BC; (2) summary of estimates of sea lice numbers on juvenile wild Pacific salmon; and (3) determine the statistical strength of association in between sea lice infestations on Atlantic Salmon farms and prevalence on wild juvenile populations in BC.

Estimates of number of copepodids produced by Atlantic Salmon farms in BC

The estimation of the number of infective *L. salmonis* copepodids produced by Atlantic Salmon farms during the period of juvenile salmon outmigration under current farm management practices was achieved in two steps: (1) estimating the total number of adult *L. salmonis* female sea lice in each FHSZ (Appendix A); and (2) estimating the total number of copepodids derived from those adult female *L. salmonis* based on published peer-reviewed modeling approaches (Appendix B) and considering environmental conditions on the farms (see Appendix C).

Data sources

In BC, active facilities must conduct sea lice monitoring following prescribed protocols and frequency based on the juvenile wild salmon migration windows as described above.

License holders must count sea lice on farms at prescribed frequencies during the different windows. During the non-migration window, sea lice must be counted in a minimum of three stocked containment structures once a month. During the pre-migration window, all containment structures must be counted at least once. Finally, during the out-migration window, sea lice must be counted in a minimum of three stocked containment structures within the first week and then once every two weeks. Licence holders must submit the results to DFO by the 15th of the following month during the non-migration window; and within 48 hours of each sea lice counting event during the pre-migration and the migration windows.

The average *L. salmonis* motile (female and male preadult and adult stages) per fish, the average *L. salmonis* females per fish and the average chalimus (*L. salmonis* and *C. clemensi* together) per fish are reported to DFO. Sea lice counts and monthly inventories are stored in DFO's Aquaculture Integrated Information System (AQUIIS). Monthly average sea lice counts on farms are available online (DFO, 2022a).

Assumptions

The following assumptions were made in estimating the number of *L. salmonis* females on Atlantic Salmon farms and the number of copepodids produced on Atlantic Salmon farms:

- *L. salmonis* counts on Atlantic Salmon farms provided a reliable estimate of adult female abundance for that farm and for that week;
- Linear interpolation is an appropriate method to estimate adult female abundance and the number of salmon on farms between sampling events;
- Spline interpolation is an appropriate method to smooth temperature and salinity data;
- Norwegian sea lice development model from Samsing et al. (2016) was applicable in British Columbia; and
- Mortality of the free-swimming stages of *L. salmonis* was due only to salinity, other causes of mortality were not considered.

Adult female sea lice on farms

The median number of *L. salmonis* adult females per week on a farm varied by years, zones and migration windows (Table 2). Among years, comparatively high median weekly estimates of *L. salmonis* adult females per farm occurred in 2015, 2020 and 2021, and comparatively low median weekly estimates occurred in 2014 and 2018. Among zones, the median weekly estimates of *L. salmonis* adult females per farm was highest in FHSZ 3.5 (Central Coast) and lowest in FHSZ 3.1 (Sunshine Coast).

Of most relevance to this advice are the differences observed among the different juvenile wild salmon migration windows. Comparatively high median weekly estimates of *L. salmonis* adult females per farm occurred in the non-migration window (July to January) while comparatively low median weekly estimates occurred in migration window (March to June) (Table 2).

To highlight the differences in number of *L. salmonis* adult females per week on farms, Figure 2 illustrates the total number of *L. salmonis* adult females per week on Atlantic Salmon farms in each Fish Health Surveillance Zones (FHSZ) on a continuous timeline from 2013 to 2021, inclusively. Generally, the total number of females followed a seasonal trend on farmed Atlantic Salmon which was more recognizable in some FHSZ than in others.

Typically the number of *L. salmonis* adult females increased in the non-migration window and declined in the pre-migration and out-migration windows. This pattern reflects the combined influences of parasite spill-over from returning wild salmon in the late summer and autumn and a more rapid population growth in the warmer months; as well as the effects (reductions) of on-farm sea-lice treatments prior to the juvenile wild salmon outmigration window in the late winter and early spring. However, there are some exceptions in which the total number of *L. salmonis* adult females increased throughout the out-migration window. For example, the number of *L. salmonis* adult females increased during the out-migration window in 2015 and 2018 in FHSZ 2.3; or in 2020 in FHSZ 3.2 which had an increasing ~~e in~~ trend or higher levels than in previous out-migration windows in the same FHSZ.

Table 2. Minimum, median and maximum weekly estimates of Lepeophtheirus salmonis adult females on Atlantic Salmon farms in British Columbia between 2013 and 2021. Data consist of a total of 19,422 observations from 84 farms, and are summarized here by year, Fish Health Surveillance Zone (FHSZ) and migration window. The same data were used to generate Figure 2. FHSZ: 2.3: Southwest Vancouver Island, 2.4: Northwest Vancouver Island, 3.1: Sunshine Coast, 3.2: Discovery Islands, 3.3: Broughton Archipelago, 3.4: Queen Charlotte Strait, and 3.5: Central Coast. Migration windows are defined as pre-migration (February), out-migration (March to June), and non-migration (July to January).

		Number of farms	**Number of observations**	**Minimum**	**Median**	**Maximum**
Year	2013	54	1,588	0	91,190	17,267,338
	2014	59	1,986	0	83,297	4,832,039
	2015	68	2,318	0	187,379	7,700,548
	2016	66	2,065	0	123,046	5,931,768
	2017	66	2,126	0	123,906	12,826,529
	2018	64	2,190	0	81,410	17,379,755
	2019	71	2,415	0	98,165	9,600,534
	2020	62	2,213	0	188,183	6,630,405
	2021	62	2,166	0	179,984	7,419,493
FHSZ	2.3	15	3,808	0	148,147	15,354,943
	2.4	13	3,479	0	196,750	17,379,755
	3.1	6	1,232	0	32,583	1,558,183
	3.2	10	2,309	0	156,971	5,931,768
	3.3	20	4,937	0	84,976	7,709,777
	3.4	12	2,277	0	234,262	13,065,948
	3.5	8	1,380	0	301,470	20,121,870
Window	Pre-migration	82	1,674	0	136,257	14,212,333
	Out-migration	84	6,794	0	78,853	13,221,418
	Non-migration	83	10,954	0	181,608	20,121,870

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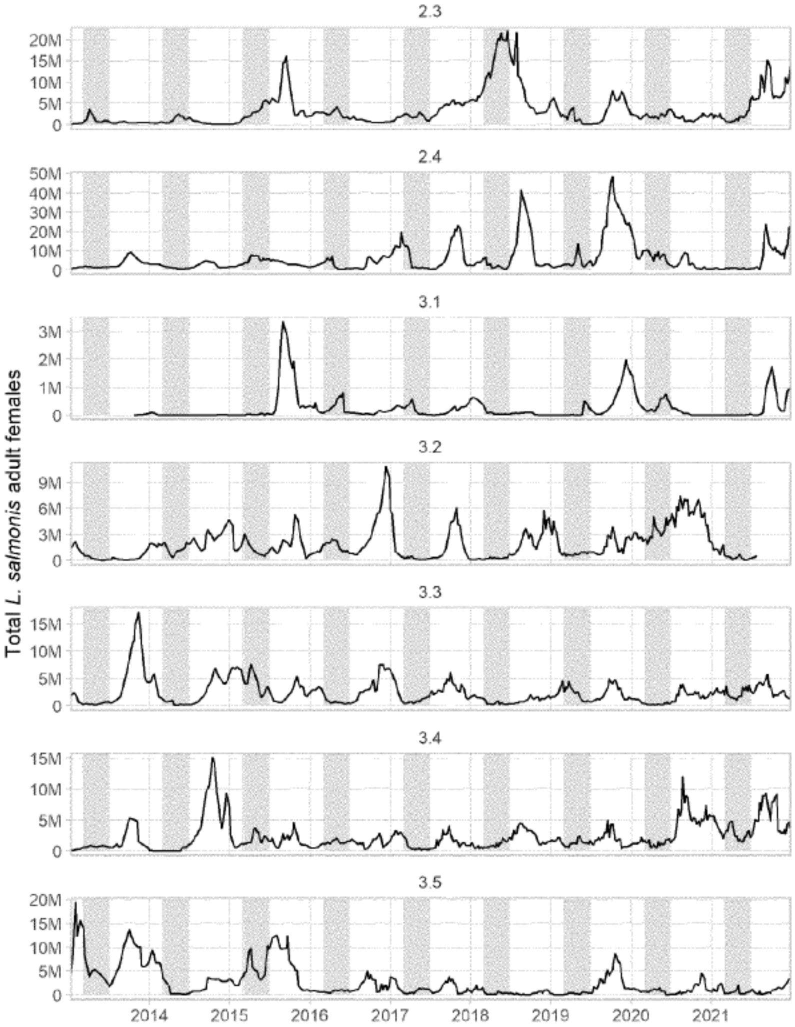


Figure 2. Estimates of total adult female Lepeophtheirus salmonis on Atlantic Salmon farms in the seven Fish Health Surveillance Zones (FHSZ) in British Columbia on a continuous time scale between 2013 and mid-2021. Blue areas indicate juvenile out-migration period (March to June inclusively). Note the scale of the y-axis varies across FHSZ. Data consist of a total of 19,422 observations from 84 farms. The same data were used to generate Table 2. FHSZ descriptions2.3: Southwest Vancouver Island, 2.4: Northwest Vancouver Island, 3.1: Sunshine Coast, 3.2: Discovery Islands, 3.3: Broughton Archipelago, 3.4: Queen Charlotte Strait, and 3.5: Central Coast.

Infective copepodid from farms

The median number of *L. salmonis* copepodids per week on a farm varied by years, zones and migration windows (Table 3). Among years, comparatively high median weekly estimates of *L. salmonis* copepodids per farm occurred in 2015, 2020 and 2021, and comparatively low median weekly estimates occurred in 2014 and 2018. Among zones, the median weekly estimates of *L. salmonis* copepodids per farm was highest in FHSZ 3.5 (Central Coast) and lowest in FHSZ 3.1 (Sunshine Coast).

To highlight the differences in number of *L. salmonis* copepodids ~~adult females~~ per week on farms, Figure 3 illustrates the total number of *L. salmonis* copepodids per week on Atlantic Salmon farms in each Fish Health Surveillance Zones (FHSZ) on a continuous timeline from 2013 to 2021, inclusively. Generally, seasonal variations in the number of infective copepodids (Figure 3) produced by farms ~~infestations~~ tend to follow those of the adult females (Figure 2). Typically the number of *L. salmonis* ~~adult~~ copepodids produced on Atlantic Salmon farms increased in the non-migration window and declined in the pre-migration and out-migration windows. However, similarly to the number of adult females, there are some exceptions in which the total number of copepodids produced increased during the out-migration window (e.g., in 2015 and 2018 in FHSZ 2.3; or in 2020 in FHSZ 3.2).

Of most relevance to this advice are the differences observed among the different juvenile salmon migration windows. Comparatively high median weekly estimates of *L. salmonis* copepodids per farm occurred in the non-migration window (July to January) while comparatively low median weekly estimates occurred in migration window (March to June) (Table 3).

Table 3. Minimum, median and maximum weekly estimates of the number of infective (or viable) Lepeophtheirus salmonis copepodids produced by infestations on an Atlantic Salmon farm in British Columbia between 2013 and 2021. Data consist of a total of 19,422 observations from 84 farms, and are summarized here by year, Fish Health Surveillance Zone (FHSZ) and migration window. The same data were used to generate Figure 3. FHSZ: 2.3: Southwest Vancouver Island, 2.4: Northwest Vancouver Island, 3.1: Sunshine Coast, 3.2: Discovery Islands, 3.3: Broughton Archipelago, 3.4: Queen Charlotte Strait, and 3.5: Central Coast. Migration windows are defined as pre-migration (February), out-migration (March to June), and non-migration (July to January).

		Number of farms	Number of observations	Minimum	Median	Maximum
Year	2013	54	1,588	0	60,686,582	10,257,985,037
	2014	59	1,986	0	51,162,601	3,769,483,342
	2015	68	2,318	0	115,834,439	5,067,450,151
	2016	66	2,065	0	75,162,796	4,391,710,046
	2017	66	2,126	0	77,925,846	8,193,749,841
	2018	64	2,190	0	59,414,155	10,076,254,197
	2019	71	2,415	0	68,574,393	5,900,434,861
	2020	62	2,213	0	122,292,399	3,608,308,890
	2021	62	2,166	0	116,235,931	4,168,147,778
FHSZ	2.3	15	3,808	0	72,668,796	7,352,045,836
	2.4	13	3,479	0	129,313,561	10,076,254,197
	3.1	6	1,232	0	12,325,875	570,816,102
	3.2	10	2,309	0	113,288,093	4,391,710,046
	3.3	20	4,937	0	54,810,126	5,487,126,436
	3.4	12	2,277	0	183,598,711	8,325,268,909
	3.5	8	1,380	0	251,022,083	10,957,682,266
Window	Pre-migration	82	1,674	0	96,621,746	10,257,985,037
	Out-migration	84	6,794	0	53,106,438	9,334,247,617
	Non-migration	83	10,954	0	112,602,435	10,957,682,266

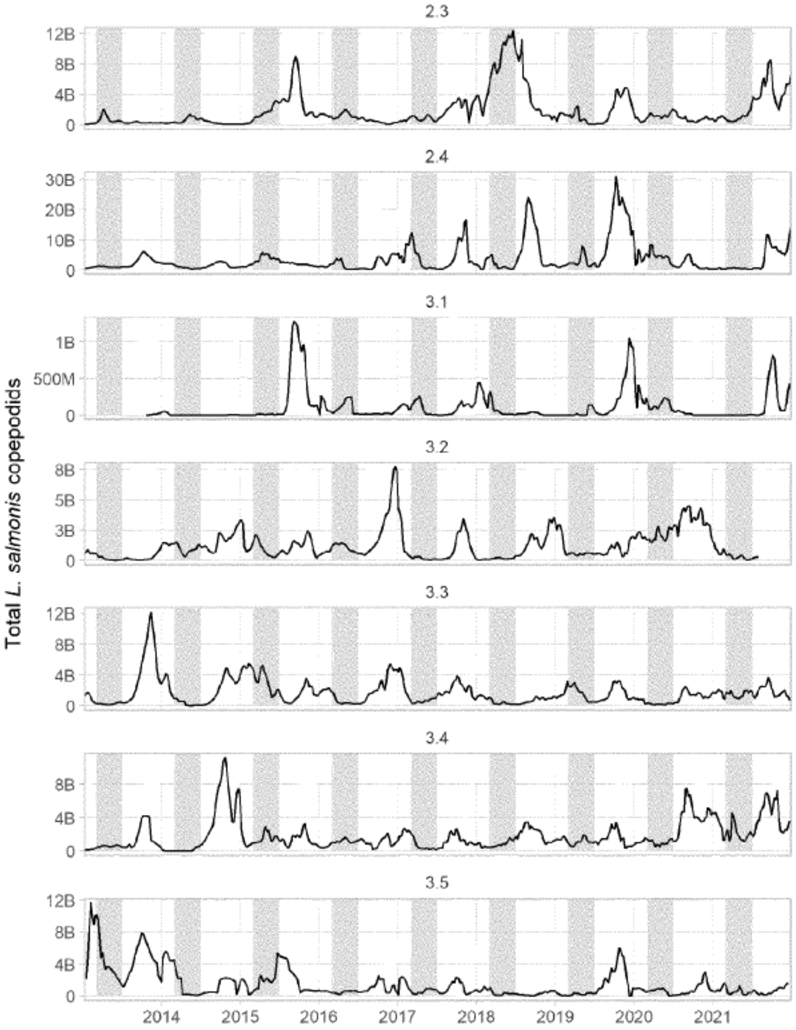


Figure 3. Estimates of total Lepeophtheirus salmonis copepodids (infective larvae) on Atlantic Salmon farms in the seven Fish Health Surveillance Zone in British Columbia on a continuous time scale between 2013 and mid-2021. Blue areas indicate juvenile out-migration period (March to June inclusively). Note the scale of the y-axis varies across FHSZ. Note the scale of the y-axis varies across FHSZ. Data consist of a total of 19,422 observations from 84 farms. The same data were used to generate Table 3. FHSZ descriptions: 2.3: Southwest Vancouver Island, 2.4: Northwest Vancouver Island, 3.1: Sunshine Coast, 3.2: Discovery Islands, 3.3: Broughton Archipelago, 3.4: Queen Charlotte Strait, and 3.5: Central Coast.

Estimates of sea lice on juvenile wild Pacific salmon in BC

This section summarized the *L. salmonis* counts on juvenile Pacific salmon species in BC between 2016 and 2021.

Data sources

The summary of *L. salmonis* numbers on wild juvenile Pacific salmon were based on reports using consistent methods of fish collection and sea lice enumeration through microscopic examination of each fish. Some companies operating marine finfish aquaculture sites in BC, in some instances in partnership with First Nations, contract third parties to conduct monitoring of sea lice on out-migrating juvenile wild salmon ~~sea lice monitoring~~. All reports are available online.

As of January 2022, reports were available for surveys conducted in six different coastal regions (Broughton Archipelago, Discovery Islands, Port Hardy, Central Coast, Clayoquot Sound, and Quatsino Sound) for some or all years between 2014 and 2021. All reports include summary statistics related to sea lice observed on fish captured during the surveys. Only reports in four regions included the sea lice counts at the fish level in appendices (Table 4).

Table 4. Summary of juvenile wild salmon sea lice monitoring reports in British Columbia. Data summarized in January 2022.

Region	Surveyed years	References	Years with fish-level counts
Broughton Archipelago	2015-2021	MBC (2016a, 2017a, 2018a, 2019a, 2020c)	2016-2021
Discovery Islands (Campbell River)	2016-2021	MBC (2018b, 2019b, 2020a, 2021a)	2017-2021
Quatsino Sound	2015-2021	MBC (2016b, 2017b, 2018c, 2019c, 2020d, 2021b)	2016-2021
Clayoquot Sound	2016-2021	MBC (2016c, 2017c, 2018d, 2019d, 2020b, 2021c)	2016-2021

Assumptions

The following assumptions were made in summarizing the *L. salmonis* counts on wild juvenile Pacific salmon:

- Juvenile wild salmon sampling site is the ~~point~~ location of *L. salmonis* infestation; and
- Fish sampled within the same ISO week were assumed to belong to one sampling event.

Commented [SJ1]: This was an assumption for the logistic model

Sampling area and fish description

Figure 4 indicates the four areas for which fish-level counts of sea lice on wild fish are available: Clayoquot Sound in FHSZ 2.3, Quatsino in FHSZ 2.4, Discovery Islands as FHSZ 3.2 and Broughton Archipelago as FHSZ 3.3. Sampling was carried out from March through July at various sites and points in time between 2016 and 2021. A total of 18,824 juvenile wild salmon were caught using beach seines at various sites in the above areas (Table 5).

The remainder of this analysis focuses on Chum and Pink salmon given that together, they represented 95% (17,885 of 18,824) of sampled juvenile wild salmon. More specifically, Chum Salmon represented 95% (4,701 of 4,931) and 87% (2,199 of 2.533) of sampled fish in

Clayoquot Sound and Quatsino Sound, respectively. The remainder of the analyses will therefore focus on Chum Salmon in those areas. In Discovery Islands, Chum and Pink salmon represented 55% (3,745 of 6,788) and 40% (2,744 of 6,788), respectively. In Broughton Archipelago, Chum and Pink salmon represented 51% (2,347 of 4,572) and 47% (2,138 of 4,572), respectively. Both Chum and Pink salmon were therefore included in the analyses in the Discovery Islands and Broughton Archipelago.

Juvenile Chum and Pink salmon captured between March and July at various sampling locations in BC between 2016 and 2021 ranged from 0.08 to 35 g with a median weight of 0.60 g and a mean weight of 0.99 g (Figure 5). Overall, 95% of all sampled fish in the four regions weigh less than 3 g. In Discovery Islands and Broughton Archipelago, the weights of sampled Chum Salmon tended to be heavier than Pink Salmon. More specifically, median weights of Chum Salmon were 0.60, 0.57, 0.69 and 0.70 g in Clayoquot Sound, Quatsino Sound, Discovery Islands and Broughton Archipelago, respectively, while median weights of Pink Salmon were 0.48 and 0.52 g in Discovery Islands and Broughton Archipelago, respectively.

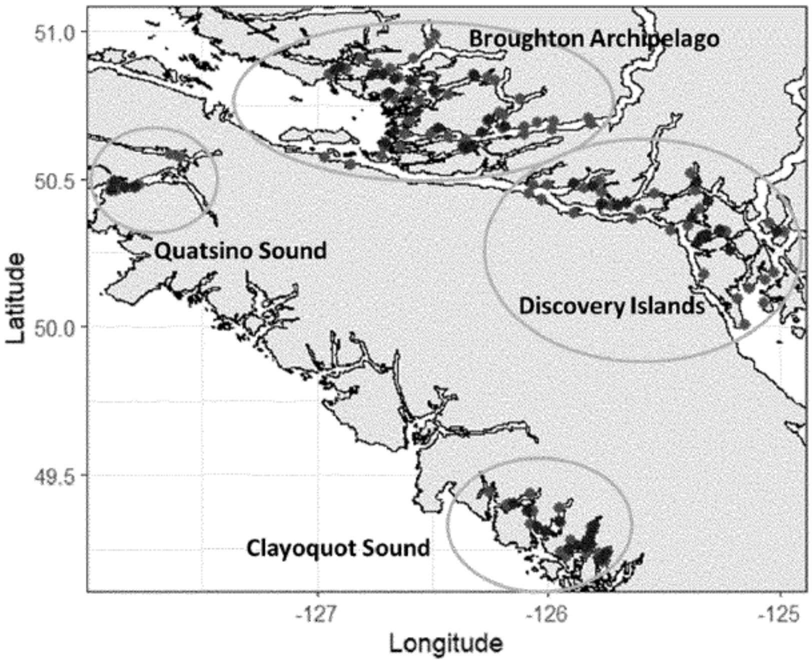


Figure 4. Juvenile wild salmon sea lice monitoring areas, farms and sampling sites. Red points: locations of salmon aquaculture sites, blue points: wild salmon sampling sites. The monitoring areas overlap with some to the Fish Health Surveillance Zones (FHSZ): Clayoquot Sound (in FHSZ 2.3), Quatsino Sound (in FHSZ 3.3), Discovery Islands (FHSZ 3.2) and Broughton Archipelago (FHSZ 3.3).

Table 5. Number of juvenile wild salmon caught and examined for sea lice in four regions of British Columbia ~~between~~ from 2016 to~~and~~ 2021.

Region	***Species***	***2016***	***2017***	***2018***	***2019***	***2020***	***2021***	***Total***
Clayoquot Sound (in FHSZ 2.3)	Chinook Salmon	0	0	0	0	0	0	*0*
	Chum Salmon	905	1,122	696	428	696	854	*4,701*
	Coho Salmon	0	84	45	1	29	32	*191*
	Pink Salmon	0	0	1	0	0	0	*1*
	Sockeye Salmon	0	38	0	0	0	0	*38*
	Total	**905**	**1,244**	**742**	**429**	**725**	**886**	***4,931***
Quatsino Sound (in FHSZ 2.4)	Chinook Salmon	19	0	6	6	5	3	*39*
	Chum Salmon	235	479	325	441	302	417	*2,199*
	Coho Salmon	1	58	37	35	79	42	*252*
	Pink Salmon	2	0	0	7	0	1	*10*
	Sockeye Salmon	0	0	31	2	0	0	*33*
	Total	**257**	**537**	**399**	**491**	**386**	**463**	***2,533***
Discovery Islands (FHSZ 3.2)	Chinook Salmon	0	26	79	9	6	0	*120*
	Chum Salmon	0	942	722	599	564	918	*3,745*
	Coho Salmon	0	88	34	21	33	0	*176*
	Pink Salmon	0	374	434	510	578	848	*2,744*
	Sockeye Salmon	0	0	1	2	0	0	*3*
	Total	**0**	**1,430**	**1,270**	**1,141**	**1,181**	**1,766**	***6,788***
Broughton Archipelago (FHSZ 3.3)	Chinook Salmon	0	2	0	1	0	0	*3*
	Chum Salmon	512	562	281	246	497	249	*2,347*
	Coho Salmon	25	19	11	24	5	0	*84*
	Pink Salmon	430	411	356	230	402	309	*2,138*
	Sockeye Salmon	0	0	0	0	0	0	*0*
	Total	**967**	**994**	**648**	**501**	**904**	**558**	***4,572***
TOTAL IN ALL REGIONS		**2,129**	**4,205**	**3,059**	**2,562**	**3,196**	**3,673**	***18,824***

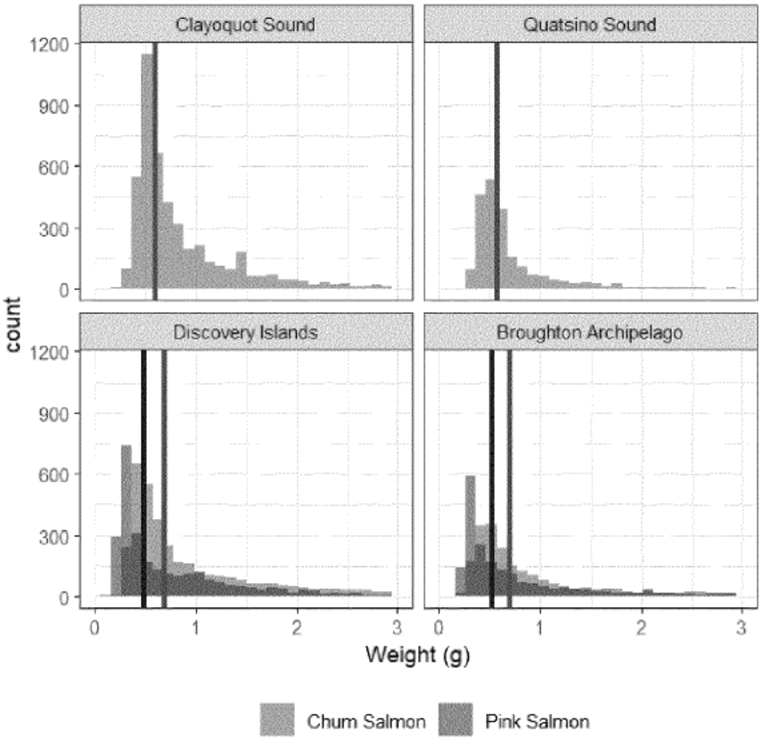


Figure 5. Weight distribution of Chum Salmon (Oncorhynchus keta) and Pink Salmon (Oncorhynchus gorbuscha) sampled between 2016 and 2021 presented by monitoring areas. Sound and Quatsino Sound include Chum Salmon only while Discovery Islands and Broughton Archipelago include Chum and Pink salmon. Right-skewed distributions are observed in all the distributions. As 95% of all sampled fish in the four regions weigh less than 3 g, histograms are truncated at 3 g. Blue and red vertical lines represent the median weights of Chum and Pink salmon, respectively. The monitoring areas partially overlap with some Fish Health Surveillance Zones (FHSZ): Clayoquot Sound (in FHSZ 2.3), Quatsino Sound (in FHSZ 3.3), Discovery Islands (FHSZ 3.2) and Broughton Archipelago (FHSZ 3.3).

Sea lice on wild juvenile Pacific salmon

Figure 6 reports on the abundance, prevalence, intensity and density of sea lice infestation on wild juvenile Pacific salmon (Chum Salmon only in Clayoquot Sound and Quatsino Sound) and Chum and Pink salmon in Discovery Islands and Broughton Archipelago). Each point represents the level of sea lice infestation (as abundance, prevalence, intensity, or density) for each sampling event. Every year, fish samples were collected from multiple sites during two to four sampling events ~~occurred~~ in each of the four regions.

Relatively higher levels of *L. salmonis* infestation prevalence were observed in Clayoquot Sound compared to the other three regions. Infestation levels on Chum Salmon in Clayoquot Sound also varied by year with highest levels reports in 2018.

Overall, 88% of *L. salmonis* observed on wild juvenile salmon were copepodids and chalimus, and 12% were pre-adults or adults (Figure 7). This suggests a short period between the time between the moment that the fish was infested with the parasites and the moment the fish were caught.

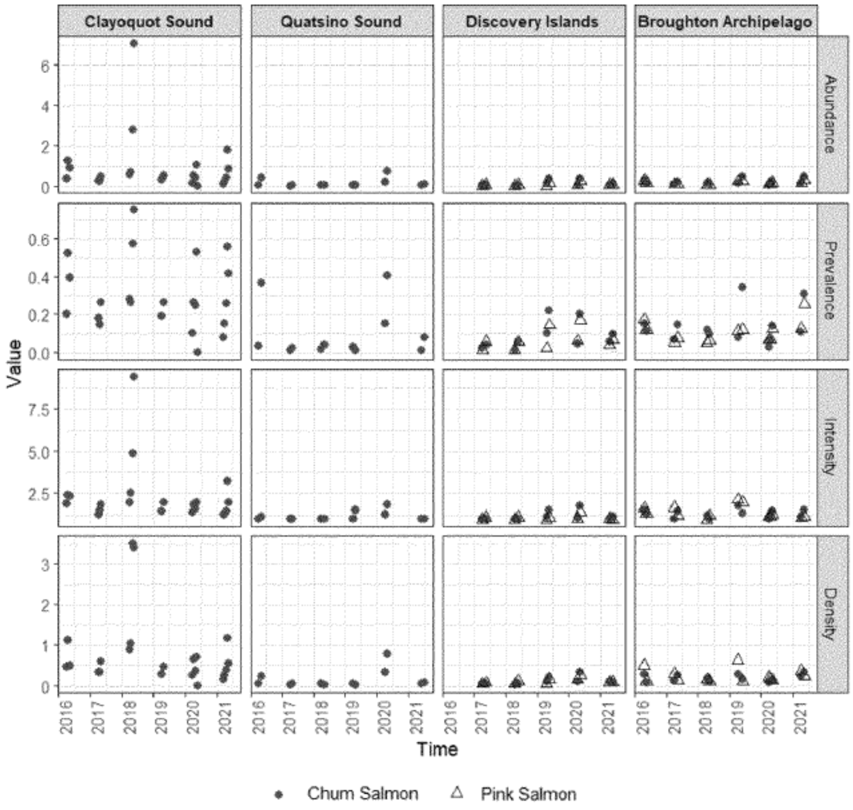


Figure 6. Abundance, prevalence, intensity, and density of Lepeophtheirus salmonis on juvenile Chum Salmon (Oncorhynchus keta) and Pink Salmon (Oncorhynchus gorbuscha) sampled between 2016 and 2021. Clayoquot Sound and Quatsino Sound include Chum Salmon only, while in Discovery Islands and Broughton Archipelago, Chum (black dots) and Pink salmon (red triangles) are shown. Abundance is the number of sea lice divided by the total number of fish; prevalence is the number of infested fish divided by the total number of fish; intensity is the number of sea lice divided by the number of infested fish; and density is the number of sea lice divided by the total weight of fish in grams. Source of data: Juvenile wild salmon sea lice monitoring reports conducted by Mainstream Biological Consulting (see Table 1 for references).

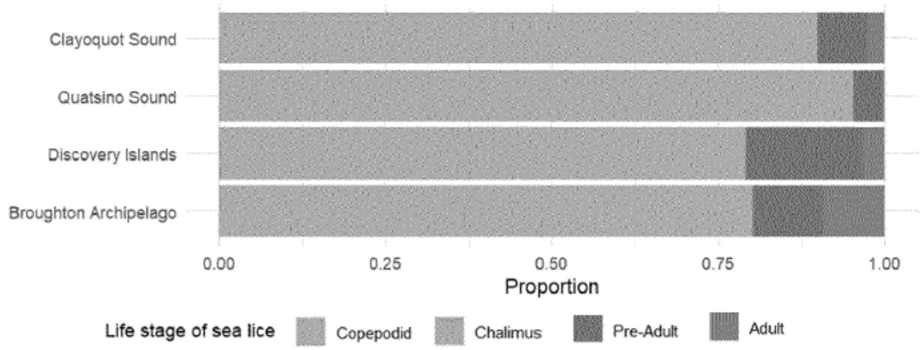


Figure 7. The proportion of Lepeophtheirus salmonis life stages observed on wild Pacific salmon captured in four regions of British Columbia between 2016 and 2021. Copepodid and chalimus are immature stages, while pre-adult and adult are relatively mature stages. ~~In~~ Clayoquot Sound and Quatsino Sound include Chum Salmon only, while ~~in~~ Discovery Islands and Broughton Archipelago include Chum and Pink salmon.

Association between sea lice infestations on Atlantic Salmon farms and prevalence on juvenile wild Pacific salmon populations

We explored the statistical association between *L. salmonis* infestations on Atlantic Salmon farms and sea lice prevalence on wild juvenile salmon in four coastal regions of BC: Clayoquot Sound, Quatsino Sound, Discovery Islands, and Broughton Archipelago (Figure 4). Refer to Appendix D for higher resolution of maps of wild juvenile salmon sampling sites and Atlantic Salmon farms in each region.

Data sources

Data from the first two sections were compiled together for the analyses in this section. Refer to Appendix E for methods of how the overall *L. salmonis* infestation pressure was estimated at each sampling site.

Assumptions

The following assumptions were made in evaluating the association between the infestation pressure of *L. salmonis* from Atlantic Salmon farms and the probability of *L. salmonis* infestation on wild juvenile salmon in BC:

- Juvenile wild salmon sampling site is the ~~point~~ location of *L. salmonis* infestation;
- Sampling events with fewer than 10 fish sampled are not representative of the population and hence were not included in the regression analysis;
- The total number of copepodids on any given week is comprised by the nauplii that became copepodid on that week and the copepodids from previous weeks that have survived up to that week and remain infective; and
- Juvenile Pink and Chum salmon are equally susceptible to *L. salmonis* infestation.

Commented [JJ2]: This is already written in page 12.

Infestation pressure from farms and prevalence on wild fish

To associate the sea lice infestation pressure from Atlantic Salmon farms and the probability of *L. salmonis* infestation on wild juvenile salmon, we estimated the number of infective copepodids resulting from the infestations on farmed salmon.

First, infestation pressure was ~~assessed~~ estimated based on the number of infective copepodids derived from infestations on Atlantic Salmon farms at a specific time and on the distance between wild salmon sampling locations and neighboring Atlantic Salmon farms within 30 km of seaway distance.

Second, prevalence of wild salmon was calculated by using the sampling data of out-migrating juvenile wild salmon (see previous section). For each wild juvenile salmon sampling event, an average of 23 fish were caught and examined. The fish captured in each sampling event (location, week of the year, and year) were considered as a unique combination of wild salmon sampling site, sampling year and sampling week. Prevalence was calculated by dividing the number of infected fish with the number of sampled fish at each sampling occasion.

After calculating the prevalence at each timing and each sampling location, infestation pressure corresponding to the timing and location of the prevalence was obtained. Therefore, each analytical unit represents a unique combination of sampling site-year-week with a value of infestation pressure and prevalence of wild salmon.

Figure 8 presents the number of unique combinations ~~for which there was~~with zero prevalence or non-zero prevalence on wild salmon. ~~Sea lice were present (non-zero prevalence) on most unique combinations in all four FHSZ.~~ The proportion of zero prevalence in all unique combinations were 0.17, 0.41, 0.45, and 0.28 for Clayoquot Sound, Quatsino Sound, Discovery Islands, and Broughton Archipelago, respectively. Overall, there is a~~n apparent~~ trend of increasing range of *L. salmonis* prevalence on wild salmon with increasing infestation pressure from the farms (Figure 9).

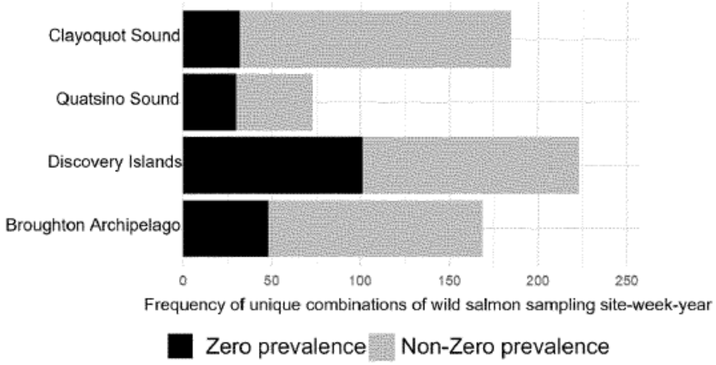
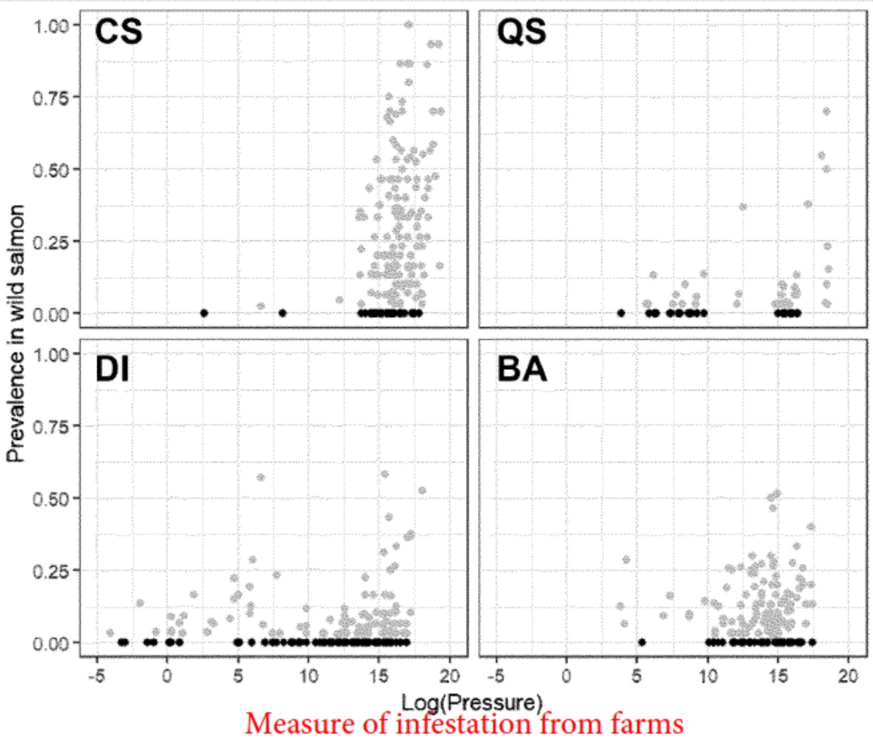


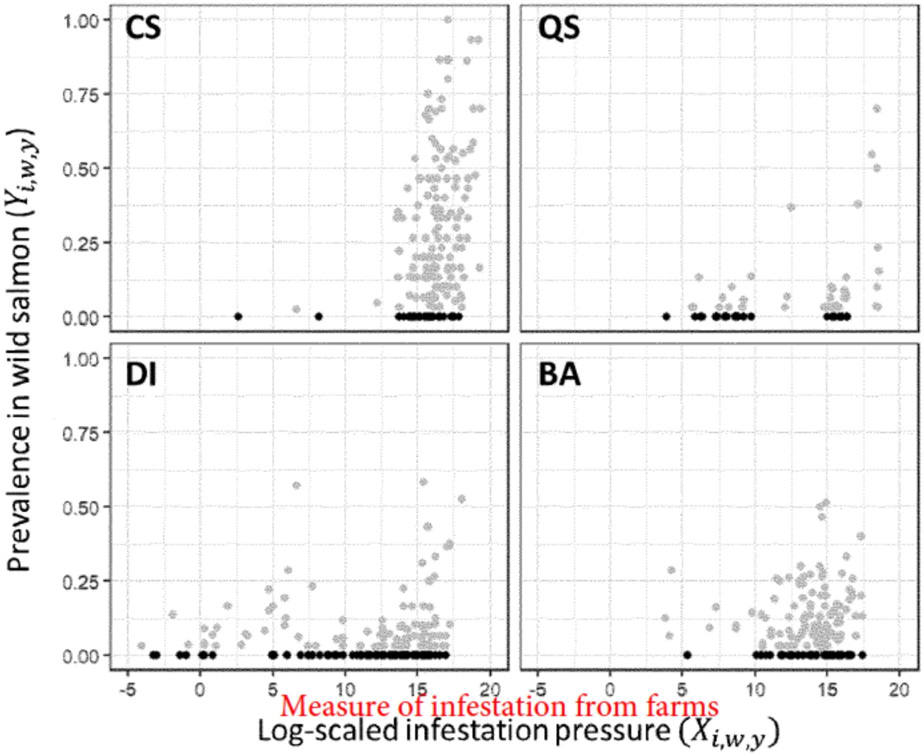
Figure 8. Frequency of zero prevalence and non-zero prevalence of Lepeophtheirus salmonis infestation on juvenile Chum Salmon (Oncorhynchus keta) and Pink Salmon (Oncorhynchus gorbuscha) for ~~each~~ unique combinations of sampling site-week-year. Clayoquot Sound and Quatsino Sound include Chum Salmon only while Discovery Islands and Broughton Archipelago include Chum and Pink salmon. ~~Dark~~ Black and gray~~light~~ areas represent zero prevalence and non-zero prevalence, respectively.

Proportion of salmon infested in a given "sampling event"



Measure of infestation from farms

These data suggest strong positive correlations, but the full dataset was never analysed (see point 7 in letter and Appendix A).



Proportion of salmon infested in a given "sampling event"

Measure of infestation from farms

Figure 9. Distribution of Lepeophtheirus salmonis log infestation pressure (Xi,w,y) estimates from Atlantic Salmon farms in British Columbia and prevalence (Yi,w,y) on juvenile Chum Salmon (Oncorhynchus keta) and Pink Salmon (Oncorhynchus gorbuscha) at unique combinations of wild salmon site-week-year sampling event in various monitoring areas between 2016 and 2021. Clayoquot Sound (n = 185) and Quatsino Sound (n = 73) include Chum Salmon only while Discovery Islands (n = 223) and Broughton Archipelago (n = 169) include Chum and Pink salmon. Dark and light points represent zero prevalence and non-zero prevalence, respectively. Log (infestation pressure) values lower than -5 in the Discovery Islands are not shown. Abbreviation: CS: Clayoquot Sound, QS: Quatsino Sound, DI: Discovery Islands, and BA: Broughton Archipelago.

Logistic regression model

The high proportion of zero prevalence values on wild salmon indicated the application of a logistic regression model to explore the relationship between the infestation pressure from the Atlantic Salmon farms (infestation pressure) and the prevalence of wild salmon. In this model prevalence is expressed as either zero (if prevalence = 0) or non-zero (if prevalence > 0) at each given sampling site-year-week.

While Chum Salmon is the dominant species caught in Clayoquot Sound and Quatsino Sound, Chum and Pink salmon represent together at least 95% of fish caught in Discovery Islands and Broughton Archipelago. The effect of fish species on the predicted probability of infestation on out-migrating wild juvenile salmon was initially included in the model and found to be not significant in both Discovery Islands and Broughton Archipelago (P = 0.83 and P = 0.94, respectively). In these regions, Chum and Pink salmon were therefore analyzed together for the remaining analyses.

With increasing values of infestation pressure, the predicted probability of infestation approaches one, which means that wild salmon collected under these conditions are more likely to contain at least one infested fish. However, given the wide confidence intervals, due the relatively few data points with high infestation pressure, this association should be interpreted with care.

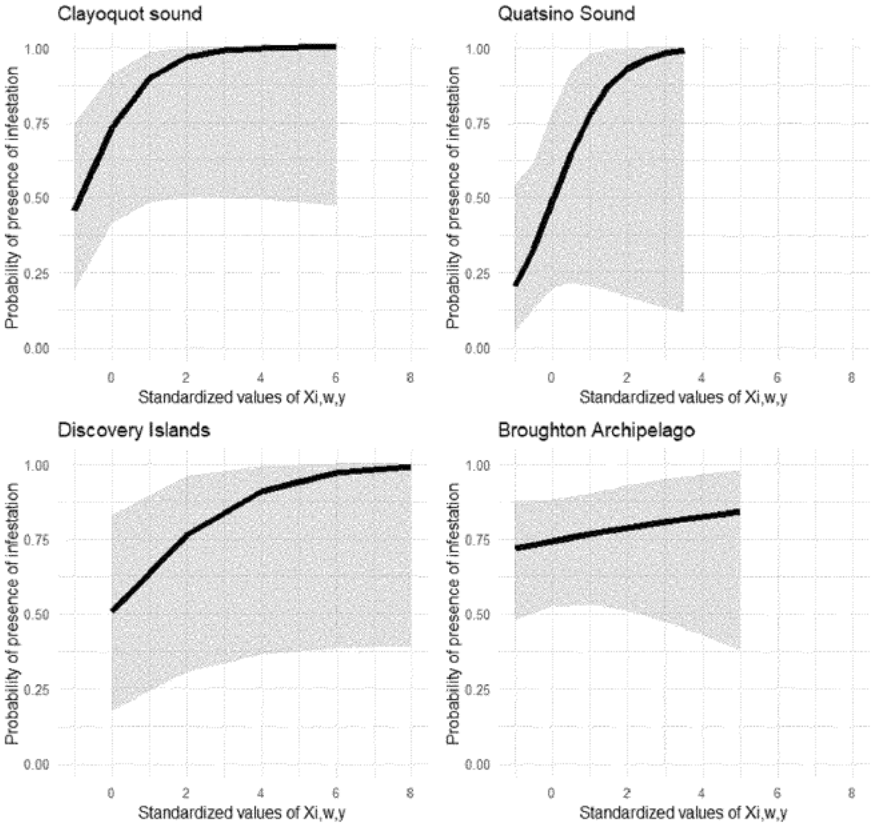


Figure 10. Margins plots based on logistic regression illustrating the relationship between the standardized Lepeophtheirus salmonis infestation pressure (the main predictor of interest, Xi,w,y) from the study farms (X-axis) on the predicted probability of presence of infestation on out-migrating wild juvenile salmon (Y-axis). The grey area represents 95% confidence interval around the prediction line (black). Clayoquot Sound and Quatsino Sound include Chum Salmon only while Discovery Islands and Broughton Archipelago include Chum and Pink salmon.

An apparent positive association was observed between infestation pressure attributable to copepodids originating from Atlantic Salmon farms and the probability of the presence of infestation in a sampling group of out-migrating juvenile salmon (Figure 10). However, the apparent association between the two variables was shown to lack statistical significance in the four regions (Table 5), which implies that the sea lice infestation on wild salmon was not ~~did not seem to be~~ substantially affected by the sea lice from salmon farms. Further work is required to verify the validity of model ~~or that~~ assumptions ~~may or may not have been correct~~.

Table 6. Results of logistic regression models evaluating the effect of Lepeophtheirus salmonis infestation pressure (Xi,w,y) from salmon farms on the log-odds of the presence of infestation with the same species of sea lice on out-migrating juvenile Chum (Oncorhynchus keta) and Pink (Oncorhynchus gorbuscha) salmon (Y). Clayoquot Sound and Quatsino Sound include Chum Salmon only while Discovery Islands and Broughton Archipelago include Chum and Pink salmon.

Region	Coefficient	95% Confidence Interval	p-value
Clayoquot Sound	1.19	-0.06 ~ 2.43	0.06
Quatsino Sound	1.30	-0.34 ~ 2.95	0.12
Discovery Islands	0.57	-0.03 ~ 1.17	0.06
Broughton Archipelago	0.12	-0.25 ~ 0.50	0.52

Discussion

Previous studies reported on the association *L. salmonis* infestation on salmon farms and on wild salmon. Analyses of sea lice count and management data from farmed and wild salmon collected over 10 years (2007–2016) in the Muchalat Inlet region of Canada indicated a significant positive association between the sea lice abundance on farms and the likelihood that wild fish would be infested (Nekouei et al., 2018). Additionally, an analysis in the Broughton Archipelago of Western Canada show that the number of pink salmon returning to spawn in the fall predicts the number of female sea lice on farm fish the next spring, which, in turn, accounts for 98% of the annual variability in the prevalence of sea lice on out-migrating wild juvenile salmon. However, productivity of wild salmon is not negatively associated with either farm lice numbers or farm fish production (Marty et al., 2010). On the other hand, quantitative ecological modelling emphasized that sea lice abundance on out-migrating wild salmon can be substantially increased as a result~~ing~~ of increased ~~from the~~ infestation pressure from farms (Krkošek et al., 2007).

Commented [SJ3]: This reference goes beyond an association and relates to impact

Conclusions

Our analyses provide quantitative estimates of weekly farm-level, farm-origin sea lice contribution to the overall load of *L. salmonis* copepodids in the marine environment in BC. The estimates vary greatly among year, seasons and FHSZ. As sea lice are naturally occurring parasites, the contribution from farms is in addition to the naturally occurring reservoir of copepodids ~~reservoir~~. However, the relative contribution of the farms to the overall load of copepodids was not part of this analysis.

The association between the estimated number farm-origin of copepodids (infective larvae) and the probability that wild juvenile salmon are infested with *L. salmonis* varied among regions. The positive coefficients of the logistic regression model analyses for all four areas suggest that farm-origin *L. salmonis* contribute to the background level of sea lice that can potentially infest juvenile salmon. However, the absence of statistical significance reflects the high variability in non-zero prevalence and uncertainty in the validity of our assumptions.

Overall, the analysis suggests that the occurrence of *L. salmonis* infestation on wild migrating juvenile Pacific salmon cannot be explained solely by infestation pressure of farm-sourced copepodids.

Contributors

All contributors are from Fisheries and Oceans Canada:

- Derek Price, Pacific Region, Aquaculture Management Division
- Jaewoon Jeong, NCR, Aquaculture Regulatory Science
- Caroline Mimeault, NCR, Aquaculture Regulatory Science
- Simon Jones, Pacific Region, Aquaculture Regulatory Science
- Stewart Johnson, Pacific Region, Aquaculture Regulatory Science
- Jay Parsons, NCR, Aquaculture Regulatory Science
- Lily Weber, NCR, Aquaculture Regulatory Science

Approved by

The Science Response can be approved by a science manager/director at a Division level of responsibility or higher, or by their delegated authority. Each region has the opportunity to identify the relevant level of approval that is necessary on a case by case basis, but the person who approved the final document must be identified along with the approval date.

Sources of Information

Bricknell, I. R., Dalesman, S. J., O'Shea, B., Pert, C. C. and Luntz, A. J. M. 2006. Effect of environmental salinity on sea lice *Lepeophtheirus salmonis* settlement success. Dis Aquat Organ 71(3): 201-212.

DFO. 2022a. Industry sea lice counts at BC marine finfish aquaculture sites. Fisheries and Oceans Canada. https://open.canada.ca/data/en/dataset/3cafbe89-c98b-4b44-88f1-594e8d28838d.

DFO. 2022b. Marine Finfish Aquaculture Licence under the Fisheries Act. Aquaculture Management Pacific Region. Fisheries and Oceans Canada. 63 p.

Groner, M. L., McEwan, G. F., Rees, E. E., Gettinby, G. and Revie, C. W. 2016. Quantifying the influence of salinity and temperature on the population dynamics of a marine ectoparasite. Can. J. Fish. Aquat. Sci. 73(8): 1281-1291.

Hamre, L., Eichner, C., Caipang, C. M., Dalvin, S., Bron, J., Nilsen, F., Boxshall, G. and Skern-Mauritzen, R. 2013. The salmon louse *Lepeophtheirus salmonis* (Copepoda: Caligidae) life cycle has only two chalimus stages. PLoS One 8: e73539.

Hamre, L. A., Bui, S., Oppedal, F., Skern-Mauritzen, R. and Dalvin, S. 2019. Development of the salmon louse *Lepeophtheirus salmonis* parasitic stages in temperatures ranging from 3 to 24°C. Aquacult. Env. Interac. 11: 429-443.

Heuch, P. A., Nordhagen, J. R. and Schram, T. A. 2000. Egg production in the salmon louse[*Lepeophtheirus salmonis* (Krùyer)] in relation to origin and water temperature. Aquacul. Res. 31: 805-814.

Johnson, S. C. and Albright, L. J. 1991. The developmental stages of *Lepeophtheirus salmonis* (Krøyer, 1837) (Copepoda: Caligidae). Can. J. Zool. 69(4): 929-950.

Appendix C – Supporting ATIP documents for external reviewer

The following pages provide an email exchange between senior DFO participants and an industry-associated professor who regularly advises BC salmon-farming companies, confirming that the latter was the sole external reviewer of the Science Reponse Report. These documents were obtained under the Access to Information and Privacy (ATIP) request #A-2022-00420. Our annotations to the original documents are in **red.**

From: Parsons, Jay
Sent: Wednesday, June 8, 2022 7:52 AM
To: [redacted]
Cc: Mimeault, Caroline
Subject: sea lice science response

Hi Crawford,

I hope you are doing well.

I am contacting you about the science advice related to sea lice that we have been working on. We are coming close to completion of the first phase of this work and I am reaching out to ask if you would be available and interested in providing a review of this work.

This work is meant to be the first part of a two part process. In this first part, we estimated the association between sea lice infestation pressure from Atlantic salmon farms and sea lice infestation on juvenile wild Pacific salmon in four regions of British Columbia. We have done so by first estimating the number of copepodids produced on Atlantic salmon farms, then summarized sea lice on juvenile wild Pacific salmon in four areas of BC and finally by exploring the association. This first part of the process is being delivered as a CSAS Special Response and is the part for which I am reaching out. The second part will be a risk assessment of sea lice from salmon farms in BC. The scope and timelines of the second part remain to be determined at this point, but will be delivered as a full peer reviewed CSAS process.

We are hoping to finalize this work in June so we are facing tight timelines. We were hoping to be able to send a copy of the paper for review next week followed by a short virtual meeting on June 24. Are you interested and have time to provide comments on this work?

Let me know if you have questions.

Thank you,

Jay

s.19(1)

From: Parsons, Jay
Sent: Monday, June 13, 2022 6:22 PM
To: Morin, David
Cc: Shaw, Kerra
Subject: sea lice CSAS science response

Hi David,

I just wanted to provide a quick update on where we are at on the sea lice CSAS Science Response. We have set up a national steering committee for the review of the Science Response and Estelle Couture in CSAS is chairng the SC and will chair the review meeting. We just received approval of the Terms of Reference today from Brenda and Alistair (AMD Pac and AMD NCR directors).

We also just finalised today the draft response that has been led by Caroline with input from Jaewoon Jeong, myself, Stewart Johnson (Pac Sci), Simon Jones (Pac Sci) and Derek Price (Pac AMD he is an epidemiologist who has been contributing significant to the modelling efforts, etc.).

The response will soon be sent out to reviewers by email and we expect comments back within a week. We will then address the comments and also hold a virtual CSAS meeting on June 24th to finalise discussions on the response.

In addition to Estelle who will chair the process and the team that put the draft response together, we will also invite Kerra, Michael Ott (AMD NCR) and Adrinne Paylor, Lauar Sitter and Alendandra Oswell from AMD Pacific to participate in the review. And we will have one external reviewer Dr. Crawford Revie from Scotland who is one of the top international sea lice experts and has and is doing similar research on the topic we will be reviewing. Confirmation of single reviewer

The Terms of Reference will soon be posted on the DFO CSAS website schedule.

And we will set up a meeting with DFO Comms to discuss a communication strategy around the response, its findings and implications and the follow-up steps, especially linkage to the next steps of the full risk assessment and associated analyses.

Thanks and let us know if any questions.

Jay

From: Parsons, Jay
Sent: Wednesday, June 22, 2022 8:14 AM
To: Couture, Estelle; Mimeault, Caroline
Subject: FW: Nation CSAS Science Response Process - Sea Lice on Farmed and Wild salmon in British Columbia

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Pvi - aucun problème majeur, ce qui est excellent ! Je vais lui répondre au sujet de sa question.
Jay

From: Crawford Revie <[redacted]
Sent: Wednesday, June 22, 2022 5:15 AM
To: Parsons, Jay [redacted]
Subject: Re: Nation CSAS Science Response Process - Sea Lice on Farmed and Wild salmon in British Columbia

Jae,

I have had a fairly in-depth read through the paper (though I have to admit that I have not yet had time to work through all the appendices!)... I found it mostly to be very clear; At present I have no major concerns and only a few minor comments/suggestions...

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Hopefully this gives you some helpful feedback? I will bring a few more minor points to the meeting on Friday... and, assuming that I can get my 'comparative' analyses completed tomorrow, I will provide some comments around those...

Regards,
Crawford

s.19(1)

On 21/06/2022 22:07, Parsons, Jay wrote:

Hi Crawford,

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Thanks, Jay

From: Couture, Estelle <Estelle.Couture@dfo-mpo.gc.ca>
Sent: Tuesday, June 14, 2022 11:14 AM
To: Mimeault, Caroline <Caroline.Mimeault@dfo-mpo.gc.ca>; Jeong, Jaewoon <Jaewoon.Jeong@dfo-mpo.gc.ca>; Jones, Simon <Simon.Jones@dfo-mpo.gc.ca>; Johnson, Stewart <Stewart.Johnson@dfo-mpo.gc.ca>; Parsons, Jay <Jay.Parsons@dfo-mpo.gc.ca>; Price, Derek <Derek.Price@dfo-mpo.gc.ca>; Shaw, Kerra <Kerra.Shaw@dfo-mpo.gc.ca>; Paylor, Adrienne <Adrienne.Paylor@dfo-mpo.gc.ca>; Ott, Michael <Michael.Ott@dfo-mpo.gc.ca>; [redacted] Sitter, Laura <Laura.Sitter@dfo-mpo.gc.ca>; Oswell, Alexandria <Alexandria.Oswell@dfo-mpo.gc.ca>; Paulic, Joclyn <Joclyn.Paulic@dfo-mpo.gc.ca>
Subject: Nation CSAS Science Response Process - Sea Lice on Farmed and Wild salmon in British Columbia

Hello everyone,

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This process will take place in two phases:

1. We ask each participant to please review and provide your comments in Track Changes and comment boxes and send them to Caroline Mimeault (cced here) and myself, Estelle Couture by **Monday COB June 20th, 2022.** This will give the author team time to consider the comments before the meeting.
2. On Friday June 24th, we will hold a virtual meeting to review the comments and discuss any outstanding issues. An invitation will follow shortly.

If you have any questions or concern, please don't hesitate to contact me.
Regards,
Estelle Couture
National Manager, Canadian Science Advisory Secretariat
Fisheries and Oceans Canada / Government of Canada

Gestionnaire nationale, Secrétariat canadien des avis scientifiques
Pêches et Océans Canada / Gouvernement du Canada

Government of Canada Gouvernement du Canada
Canada

s.19(1)

From: Parsons, Jay
Sent: Wednesday, June 22, 2022 8:17 AM
To: 'Crawford Revie'
Bcc: Mimeault, Caroline; Couture, Estelle
Subject: RE: Nation CSAS Science Response Process - Sea Lice on Farmed and Wild salmon in British Columbia

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Hi Crawford,

Thank you so much. That is great to know that you don't have any major comments. And yes we can discuss figure 8. And yes the AQUIIS database is an internal DFO Aquaculture Management database that the use to capture the data they collect, including sea lice, drugs and pesticides use, etc. Derek was able to access this data for the analyses we did in the first part and then of course for the association analysis.

Look forward to talking soon.

Thank you, Jay

From: Crawford Revie <[redacted]
Sent: Wednesday, June 22, 2022 5:15 AM
To: Parsons, Jay <Jay.Parsons@dfo-mpo.gc.ca>
Subject: Re: Nation CSAS Science Response Process - Sea Lice on Farmed and Wild salmon in British Columbia

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> **Estelle Couture**

s.19(1)

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Modelling parasite impacts of aquaculture on wild fish: The case of the salmon louse (*Lepeophtheirus salmonis*) on out-migrating wild Atlantic salmon (*Salmo salar*) smolt

Meadhbh Moriarty[*], Stephen C. Ives, Joanne M. Murphy, Alexander G. Murray

Marine Scotland Science, Marine Laboratory, 375 Victoria Road, Aberdeen AB11 9DB, Scotland

ARTICLE INFO

Keywords:
Parasite induced mortality
Thresholds
First principles modelling
Spatial management
Conceptual framework

ABSTRACT

For effective wild salmon (*Salmo salar*) conservation in areas where aquaculture of salmon is practiced it is necessary to identify where the key parasite, the salmon louse (*Lepeophtheirus salmonis*), will have an impact on these wild salmon. A simple modelling structure is implemented in a sample system in Scotland for assessing interaction between wild salmon and salmon lice from salmon farms. The model is demonstrated for case studies of smolt sizes and migration routes through salmon lice concentration fields derived for average farm loads from 2018 to 2020. Lice modelling describes production and distribution of lice, infection rates on hosts and biological development of lice. The modelling framework allows explicit assessment of the relationships between lice production, lice concentration and impact on hosts as they grow and migrate. Lice distribution in the environment is determined using a kernel model, which summarises mixing in a complex hydrodynamic system. Smolt modelling describes their initial size, growth and migration pathways. This is illustrated for a set of parameter values applied to 10 cm, 12.5 cm and 15 cm salmon smolts. We found that salmon lice impact depends on initial size of host, smaller smolts will be more susceptible, while larger smolts are less impacted by a given number of lice encounters and migrate more rapidly. This modelling framework can be adapted to allow evaluation of threshold concentrations of lice in the water that should not be exceeded to avoid impacts on smolt populations.

1. Introduction

Scottish salmon (*Salmo salar*) farming, which in 2021 produced 205,393 tonnes worth ~£ 1BN at first sale (Munro, 2022), is a major contributor to year-round employment in relatively remote areas of Scotland and to UK food exports (Blázquez, 2021). However, the industry's sustainability is threatened by the salmon louse (*Lepeophtheirus salmonis*), an ectoparasitic copepod. Salmon lice are one of multiple pressures impacting wild salmon populations. These pressures may include climate change impacts on both freshwater and marine environments, predators, genetic introgression from escaped or stocked fish and bycatch in fisheries (Dadswell et al., 2021; Forseth et al., 2017; Gilbey et al., 2020; Hawkins, 2021). However, salmon populations already in poor conservation status, as is the case in many Scottish rivers (Marine Scotland, 2021), are the most sensitive to additional impacts due to salmon lice (Vollset et al., 2016). These salmon lice impacts cause both high management costs of £ 0.34 kg^{-1} to farmed production (Abolofia et al., 2017) and effects on wild salmon populations (Vollset et al., 2016).

Sea lice are a naturally occurring parasite often found on wild salmonids. However, due to the rapid expansion of salmon aquaculture, the majority of salmon lice are produced on farms, with relatively few lice produced from wild salmonids, owing to their much smaller populations (Butler, 2002). In Norway, farmed salmonids outnumbered comparative wild populations by up to 281:1 between 2013 and 2017 with 99.1% of adult female lice produced from farmed populations (Dempster et al., 2021). Other species of sea lice from the genus *Caligus* can also infest a range of fish species, including salmon (Hemmingsen et al., 2020). While some species, notably *C. rodgecressyi* in Chile, are a major problem for salmon, in the North Atlantic region *C. elongatus* is a parasite of much less concern than *L. salmonis*. *L. salmonis* also parasitises other salmonid species, including sea trout (*S. trutta*) present in Scottish coastal waters.

Salmon lice develop through multiple stages (Hamre et al., 2013) hatching as non-feeding planktonic nauplii which mature to infectious copepodids. Their planktonic larval stages allow them to be transported from their source farm, over distances of tens of kilometres, dependent

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on local hydrodynamics (Salama et al., 2018; Rabe et al., 2020). This large-scale dispersal increases the potential for transmission between farm and wild populations with multiple studies showing increased prevalence of lice on wild salmonids in areas including salmon farms (Butler, 2002, Marshall, 2003, Middlemas et al., 2013). If they successfully infect a host the copepodids mature through attached chalimus stages, before becoming mobile pre-adults and then adults that graze on their hosts mucus, skin and blood. Should numbers of mobile lice on a fish exceed sustainable levels they can impact the individual hosts welfare or cause mortality (Grimnes and Jakobsen, 1996; Finstad et al., 2000; Wagner et al., 2008; Fjelldal et al., 2020; Ives et al., 2023).

A range of tools and methodologies can improve our knowledge of both salmon lice and salmon smolt behaviour. Numerical modelling tools can be used to predict the spread of infectious salmon lice larvae from a point source (e.g. Gillibrand and Willis, 2007, Salama et al., 2018, Murray et al., 2022a), using the information gleaned from field observations (e.g. Penston et al., 2004, Pert et al., 2014, Brooker et al., 2018) and laboratory-based experimental work (Johnson and Albright, 1991; Brooker et al., 2018). Additionally, laboratory experiments and field data have provided information on salmon smolt physiological behaviours such as changes in growth in response to salmon lice infection (Grimnes and Jakobsen, 1996) and differences in return rates between wild and hatchery reared salmon (Jonsson et al., 2003). Modelling tools are also used to interpret the possible migratory movements of smolts (e.g. Ounsley et al., 2020, Mcilvenny et al., 2021). Combining inference from salmon louse models and smolt models can allow predictions of the likely risk of pathogen-host interaction and allow us to estimate likely lice loads on the migrating smolts at various spatial and temporal resolutions.

Murray and Moriarty (2021) demonstrate the fine-scale processes involved in salmon louse infestation of salmonids. Using existing assessments of infectious copepodid production, namely the production of larvae from potential ovigerous female lice on salmon farms, a model of copepodid concentration was developed based on a simple kernel of their distribution around farms. The copepodids were assumed either to disperse evenly, or to be transported in a concentrated plume, allowing comparison of the range of different concentration distributions. These distributions were combined with a model of infestation based on small-scale movements of copepodids in the immediate vicinity of a swimming fish. The rates of infestation of wild fish can then be used to estimate the impact on fish survival. Here, following on from previous work, we model dispersion away from farm source, with a kernel decay function applied following Salama et al. (2016). This allows us to model a simple description of copepodid concentrations in the environment (a “licescape”) of Scottish waters.

The objective of this study is to further develop the model presented in Murray and Moriarty (2021), to assess how the growth of a smolt as it migrates increases the concentration threshold of lice in the environment that may lead to its mortality. To achieve this goal we apply simple deterministic models for an example scenario in an idealised system, for three different sized fish migrating through the Scottish west coast towards their oceanic feeding grounds. We assess the utility of these combined models to help provide inference to better manage risks associated with salmon lice interaction with wild fish, and discuss the next steps required to develop this model further for use in sea lice management.

2. Methods

2.1. Conceptual model

To effectively manage the risk of interaction between salmon lice and wild salmon smolts, we must integrate the results of two model structures. The first model describes salmon lice distribution and abundance in an idealised system for Scotland’s inshore and coastal waters (Fig. 1, light grey boxes). This model accounts for key biological processes known to impact the distribution and abundance of salmon lice. The second model describes general smolt migration trajectories and size, from first contact with sea water until they have successfully migrated out of Scottish coastal waters (Fig. 1, dark grey circles). The assessment of impact is based on the number of mobile lice per gram of host at its final weight.

This conceptual model (Fig. 1) builds on Murray and Moriarty (2021), it is demonstrated in an idealised system in order to explore the interaction between the salmon louse parasite and potential host salmon smolts as they grow and migrate through Scottish waters. To demonstrate impact we apply the threshold intensities associated with 20% (0.1–0.2 lice g^{-1}), 50% (0.2–0.3 lice g^{-1}) and 100% (>0.3 lice g^{-1}) mortality assessed by Taranger et al. (2015). Model variance and uncertainty is not explored here, we point towards key data needs and model development requirements that need to be filled prior to application of our conceptual model for management purposes.

2.2. Study area

Our study area encompasses Scottish coastal waters, as shown in Fig. 2. All seawater salmon aquaculture farms within the model domain are assumed to have the potential to produce salmon lice. One catchment area, in Loch Linnhe, was identified to demonstrate the application of these models to inform on risk to wild salmon smolts (Fig. 2). Loch Linnhe, one of Scotland’s largest sea lochs, is located on the west coast, spanning about 60 km from Fort William in the North to the Sound of Mull and Firth of Lorne in the South. The unique characteristics of the Loch Linnhe system has led it to be the study area for many research

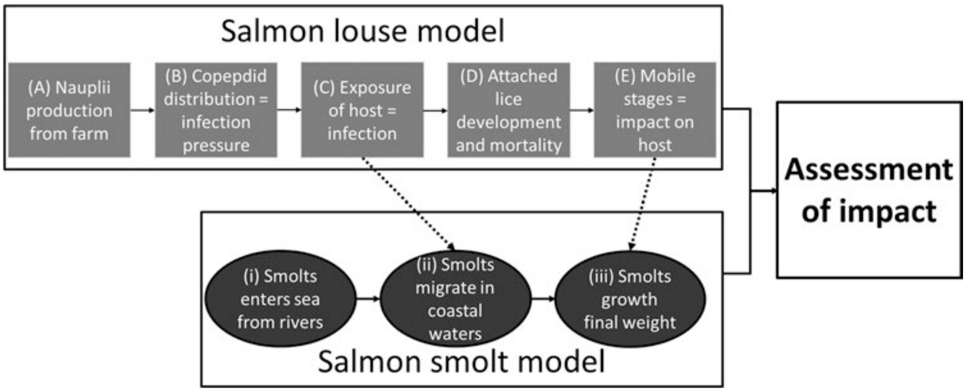

Fig. 1. High level conceptual diagram showing structure of interacting salmon lice (light grey) and salmon smolts (dark grey) models used to calculate risk maps for an assessment of impact of salmon louse on wild smolts in the environment. Solid lines indicate where one equation informs the next stage of modelling while dashed lines indicate where models interact.

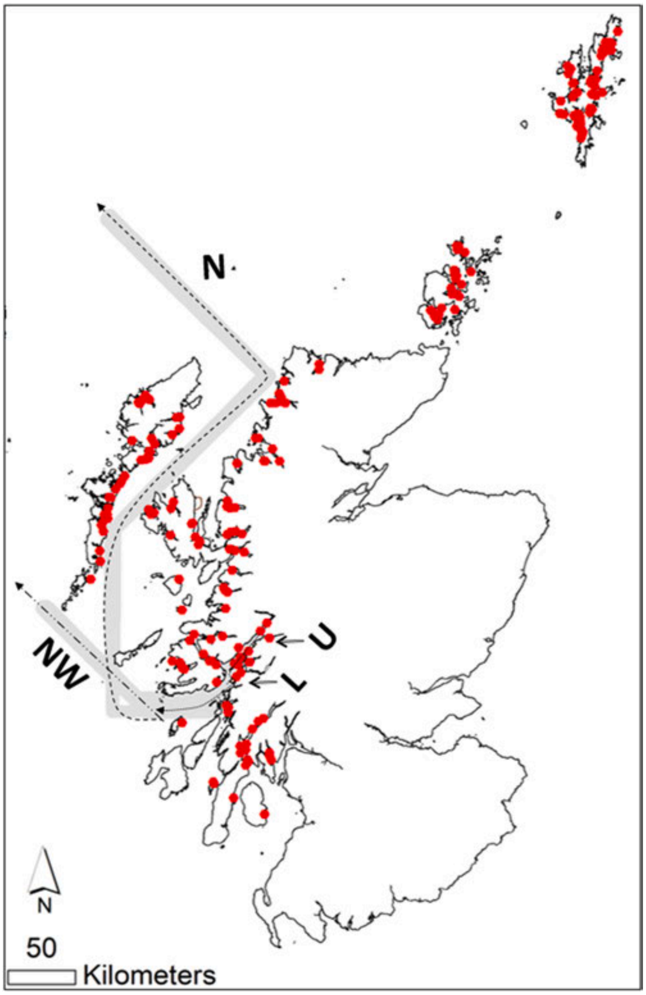

Fig. 2. Map depicting salmon aquaculture farm locations(red circles) used to simulate lice concentrations.). Illustration of smolts general migration routes in black with variance in simulations shown in grey (n = 10,000) from upper (U) and lower (L) Loch Linnhe (Inshore Zone), and then through coastal waters to the shelf edge (North West (NW) or North (N)) which are used to calculate examples of exposure to lice infection.

projects, investigating environmental conditions (Rabe and Hindson, 2017 and references therein) as well as the impact of aquaculture (for example Salama et al., 2018).

Loch Linnhe is one of the longer loch systems in Scotland, thus allowed us to investigate inference for longer migrations past multiple salmon farms, compared to a shorter migration in the lower loch passing fewer salmon farms. Two starting positions are used to simulate smolt movement from this area, one in the upper loch and the second in the lower loch (Fig. 2). The second release location simulates the smolts transition from the behaviours used to traverse the inshore environment to the directional behaviours required to successfully migrate through coastal areas to their oceanic feeding grounds. Splitting into inshore and coastal sections also allows integration of the models to assess exposure and subsequent infection from inshore and coastal areas.

2.3. Salmon Lice Model

We apply a simple deterministic approach to describing salmon lice behaviour and distribution, modelling the process in five steps, following on from Murray and Moriarty (2021), and extending this to include post-infection survival of lice on the host and their impact on this host. The model (Fig. 1) consists of: (A) production of viable nauplii from farms, (B) copepodid distribution in the environment, (C) infestation of fish by copepodids, (D) maturation and mortality of attached chalimus stages on the host, and (E) mobile lice populations relative to thresholds for impact on fish health. While much existing modelling focuses on A and B, here we focus on developing steps C through E to holistically assess how concentrations of copepodids in the environment may relate to impact on salmon smolt mortality. Modelling was carried out using R version 4.1.2 (R Core Team, 2021). All parameter values used in equations are listed in Table 1 below.

(A) Production of viable nauplii: Salmon lice are produced from fish farms located along the Scottish west coast and western and northern isles (Munro, 2022), the most abundant parasite is *L. salmonis,* so we have restricted the modelling of the biology to *L. salmonis*. Production of nauplii from a salmon farm (N) is a function of the number of fish on the farm (F), numbers of adult ovigerous female lice per fish (n_f), and viable egg production rate for ovigerous females (R),

$$N \quad F \times n_f \times p_o \times R \tag{1}$$

Numbers of adult female lice per fish (n_f) are reported weekly by each farm (aquaculture.scotland.gov.uk), here p_o, the proportion of adult female lice to be ovigerous, is estimated as 58%. This is based on the rate egg strings are produced per adult female: Heuch et al. (2000) found that at 7.1˚C females survived for up to 191 days, producing up to 11 pairs of egg strings which, assuming an even spread over time, equals an egg string pair every ~17 days. Assuming egg strings release over 10 days, as we do in calculating egg production rate, we can say gravid females are present in the population during 10 of 17 days, or approximately 58% of the time. Numbers of fish (F) are not reported, but an estimate from farm maximum consented biomass can be made using the equation:

$$F \quad sW_t/W_h, \tag{2}$$

where s is a multiplier used to account for overstocking for fish that are harvested early or die during production, W_t is consented biomass in kg and $W_h$is the average weight of fish in (kg) through the production cycle. Here we assume $s \quad 1.5$ and $W_h \quad 3$ kg on all farms. We recognise that with production moving increasingly towards harvesting earlier in the production cycle some farms will perhaps have $s \quad 1.7$ or 2, but may use a higher harvesting values of perhaps $W_h \quad 4 – 5$ kg. Thus, there may be higher or lower numbers of farmed fish in a system. Farm fish numbers would provide better inference when applying any model for management of sea lice, Eq. 2 is designed to estimate reasonable higher values to screen for areas at risk of high lice numbers.

Following existing model practice, we assume ovigerous females produce two egg strings each containing 150 eggs, which are replaced approximately every ten days (e.g. Skarðhamar et al., 2018, Murray and Moriarty, 2021). This gives the egg production generated per ovigerous female louse of 30 eggs d^{-1}. Hatching success is assumed to be 87% in saline waters at 10˚C (Samsing et al., 2016) giving viable egg production, (R) of 26.1 eggs d^{-1}.

We consider the average lice over the 2018–2020 time period on each farm. The number of lice per fish varies by farm and date (Murray et al., 2021). The average for the 2018–2020 time period is 0.63 ± 0.56 adult female lice (mean ± standard deviation). We assume that all farms within the simulation are operating at full capacity. The location of farms are used as a source point to describe lice distribution and decay from source and all active farms in the 2018–2020 period are included in this analysis (http://aquaculture.scotland.gov.uk/). Farms fallowed within this time are not included as there is no recent information for lice loads. This average adult female lice value scenario is used to investigate the likely implications for wild fish travelling through the inshore and coastal zones in Scottish waters given typical values of lice loads on farms.

(B) Copepodid distribution in the environment: Building on the inference from Murray and Moriarty (2021), using the average

Table 1
Parameters, variables and values described in equations, NA used to indicate calculated values, i.e. no typical value. * depicts initial values used in equations. Three different parameter values are described; "modelled" indicates values that are calculated in equations in this paper; "derived" indicates values which are calculated elsewhere and applied here, "empirical" indicates values taken directly from experimental data.

Symbol	Units	Typical value	Parameter	Description
F	Fish count	Farm dependant	Modelled	Numbers of salmon on farm described in Eq.1
N	Lice count	Farm dependant	Derived	Number of nauplii produced from a salmon farm described in Eq.1
n_f	Lice count	Farm dependant	Empirical	Numbers of adult female lice per fish (http://aquaculture.scotland.gov.uk)
p_o	rate	58%	Modelled	Proportion of ovigerous adult female lice (Heuch et al., 2000)
R	eggs d^{-1}	26.1	Derived	Viable egg production rate for ovigerous females (Skarðhamar et al., 2018; Murray and Moriarty, 2021; Samsing et al., 2016)
s	Porportion	1.5	Modelled	Multiplier for overstocking for fish harvested early or die during production
W_t	kg	Farm dependant	Empirical	Consented biomass in kg (http://aquaculture.scotland.gov.uk)
W_h	kg	3	Empirical	Average weight of fish at harvest
N_x	Lice count	Farm dependant	Modelled	Number of copepodids reaching x km from source farm
x	km	0–35 km	Modelled	Distance from source farm
T	Lice count	Farm dependant	Modelled	Total number of infectious copepodids in kernel around a farm
x_{max}	km	35	Derived	Fitted maximum distance in decay curve (Salama et al., 2016)
α	NA	4.5	Modelled	Fitted exponential value in kernel decay function (Salama et al., 2016)
δx	km	NA	Modelled	Distance as it tends towards zero
U_w	cm^3 s^{-1}	Eq. 6	Modelled	Volume of water per second from which copepodids contact a moving fish
B	Body lengths s^{-1}	1	Empirical	Fish speed (Middlemas et al., 2017)
l_f	cm	10–15*	Empirical	Fish length
r_f	cm	0.71*	Modelled	Fish radius (Appendix 1)
v_f	cm^3	20*	Modelled	Fish volume (Appendix 1)
X	cm	1.795	Derived	Time from stimulation over which copepodids move towards a host (Appendix 1)
L_s	cm s^{-1}	1.795	Derived	Copepodid velocity (Appendix 1)
τ_{max}	s	1	Modelled	Time from stimulation over which copepodids move towards a host
K	Lice s^{-1}	Eq. 8	Modelled	Rate at which copepodids contact the host (Murray and Moriarty, 2021)
a	rate	0.5	Modelled	Probability of attachment on contact
Z	m	2	Empirical	Depth lice mix over (Murray and Moriarty, 2021)
C_x	Lice m^2	Eq. 5	Modelled	Concentration of copepodid at distance x
C_t	Lice-days m^2	NA	Modelled	Threshold concentration causing unacceptable load per fish
M	Lice s^{-1}	Eq. 9	Derived	Infection mobile lice gK (Tucker et al., 2002)
$T1$	Lice g^{-1}	0.1	Empirical	20% mortality threshold (Taranger et al., 2015)
$T2$	Lice g^{-1}	0.2	Empirical	50% mortality threshold (Taranger et al., 2015)
$T3$	Lice g^{-1}	0.3	Empirical	100% mortality threshold (Taranger et al., 2015)
D	days	16	Empirical	Time in days
g	proportion	0.653	Empirical	Surviving lice infection to mobile
w_f	g	20*	Derived	Fish weight (Morris et al., 2019)
y	d^{-1}	0.0059	Modelled	Exponent for smolt growth
Z	m	2	Modelled	Depth over which most copepodids are present
l_{fish}	northings / eastings	Variable	Modelled	Location of a given fish in simulation
t_n	NA	1	Modelled	Given time step in simulation
$\sigma\varepsilon$	NA	NA	Modelled	Random movement term
θ	NA	Variable	Modelled	Vector for the direction of travel

properties from hydrodynamic models in Scotland has been used to derive a kernel of probability of lice copepodids with distance from a source farm using the decay curve of:

$$N_x \quad N_0(1 \quad x/x_{\max})^{\alpha} \tag{3}$$

Where α 4.5, x denotes distance from source, and $x_{\max}$ 35 km (Salama et al., 2016). N_x represents the total number of copepodids distributed on the curve, calculated on a farm-by-farm basis, based on the number of fish on the farms assuming maximum consented biomass, for the average lice scenario described in part (A). This is achieved by normalising the curve with N_0 1, so that the integral of N_x T, i.e:

$$T \quad \int_{x \quad 0}^{x \quad x_{\max}} N_x \tag{4}$$

These dispersion models generate local concentrations of risk of infectious copepodids C at given distances x i.e:

$$C_x \quad (N_x \quad N_{x \quad \delta x}) / ((\pi x^2 \quad \pi(x \quad \delta x)^2)), \tag{5}$$

where δx tends towards zero. Concentration is expressed in units of lice m^{-2} which helps to standardise distributions. To calculate the encounter rate, C_x is divided by the depth, Z, over which lice are distributed. However, exposure of smolts to lice is a function of average copepodid concentration C and time smolts are in contact with this concentration. Resultant C_t has units of lice-days m^{-2}.

During this dispersal process the larval lice die, we have assumed 1% h^{-1} (Salama et al., 2018), at 10 °C. This corresponds to 38% of nauplii surviving to become copepodids, these survive on average 4.2 days (Murray and Moriarty, 2021). This equates to 41.66 copepodids for each ovigerous female louse distributed in the environment at a given time. For illustrative purposes, a farm with 200,000 fish, with one ovigerous louse per fish, approximates to 10 million (9.576×10^6) copepodids being present in the environment at any one time. This method for describing copepodid distribution in the environment is idealised, further model development and testing is required.

(C) Exposure of host to copepodids: Infection rate is dependent on contact between copepodid and host (Murray and Moriarty, 2021). This is a function of the spatial and temporal distribution of both species, as well as swim speed of both the louse and the host.

Smolt migration speeds range from 0.4 to 3 body lengths s^{-1} (Thorstad et al., 2012), with a median speed of 1 body length s^{-1} in the Loch Linnhe (Middlemas et al., 2017), the Scottish west coast system. The volume of water per second from which lice have the potential to contact a host is calculated as:

$$U_w \quad B\left(\left(\pi\left(X+r_f\right)^2 \times l_f\right) \quad v_f\right) \tag{6}$$

where;

$$X \quad \min\left[\frac{L_s}{B}, L_s\tau_{\max}\right] \tag{7}$$

Where U_w is dependent on the length $l_f$and radius r_f of the fish subtracting its volume v_f and multiplying by its speed B in body lengths s^{-1} (Eq. 6). X, which is the distance over which lice approach smolts, is a function of lice swimming speed L_s and stamina to maintain for a given time $\tau_{\max}$ interacting with smolt migration swimming speed$B$ (Eq. 7).

The next step is to calculate infectious contact for a given exposure:

$$K \quad U_w\left(\frac{aC}{Z}\right) \tag{8}$$

Where infectious contact s^{-1}, K, is a function of average copepodid concentration C divided by the depth Z lice mix over and a probability, a, contact results in attachments. A 50% attachment probability on contact ($a \quad 0.5$) is applied following Murray and Moriarty (2021).

Salmon lice copepodids achieve short-term burst speeds, L_s, of 1–5 cm s^{-1} over $\tau_{\max}$of 1–3 s (Heuch and Karlsen, 1997). Similar to smolt swimming, a range of plausible lice swim speeds can be considered to quantify risk of attachment, which leads to uncertainty in estimation of contact. Therefore, estimations of both L_s and X are needed to apply the model. We first calculate a value of X by fitting the equations above to observed infection rates as described in Appendix 1 and summarised below.

High infection was reported by Sandvik et al. (2020) as 10 lice fish^{-1} for sentinel cage fish weighing 50–60 g, which corresponds to a length of approximately 17.5 cm for farmed fish (Appendix 1, Pert et al., 2014); this differs from 19.93 cm from Eq. 10, as used in Murray et al. (2022b) where a single shape formula was assumed for wild and farmed fish. Given a probability of contact, a 0.5, and considering mortality of chalimus of 34.7% (Section D), then 10 mobile lice correspond to $K \quad 30.6$ infectious contacts (Eq. 8). This observed infection occurred where model simulation concentrations were $C_X \quad 1.8$ lice days m^{-2} (Sandvik et al., 2020). Given $B \quad 1\ s^{-1}$ and $Z \quad 2$ m (Murray and Moriarty, 2021) we fit $X \quad L_s \quad 1.795$ cm s^{-1} copepodid swimming speed. Thus, we assume that lice are likely to swim towards smolt at 1.795 cm s^{-1} for a sustained time of 1 s before the smolt will have moved out of reach of the parasite.

(D) Attached lice development and mortality: If a louse finds a host it matures through two chalimus stages to become a pre-adult mobile louse. Maturity rates are temperature dependent, at 10 °C it approximates to 16 days (Stien et al., 2005). A proportion of lice die during the maturation phase (Stien et al., 2005), where compounded mean loss for attached copepodid and chalimus stages approximates to 34.7% (Tucker et al., 2002), this is based on data collected in laboratory conditions, and is likely to be different in nature. The mobile lice infection rate

$$M \quad gK \tag{9}$$

where, inversely the proportion surviving lice, g 0.653 and infectious contact s^{-1}, K is described in Eq. 8.

(E) Mobile stages impact on hosts: Exposure to infection of salmon lice depends on the dispersal processes of lice and on the movements of smolts in inshore and coastal waters. Vulnerability thresholds of fish to infection, in terms of numbers of lice, depends on the weight of the fish affected (e.g. 40 lice for a 30 g fish (Grimnes and Jakobsen, 1996)) leading to these thresholds usually being given as lice g^{-1} (Taranger et al., 2015). Threshold intensities for mortality assessed by Taranger et al. (2015) are T1 0.1 lice g^{-1} which is associated with 20% mortality, T2 0.2 lice g^{-1} related to 50% mortality, and T3 0.3 lice g^{-1} which is linked to 100% mortality (Table 2).

The equations described above are used to calculate concentrations of salmon lice in the environment which can then be used to infer contact events should smolt migration paths overlap. The probability of infection, $a \quad 0.5$, is used to infer the related infection events for an individual smolt. The number of infection events is multiplied by the proportion of surviving lice, $g \quad 0.653$, to calculate the lice infection on a given smolt. Once the number of lice on the fish is established, we must consider the size the smolt will reach by the time the lice mature to estimate the likely impact (see Salmon Smolt Model, section iii for details).

2.4. *Salmon Smolt Model*

The salmon model is described in three steps (Fig. 1), smolts enter the sea from their natal rivers at a certain initial weight (i), they migrate through inshore and coastal waters, during which they are exposed to lice (ii) and they grow, reaching a final weight at the end of the migration phase considered here (iii) which determines the lice g^{-1} and hence risk of impacts from exposure to lice in the environment.

Up until this point we have applied a deterministic modelling structure, however given the uncertainty in migration routes, stochasticity is required to describe smolt movement in a given direction. This is important as the migration route drawn will influence the lice loadings, to begin to explore this aspect, within the simulations, we include some random movement within the migration route and vary the release point location. The length of Atlantic Salmon smolts emigrating from Scottish rivers varies among rivers and years with a typical lower range of 10–15 cm. For each simulation, based on a starting length of 10 cm, 12.5 cm and 15 cm, directed swimming behaviours and a set swim speed of 1 B s^{-1}, 5000 simulated post-smolts were initialized at each strategic origin point in upper and lower Loch Linnhe, giving 10,000 simulated runs in total. This small number of simulations provided a sample of outcomes which indicate some of the potential distances, and areas, Scottish salmon post-smolts may travel through to reach their feeding grounds, and therefore an illustration of salmon lice infection risks.

(i) Smolts enter sea from rivers:

Salmon smolts go to sea in April to May (Malcolm et al., 2015), when water temperatures typically are around 10 °C, so this temperature is used for default biological parameterisation.

The release locations simulate smolt origin points in the inshore environment, in this case Loch Linnhe, which has a south westerly facing aspect. The 5000 simulated post-smolts were initiated in the upper loch at a mean longitudinal value of 56.6954° ± 0.001° (standard deviation) and a mean latitudinal value of 5.270129° ± 0.01° (standard deviation). The 5000 simulated post-smolts were initiated in the lower loch at a mean longitudinal value of 56.46568° ± 0.001 ° (standard deviation)

Table 2
Summary of threshold numbers (from Taranger et al., 2015) of mobile lice on hosts and environmental copepodid concentrations that induce population impacts on smolts for 10 cm, 12.5 cm and 15 cm fish for a migration swim speed B= 1, for one day.

Impact level	T1 20%	T2 50%	T3 100%
Mobile lice on fish	0.1 lice g^{-1}	0.2 lice g^{-1}	0.3 lice g^{-1}
Copepodids in water 10 cm fish	0.56 lice days m^{-2}	1.12 lice days m^{-2}	1.68 lice days m^{-2}
Copepodids in water 12.5 cm fish	0.8 lice days m^{-2}	1.6 lice days m^{-2}	2.4 lice days m^{-2}
Copepodids in water 15 cm fish	0.94 lice days m^{-2}	1.89 lice days m^{-2}	2.83 lice days m^{-2}

and a mean latitudinal value of 5.4783° ± 0.01° (standard deviation). When smolts leave the river mouth and begin their journey past salmon aquaculture farms, they must head in a south westerly direction in Loch Linnhe (Fig. 2).

(ii) Smolts migrate through coastal waters: Smolts average migration swim speeds through inshore and coastal waters have been measured at $B = 0.4 – 3$ body length s^{-1} (Thorstad et al., 2012). Here we use a median value $B = 1$ body length s^{-1} for smolts in the west coast of Scotland (Middlemas et al., 2017) as an example for default biological parameterisation. The route smolts take depends on considerations like swimming behaviour and the local coastline (Ounsley et al., 2020), which in the Scottish case involves fjordic sea lochs, islands and sounds which will all affect route and exposure to salmon lice in different ways. In the simulations here the smolts change their initial south westerly bearing and head either directly to the ocean or migrate via the Minch sea prior to reaching the oceanic waters (Fig. 2).

We have applied directed-swimming behaviours to our simulations suggested by Kristoffersen et al. (2018), where the bearings are chosen based on the *a priori* assumption that they would allow Scottish post-smolts to successfully leave Scottish waters and efficiently head towards their oceanic feeding grounds. This was achieved by allowing random movements while specifying an optimum directional term to ensure fish move in the preferred direction at a given rate.

$$l_{fish}(t_{n+1}) = l_{fish}(t_n) + \sigma\varepsilon + \theta \tag{10}$$

Where the term l_{fish} represents the locational data for a given fish, at a given time(t_n). $\sigma\varepsilon$ represents the random movement term, where fish where allowed to vary their location by up to 100 m. While θ provides the value for the direction of travel at a given time.

(iii) Smolt growth: Three length values are chosen to illustrate the method here. $l_{f0} = 10cm$, is calculated to estimate the risk to smolts at the smaller end of the size variation. $l_{f0} = 12.5cm$ is the middle of the range selected here. Finally, $l_{f0} = 15cm$ is calculated to estimate the risk to smolts at the higher end of the size variation for smolts. Given length l_f in cm, then fish weight in grams is calculated as

$$w_f = \frac{l_f - 8.38}{0.21} \tag{11}$$

derived using data in Morris et al. (2019). Thus, at 12.5 cm, a smolt will weigh approximately 20 g. Assuming fish shape remains similar with size and biomass density is 1 g cm^{-3}, weight in grams and volume in cm^3 are equivalent so, average fish radius is calculated by

$$r_f = \sqrt{\frac{v_f}{\pi l_f}} \tag{12}$$

In order to determine the risk of impacts for a smolt from exposure to lice in the environment in terms of lice g^{-1}, we must calculate the growth rate. Following Mork et al. (2012) length is

$$l_{fD} = l_{f0}e^{yD} \tag{13}$$

for $y = 0.0059$ d^{-1}. Number of days, D, varies with each migration trajectory and size of fish, ranging from about 8 days for the shortest path and largest (15 cm) smolts to about 52 days on the longest path for smallest (10 cm) smolts.

Smolt growth is important for the calculation of critical lice concentrations in the environment because impact depends on mobile stage lice (Eq. 9). An average salmon louse maturation time is D ≈ 16 days at 10 °C, although there is a slight difference for male and females (Stien et al., 2005). This time interval approximates to 10% growth by Eq. 13, so for an $l_{f0} = 12.5$ cm smolt $l_{f16} = 13.7$ cm which approximates to 25 g.

The models described above allow us to calculate exposure of fish to salmon lice infection for the assumed migration trajectories of smolts and average lice loads on farms. To put this into context we must also calculate the maximum lice concentrations which are thought to cause wild salmon population impacts.

Table 2 summarises the copepodid concentrations that induce population impacts on smolts for 10 cm, 12.5 cm and 15 cm fish in one day. For $l_{f0} = 12.5$ cm fish, with final weight of 25 g, threshold T1, 20% mortality, corresponds to 2.5 mobile lice on the fish which when accounting for chalimus mortality becomes 3.8 infection events, which implies 7.7 contacts, as $a = 0.5$ probability of infection (Murray and Moriarty, 2021). Given $L_s = 1.795$ cm s^{-1} this parameter corresponds to maximum exposure level of $C_t = 0.8$ lice-days m^2 for a 12.5 cm smolt (Table 2). Note that values in Table 2 differ slightly from Murray et al. (2022b), owing to refinement of assumptions of farmed sentinel fish shape which now is allowed to differ from wild fish shape. This is the product of lice concentration *C*, and number of days the smolt travels through the salmon lice copepodid concentrations. However, the critical concentration depends on smolt size and migration speed, with a minimum concentration to avoid impacts for moderate low speeds, $B = 1/\tau_{\max}$, in this case $B = 1$.

3. Results

Fig. 3 highlights the dynamic relationship between smolt size, its migration speed and the critical environmental lice concentration. Based on the time the smolt requires to swim the length of a 10 km sea loch (Murray et al., 2011), it is clear that below 1 body lengths s^{-1} the length of the fish has a relatively small impact on the copepodid concentration threshold necessary to result in on-fish lice concentrations of 0.1 lice g^{-1}. Above this speed the copepodid concentration increases at a much greater rate resulting in copepodid concentration thresholds in excess of 32 copepodids per m^2 at fish speeds of 2.5 body lengths s^{-1} and fish lengths of 22 cm.

As an illustration for Scottish wild salmon, here we calculate the minimum exposure time for a given initial length of either 10 cm, 12.5 cm or 15 cm smolts with a cruising speed of $B = 1$. Depending on their size the salmon swim between 8.64 km d^{-1} and 12.97 km d^{-1}, using the directed swimming approach of Kristoffersen et al. (2018). Our example, Loch Linnhe, is approximately 60 km long, so fish originating from the upper loch may be exposed to elevated lice concentrations for several days as they pass down the loch (Fig. 4). For context, most Scottish sea lochs are less than 10 km, but 9 are longer than 20 km (Murray et al., 2011).

Highest copepodid concentrations occur in inshore waters of sea lochs or narrow sounds (Fig. 4). Concentrations simulated for average

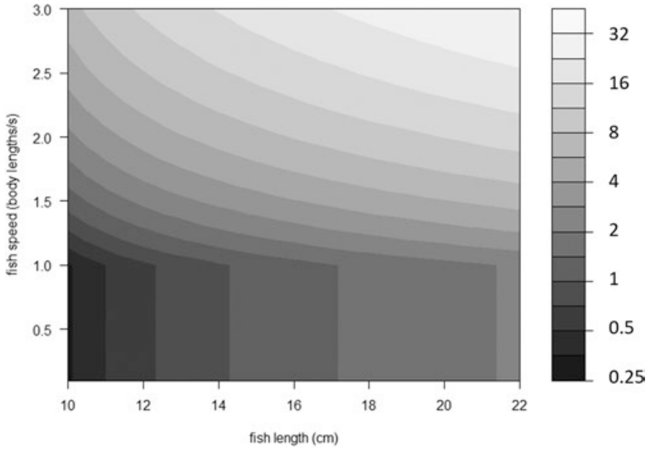

Fig. 3. Copepodid concentration threshold per m^2 (scale and associated shade on right hand bar) required for a smolt of a given size (cm) swimming at a given speed (body lengths per second) to reach a critical dose (0.1 lice per gram of host) while migrating through 10 km sea loch, assuming a 50% attachment probability on contact, 2 m mixed layer (z) and a given average copepodid swimming speed towards the host of 1.795 cm s^{-1}.

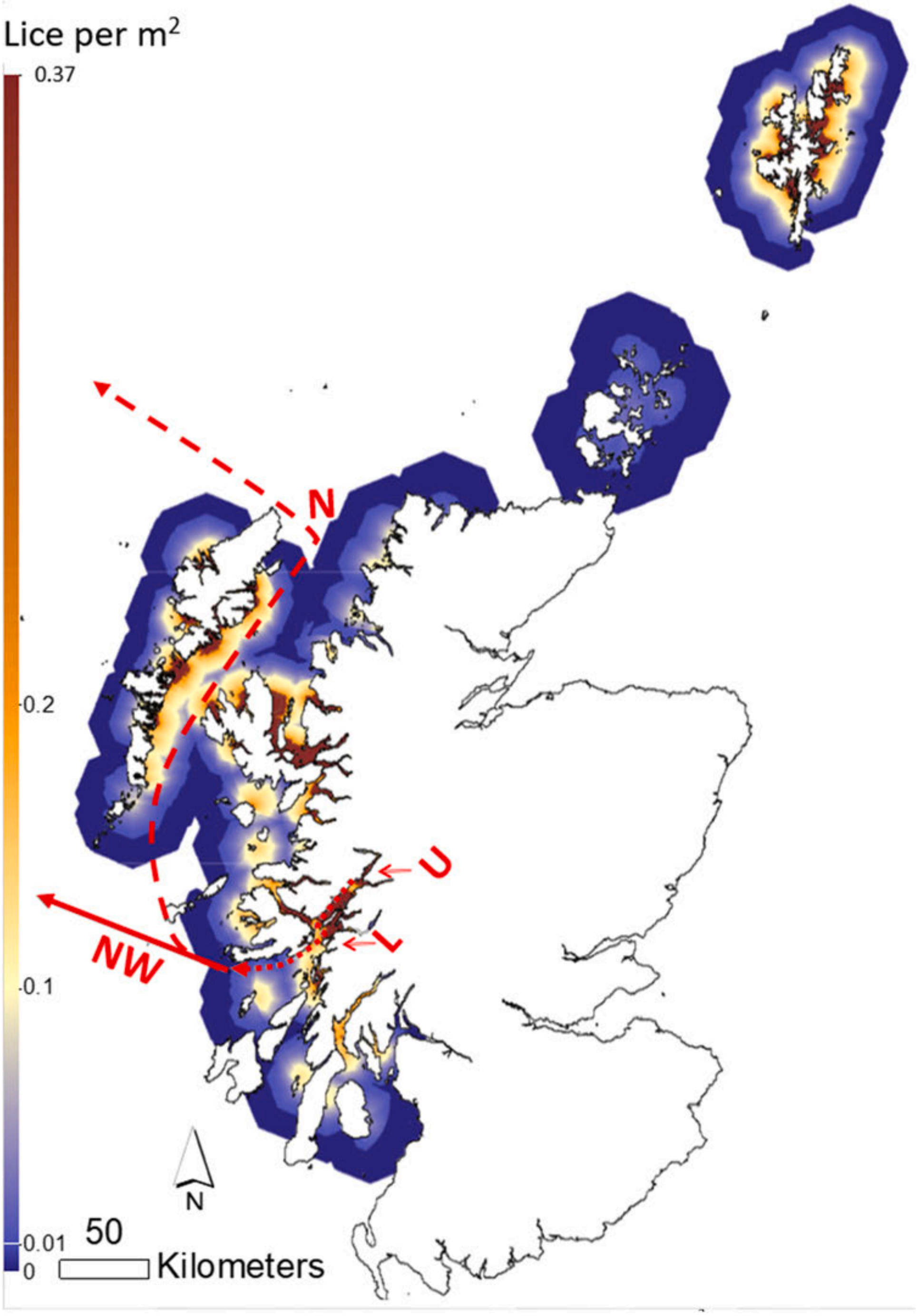

Fig. 4. Map shows the average simulated lice concentrations per m^2 around farms based on kernel distribution modelling originating from salmon aquaculture farms locations used (weighted by site consented biomass using the average adult female lice count multiplied by 0.58 to account for ovigerious females of the January 2018-December 2020 data. Illustration of smolts general migration routes (n = 10,000) from upper (U) and lower (L) Loch Linnhe, and then through coastal waters to the shelf edge (North West -NW or North -N) are used to show the general route used to calculate examples of exposure to lice infection shown in boxplot in Fig. 5.

farm lice counts 2018–2020 are below threshold T1 for one days exposure (Table 2) throughout all areas for all smolt sizes in the scenario illustrated (Fig. 2). However, migrating salmon are likely to be exposed to such concentrations for several days in inshore waters when migrating through lochs such as Linnhe. Exposure over this migration time leads to infection close to, or exceeding, T1 for 10 cm smolts within Upper and Lower Loch Linnhe under this scenario (Fig. 5). Smolts originating at the lower Loch Linnhe origin point have less distance to travel and time of exposure and are on average subject to loads below threshold T1 regardless of inshore route (Fig. 5 and Table 3). For 12.5 cm smolts, the exposure over their migration time leads to infection close to T1 when starting from Upper Loch Linnhe, the risk of exceeding T1 increases when smolts take the northward trajectory (Fig. 5). The larger 15 cm smolts are unlikely to reach exposure levels close to their T1 thresholds under any directed swimming scenarios (Fig. 5, Table 3).

4. Discussion

Understanding the mechanisms and risks of parasite transmission from aquaculture to wild fish is dependent on understanding ecological processes (Krkosek et al., 2009). The modelling presented here integrates and expands on research that has been carried out over several decades to enable evaluation of lice dispersal and predicted impact on wild salmon in the Scottish context, which currently does not have the same data availability as other exemplary areas such as Norway. This work includes salmon smolt migration and biology of impacts of lice on salmon, bringing these components together in a modelling framework (Fig. 1) using example system lice values (Fig. 4). We have developed

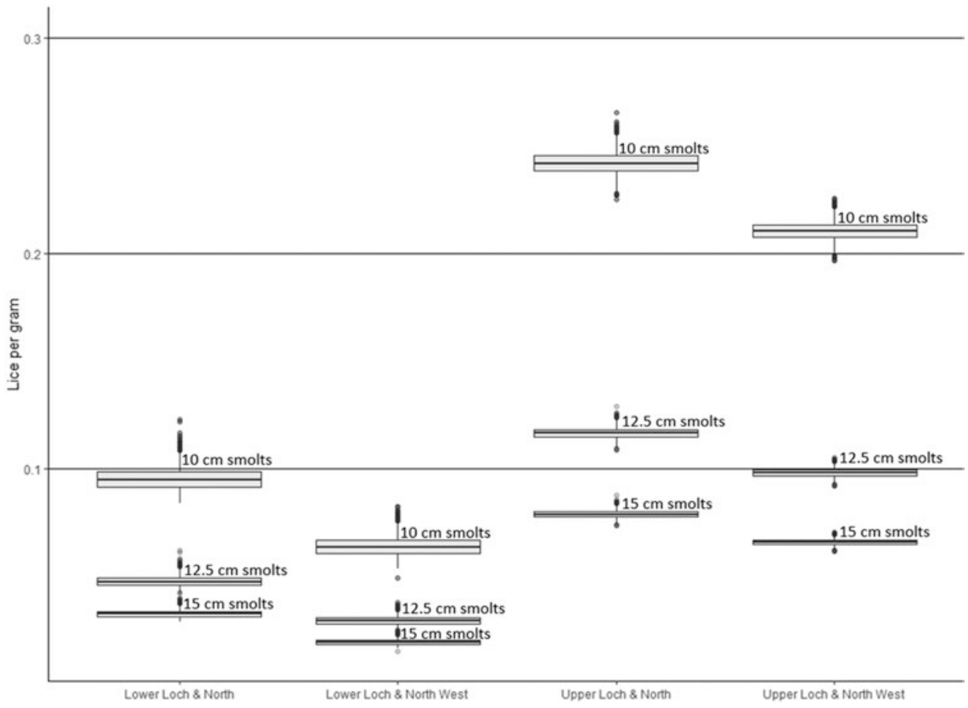

Fig. 5. Boxplots showing median (middle line), the 25th and 75th percentiles (lower and upper hinges), whiskers are depicting 95% confidence intervals for infestation pressure (lice per gram) encountered by 10 cm, 12.5 cm and 15 cm smolts in the average lice load scenario on each of the four simulated migration routes (n = 10,000). Lines indicate the T1 (20% mortality, 0.1 lice per gram), T2 (50% mortality, 0.2 lice per gram) and T3 (100% mortality, 0.3 lice per gram) and for each size.

Table 3
Mean mobile lice infection on smolts at initial length of 10 cm, 12.5 cm and 15 cm with final weights in (g), B = 1 for the example scenario illustrated in Fig. 4.

Inshore Infection	Coastal Waters Infection	Total Infection
10 cm fish, 12.2 g, B 1		
Upper Loch	Travel North	0.24 lice g^{-1}
0.21 lice g^{-1}	0.03 lice g^{-1}	
	Travel North West	0.21 lice g^{-1}
	$<$ 0.001 lice g^{-1}	
Lower Loch	Travel North	0.1 lice g^{-1}
0.06 lice g^{-1}	0.04 lice g^{-1}	
	Travel North West	0.06 lice g^{-1}
	$<$ 0.001 lice g^{-1}	
12.5 cm fish, 25 g, B 1		
Upper Loch	Travel North	0.12 lice g^{-1}
0.1 lice g^{-1}	0.02 lice g^{-1}	
	Travel North West	0.1 lice g^{-1}
	$<$ 0.001 lice g^{-1}	
Lower Loch	Travel North	
0.03 lice g^{-1}	0.02 lice g^{-1}	0.05 lice g^{-1}
	Travel North West	
	$<$ 0.001 lice g^{-1}	0.03 lice g^{-1}
15 cm fish, 38.29 g, B 1		
Upper Loch	Travel North	
0.07 lice g^{-1}	0.01 lice g^{-1}	0.08 lice g^{-1}
	Travel North West	
	$<$ 0.001 lice g^{-1}	0.07 lice g^{-1}
Lower Loch	Travel North	
0.02 lice g^{-1}	0.01 lice g^{-1}	0.03 lice g^{-1}
	Travel North West	
	$<$ 0.001 lice g^{-1}	0.02 lice g^{-1}

and parameterized a relatively simple but biologically relevant mathematical model, to show how the connection between an ecological process (migration of juvenile fishes) and an epidemiological process (exposure period to parasites), is key for understanding and managing the risk of parasitic salmon lice spreading from farmed to wild salmon. We have used point values for fish swim speed and sizes across example migration routes for wild salmon leaving Loch Linnhe. As a next stage, work is required to integrate across salmon lice dispersal distributions, fish swim speeds and sizes, and from this to predict impacts of lice at a population level for multiple river populations of wild salmon. Additional work is needed to describe the variance and uncertainty in each of the modelling components.

Model calibration and validation are key aspects of model development, giving us understanding of how specific variables impact model outputs and how these outputs relate to real world systems. All of which are critical for decision making. Investigation of the copepodid concentration threshold required to adversely impact the host fish is a complex issue. This requires data on sea lice loads and fish health which is linked to the environmental lice concentrations experienced by the fish. In many areas, modelled outputs are used to estimate lice concentration in the wild, as empirical data collection is costly and results can be variable (Skarðhamar et al., 2018, Adams et al., 2021). In Norway, the lice-induced mortality on out migrating salmon post-smolts was based on calibration of the infestation level on the virtual post-smolts against that observed on wild post-smolts genetically assigned to their rivers of origin (Johnsen et al., 2021). Empirical data on the range of smolt sizes leaving rivers, and the time spent in loch systems from Scotland are required to determine the total time that salmon smolts remain at risk of lice infection, in order to set appropriate copepodid concentration thresholds. Several studies are underway to increase the knowledge base on salmonid movements in relation to assessment of lice impacts e.g. larger scale movements of salmon through sea lochs and the Minch (https://atlanticsalmontrust.org/our-work/the-west-coast-tracking-project/).

Murray and Moriarty (2021) investigated sensitivity to model parameter variation highlighting that the copepodid concentration threshold required to reach a critical dose spans 3 orders of magnitude depending on the fish speed (average body lengths s^{-1}) and copepodid speed (average cm s^{-1}). While here, using an average copepodid speed of 1.795 cm s^{-1}, we show the copepodid concentration threshold required to reach a critical dose spans 3 orders of magnitude for smolts of different lengths (Fig. 3). Linking infestation pressure to realised mortality of fish in the wild has been attempted in Norway. However, no correlation was found between model estimates of infestation pressure and impact on host as measured in randomised control trials (Vollset et al., 2016, 2018). Thus, an improved understanding to model the links between the infestation pressure and impact on host is essential (Murray and Moriarty, 2021). This is alongside empirical work that allows comparison of lethal and sub-lethal impacts between farmed and unfarmed areas in Scotland (Wagner et al., 2008; Ives et al., 2023).

The salmon lice concentrations and distributions in inshore sea lochs and sounds traversed by wild salmon smolts determine the levels of lice infection. The length of the water body traversed, gives an estimate of exposure time, and this varies with size of salmon smolt from a particular river source. In this case study, exposure to lice in coastal waters is less than in inshore waters, but lice loads could be significantly increased under some potential smolt migration routes (Fig. 4 and Table 3), or with increases in numbers of lice released into the wider environment. The exposure of fish to infection by lice from farms depends on the distribution of copepodid concentration C and the pathway and speed of smolts. Distribution of C is here set with exponential decay under kernel models (Salama et al., 2016; Murray and Moriarty, 2021), and this distribution is illustrated for a case study assessment of risk to migrating 10 cm, 12.5 cm and 15 cm smolts on example migration routes (Fig. 4). Murray and Moriarty (2021) found that fish swimming at intermediate velocities are most susceptible to infestation, which is consistent with the observations of Samsing et al. (2015). This is because the volume of water from which copepodids can approach fish over a given time initially increases as the fish move more rapidly. Thus, smaller and/or slower smolts have more exposure to infection than larger and/or faster smolts (Eq. 8, Fig. 3), following the same routes (Fig. 4). Salmon louse infection of smolts in coastal waters is also highly dependent on route taken (Fig. 5, Table 3).

Travelling northwest to the Atlantic Ocean is likely to add relatively little additional lice infection for smolts. However, by comparison, smolts travelling north through the semi-enclosed Minch Sea may be exposed to substantial further lice infection before reaching the ocean. For the example scenario illustrated, this extra infection can be enough to reach T1, particularly for the smaller 10 cm and 12.5 cm smolts. These smolts are already being infected by lice loads of 0.21 lice g^{-1} and 0.1 lice g^{-1}, respectively, on leaving upper Loch Linnhe (Table 3). Lice infection on fish that hug the coast could be higher relative to those that take the most direct routes illustrated in our example (following Kristoffersen et al., 2018). These additional lice could have significant detrimental effects (Wagner et al., 2008) on smolts that have already been infected at relatively high lice loads in inshore waters.

The variation in lice load values is dependent on the variability within the key parameters used to calculate lice concentrations and fish movement. Differences in infection can be modelled by application of detailed hydrodynamic models and probabilistic models incorporating more variation in both physical and biological parameters which influence salmon lice and smolt behaviours. Never-the-less, the assessment based on kernel models and smolt migration here, gives a measure of averaged impact of lice that is useful for informing management policies. Regulation of lice impacts may be achieved by controlling input of lice from farms, or farming in areas of strong lice dispersal to prevent high concentrations in bottlenecks where salmon are at high local densities, or in areas that smolts can avoid passing near farms or transit rapidly.

4.1. Model limitations, assumptions and validation

For the salmon louse model, we have applied a simple approach to describing salmon louse dispersal, using a kernel of infection risk that decays with distance from source. The major assumption made here is that all areas will have a similar dispersal pattern, which is unlikely to be the case. Here, we use a single standard temperature value (10 °C) that governs our selection of a number of biological parameters included in the models. For instance, lice development time, egg numbers per individual adult female and the egg viability can all be impacted by a change in temperature. Stige et al. (2021) found that inclusion of temperature functions on these parameters resulted in modest improvements in model performance. However, the inclusion of salinity dependence in infestation success had a substantial improvement on explanatory power (Stige et al., 2021). Despite our focus on the inclusion of smolt growth as a determinant on both swim speed and infestation success, we recognise the importance of these environmental parameters in future work. In particular this variation in environmental parameters will be most valuable when our model framework is applied using coupled hydrodynamic particle tracking dispersal models. As they can account for spatial variation in lice distributions, inclusion of temperature and salinity components in the wider model framework will greatly improve our predictive capabilities making it an important next step in understanding lice impacts on Scotland's wild salmon populations.

The simulation used here to describe smolt migration is limited to consideration of three example sizes of smolt at fixed dispersal rate of 1 body length s^{-1}. Biologically relevant parameter values were used for predicting lice concentrations and attachment, and these should be considered further by sensitivity analysis and validation with observational data if possible. The model outputs reflect chosen parameters and behaviours, and demonstrate the relative importance of varying key componentssuch as fish size, migration route and release point.

Here we use the Taranger et al. (2015) mortality thresholds as the basis for our copepodid concentration thresholds. Other studies have also applied mortality thresholds to better understand lice impacts on wild salmon in Norway (Johnsen et al., 2021; Kristoffersen et al., 2018). In both studies they assessed the sensitivity in the mortality thresholds through inclusion of lower and higher thresholds with Taranger et al. (2015) used as the standard. These variations had substantial impacts in predicted levels of mortality and we would expect similar differences here.

The parameter values used in the modelling presented are based on best available data. Improved data, and modelling based on this data, will allow improved assessment of threshold salmon lice copepodids concentrations in Scottish coastal waters in terms of accuracy and our understanding of variability. Weekly adult female lice counts per fish are now published for all salmon farms in Scotland (http://aquaculture.scotland.gov.uk/) which can help us better understand fine scale lice production in specific geographic locations. Data on ovigerous lice, and particularly on the numbers of salmon on farms would allow a more accurate assessment of the numbers of larval lice entering the marine environment from farms.

Modelling infection rates could be improved by better constraints on the model of copepodid movements and attachment to hosts. Options for this include further assessments of the relationship between observed infection on sentinel cages and simulated lice concentrations in the environment (e.g. Moriarty et al., 2023). More detailed information on distribution of salmon lice copepodids in the environment is being produced through application of the Scottish Shelf Model. Salmon lice modelling has been enhanced through the Salmon Parasite In Linnhe, Lorn and Shuna (SPILLS) project (Gillibrand et al., 2023; Moriarty et al., 2023); model structure and parameterisation improved through reviews such as Murray et al. (2022a); and gap analysis, notably, through a Marine Alliance for Science and Technology for Scotland supported workshop.

4.2. Next steps

This work should help to inform on potential factors impacting wild salmon smolt infection levels, and on spatial patterns of aquatic epidemiology. The predicted smolt trajectories coupled with the simple salmon lice density maps, should provide useful insight for management purposes. Here we are laying the foundation to provide a simple but meaningful methodology of assessing interaction potential between wild salmon smolts and salmon lice originating on farms for Scottish aquaculture. Further work is required to assess the sensitivity of various parameters used within these models to understand the uncertainty and its potential consequences to the risk of mortality for wild fish. For example, lice susceptibility and behaviours of *S. trutta* can differ from *S. salar*, so the modelling requires adaption if it is to be applied to sea trout. *L. salmonis* is also found on sea farmed rainbow trout (*Oncorhynchus mykiss*), 5144 tonnes of which is produced in Scottish marine waters (Munro, 2022) and so could act as a further reservoir for salmon lice dispersal.

The simple kernel decay-based salmon lice model applied here allows a general assessment of patterns of infection risk due to salmon lice, and provides a useful starting point in developing an applied modelling structure. However, using an individual based model (IBM) driven by highly resolved hydrodynamic modelling will be more informative for localised conditions. Hydrodynamic models are used to inform IBMs of virtual particles that represent parasites or fish. These may include behavioural components that simulate active movement, such as directed swimming, reflecting migratory movements in salmon. The use of detailed hydrodynamics will allow a more specific description of lice dispersal from farms and thus a more detailed description of copepodid concentrations in the environment (or licescape). Such modelling has been applied in specific systems such as Loch Linnhe (Salama et al., 2018) and is being developed for application more widely. The Scottish shelf coastal hydrodynamic environment has been modelled (http://marine.gov.scot/themes/scottish-shelf-model) and this model has been used to track lice connection between areas (Rabe et al., 2020). This Scottish Shelf Model (SSM) will allow licescapes to be generated for Scottish coastal waters within the next steps of salmon lice modelling for Scotland.

There have been a few efforts to simulate salmon migration patterns, which provide insight into potential behaviours, the likely migration routes and local scale influences of currents and tides for different salmon populations (Booker et al., 2008; Byron et al., 2014; Moriarty et al., 2016; Mork et al., 2012; Ounsley et al., 2020). To date there is one study examining salmon smolt migration from Scottish shores (Ounsley et al., 2020), which led to the inference that Scottish smolts cannot rely on the same current – following behaviours as their Irish and Norwegian cousins (Booker et al., 2008; Mork et al., 2012). They instead must use directed-swimming behaviour to reach their feeding grounds in the Northeast Atlantic. The data describing the movement of Scottish salmon smolts leaving the river and migrating to their oceanic feeding grounds are limited and represents a priority area for further research. The area for which further data are most required is on the movement of smolts in inshore and coastal waters as these details determine their exposure time to copepodids. Further data on the effect of mobile lice loads g^{-1} on smolts welfare and survival would also improve assessment of impact of infestation intensities. Size of smolts varies too, and this affects their speed and threshold number of lice on a fish before impacts, we have highlighted it with a range of smolt sizes. Acoustic tagging is being used to obtain observational data on smolt movements (Middlemas et al., 2017) while IBMs for smolt migration are also in development (Ounsley et al., 2020). Inclusion of environmental variability in determining lice concentrations and their relative effects has also been used to improve lice based IBMs (Vollset, 2019).

Therefore, the next steps in developing this structure for management needs are; i) incorporate and validate an IBM which accounts for environmental factors and models salmon lice behaviour and development ii) incorporate and validate an IBM and develop the smolt trajectory model to assess risk from all salmon catchment areas and strategic offshore locations, and iii) develop a third IBM to simulate the trajectories and behaviours of sea trout smolts. Developing interrelating IBMs for salmon lice – smolt interactions will better inform local interaction potential and allow us to infer exposure risk on a finer scale than describing salmon lice dispersal using a kernel of infection risk that decays with distance from source and directed swimming behaviours. Understanding the risk posed to salmon smolts leaving rivers from all catchment areas will allow for localised assessments in a regulatory framework.

5. Conclusions

The modelling presented here describes the structure of interaction between salmon lice and salmon smolts and details an application under specific parameter examples in Loch Linnhe. Further development for application to specific salmon populations requires assessment of not only the typical parameters, as described, but also variation within and between systems to assess impacts at population levels. This requires assessing ranges of parameters and tailoring them to individual populations based on data ranges within these populations. This concept is illustrated here for a set of parameter values applied to notional 10 cm, 12.5 cm and 15 cm salmon smolts. Smaller smolts will be more susceptible, while larger and faster ones will be less impacted by salmon lice (Fig. 3). Salmon lice impact may be reduced through strategic location of farms, restrictions on farm biomass, and/or control of numbers of ovigerous lice per fish - particularly during salmon smolt migration. The modelling approach can be developed further to integrate many sources of research with application to manage salmon lice impact in the planning and management of aquaculture.

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Appendix 1

Short-term burst speeds, L_s, of 1–5 cm s^{-1} over τ_{max} of 1–3 s have been reported for salmon lice copepodids (Heuch and Karlsen, 1997). To quantify risk of attachment, estimations of both short-term burst speeds, L_s and associated distance travelled, X, are needed to apply the model. Here we use inference from data reported in Sandvik et al. (2020), but as modelling and associated validation improves in Scotland through projects such as SPILLS these values will be updated.

Dimensions of the fish

High infection was reported as 10 lice fish^{-1} for sentinel cage fish weighing 50–60 g (Sandvik et al., 2020). We assume the volume of the fish is directly related to the weight with a 1–1 relationship. Thus we calculate X based on contact of 10 lice with a 55 g fish which equates to 55 cm^3.

A 55 g fish corresponds to a length of between 17.5 and 20 cm. The length of 17.5 cm is an appropriate conversion for farmed fish (Murray and Moriarty, 2021) which were used in Sandvik et al. (2020). However this weight would correspond to a 20 cm wild fish in Scotland derived from data presented in Morris et al. (2019).

Given a volume of 55 cm^3 and two lengths we can calculate the associated radii of the fish using the equation $r_f \quad \sqrt{\frac{v_f}{\pi l_f}}$. For $l_f \quad 17.5, r_f \quad 1$ or for $l_f \quad 20, r_f \quad 0.94$.

Attachment of lice to fish

Given a probability of contact, a 0.5, and considering mortality of chalimus of 34.7% (Salmon Lice Model, Section D), then 10 mobile lice correspond to K 30.6 infectious contacts per day when adjusted for attachment and survival (Eq. 7).

Associated concentration of lice in environment

This observed infection occurred where model simulation concentrations were C_x 1.8 lice days m^{-2} (Sandvik et al., 2020). Given B 1 s^{-1} and Z 2 m (Murray and Moriarty, 2021) this equates to 0.9 lice m^3. The interaction between lice and smolts occurs at the scale of centimetres rather than meters, 0.9 lice m^3 is equal to 0.9 × 10^{-6} lice cm^{3}s^{-1}. We assess contact of smolts in days, d, rather than seconds, s, thus, 0.9 × 10^{-6} lice cm^{3}s^{-1} equates to 0.07776 lice cm^3 d^{-1}. Thus for a smolt to contact 30.6 lice d^{-1}, the volume of water from which copepodids can contact a moving fish,U_w,is 393.52 cm^3 s^{-1}.

Using Eq. 5, where $U_w \quad B\left(\left(\pi(X+r_f)^2 \times l_f\right) \quad V_f\right)$, we can estimate $X \quad L_s$ 1.86 cm s^{-1} copepodid swimming speed for a fish with a length of 17.5 cm or $X \quad L_s$ 1.73 cm s^{-1} for a fish at 20 cm. Thus, we take an average of these two values and assume that lice are likely to swim towards smolt at 1.795 cm s^{-1} for a sustained time of 1 s before the smolt will have moved out of reach of the parasite.

References

Abolofia, J., Asche, F., Wilen, J.E., 2017. The cost of lice: quantifying the impacts of parasitic sea lice on farmed salmon. Mar. Res. Econ. 32, 329–349. https://doi.org/10.1086/691981.

Adams, T., Marshall, S., Brown, S., Black, K., 2021. Validating a biophysical parasite model with fish farm pen and plankton trawl data. Aquacult Environ. Inter. 13, 425–437. https://doi.org/10.3354/aei00416.

Blázquez (2021) Leading food and drink exports from the UK 2020 | Statista https://www.statista.com/statistics/415651/leading-food-and-drink-exports-united-kingdom-uk/ accessed 14th December 2021.

Booker, D.J., Wells, N.C., Smith, I.P., 2008. Modelling the trajectories of migrating Atlantic salmon (*Salmo salar*). Can. J. Fish. Aquat. Sci. 65 (3), 352–361. https://doi.org/10.1139/F07-173.

Brooker, A.J., Skern-Mauritzen, R., Bron, J.E., 2018. Production, mortality, and infectivity of planktonic larval sea lice, Lepeophtheirus salmonis (Kroyer, 1837): Current knowledge and implications for epidemiological modelling. ICES J. Mar. Sci. 75, 1214–1234. https://doi.org/10.1093/icesjms/fsy015.

Butler, J.R.A., 2002. Wild salmonids and sea louse infestations on the west coast of Scotland: sources of infection and implications for the management of marine farms. Pest Manag. Sci. 58, 595–608.

Byron, C.J., Pershing, A.J., Stockwell, J.D., Xue, H., Kocik, J., 2014. Migration model of post-smolt Atlantic salmon (*Salmo salar*) in the Gulf of Maine. Fish. Oceanogr. 23 (2), 172–189. https://doi.org/10.1111/fog.12052.

Dadswell, M., Spares, A., Reader, J., 2021. The Decline and Impending Collapse of the Atlantic Salmon (Salmo salar) Population in the North Atlantic Ocean. A Review of Possible Causes *Reviews in Fisheries*. Taylor & Francis,.

Dempster, T., Overton, K., Bui, S., Stien, L.H., Oppedal, F., Karlsen, Ø., Coates, A., Phillips, B.L., Barrett, L.T., 2021. Farmed salmonids drive the abundance, ecology and evolution of parasitic salmon lice in Norway. Aquacult Environ. Inter. 13, 237–248.

Finstad, B., Bjørn, P.A., Grimnes, A., Hvidsten, N.A., 2000. Laboratory and field investigations of salmon lice (Lepeophtheirus salmonis (Krøyer)) infestation on Atlantic salmon (Salmo salar L.) postsmolts. Aquacult Res 31, 795–803. https://doi.org/10.1046/J.1365-2109.2000.00511.X.

Fjelldal, P.G., Hansen, T.J., Karlsen, O., Wright, D.W., 2020. Effects of laboratory salmon louse infection on osmoregulation, growth and survival in Atlantic salmon. Conserv Physiol. 8 (1), 1–10. https://doi.org/10.1093/conphys/coz072.

Forseth, T., Barlaup, B.,T., Finstad, B., Fiske, P., Gjøsæter, H., Falkegård, M., Hindar, A., Mo, T.A., Rikardsen, A.H., Thorstad, E.B., Vøllestad, L.A., Wennevik, V., 2017. The major threats to Atlantic salmon in Norway. ICES J. Mar. Sci. 74, 1496–1513. https://doi.org/10.1093/icesjms/fsx020.

Gilbey, J., Sampayo, J., Cauwelier, E., Malcolm, I., Millidine, K., Jackson F., Morris, D.J. 2020 A national assessment of the influence of farmed salmon escapes on the genetic integrity of wild Scottish Atlantic salmon populations Scottish Marine and Freshwater Science Vol 12 No 12 2020.

Gillibrand, P.A., Willis, K.J., 2007. Dispersal of sea louse larvae from salmon farms: Modelling the influence of environmental conditions and larval behaviour. Aquat. Biol. 1 (1), 63–75. https://doi.org/10.3354/ab00006.

Gillibrand P., Moriarty M., Brain S. (2023), Work Package 1 Final Report: Sea Lice Dispersal Modelling in Shuna Sound *Supporting Document* Marine Scotland. 2023. Salmon Parasite Interactions in Linnhe, Lorn and Shuna (SPILLS) Final Project Report. doi: 10.7489/12443-1.

Grimnes, A., Jakobsen, P.J., 1996. The physiological effects of salmon lice infection on post-smolts of Atlantic salmon. J. Fish. Biol. 48, 1179–1194.

Hamre, L.A., Eichner, C., Caipang, C.M.A., Dalvin, S.T., Bron, J.E., Nilsen, F., Boxshall, G., Skern-Mauritzen, R., 2013. The Salmon Louse Lepeophtheirus salmonis (Copepoda: Caligidae) Life Cycle Has Only Two Chalimus Stages. PLOS One. https://doi.org/10.1371/journal.pone.0073539.

Hawkins, D., 2021. Factors affecting Atlantic Salmon populations adversely; using the River Dee, Scotland, as an example. Int. Mar. Sci. J. https://doi.org/10.14302/issn.2643-0282.imsj-21-3899.

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

Heuch, P.A., Karlsen, E., 1997. Detection of infrasonic water oscillations by copepodids of *Lepeophtheirus salmonis* (Copepoda Caligida). J. Plankton Res. 19, 735–747.

Heuch, P.A., Nordhagen, J.R., Schram, T.A., 2000. Egg production in the salmon louse [*Lepeophtheirus salmonis* (Krøyer)] in relation to origin and water temperature. Aquac. Res. 31, 805–814.

Ives, S.C., Armstrong, J.D., Collins, C., Moriarty, M., Murray, A.G., 2023. Salmon lice loads on Atlantic salmon smolts associated with reduced welfare and increased population mortalities. Aquac. Environ. Interact. https://doi.org/10.3354/aei00453.

Johnsen, I.A., Harvey, A., Pål Næverlid, S.ævik, Anne, D.Sandvik, Ola, Ugedal, Bjørn, Ådlandsvik, Vidar, Wennevik, Kevin, A.Glover, Ørjan, Karlsen, 2021. Salmon lice-induced mortality of Atlantic salmon during post-smolt migration in Norway. ICES J. Mar. Sci. Volume 78 (Issue 1), 142–154. https://doi.org/10.1093/icesjms/fsaa202.

Johnson, S.C., Albright, L.J., 1991. Development, Growth, and Survival of *Lepeophtheirus salmonis* (Copepoda: Caligidae) under laboratory conditions. J. Mar. Biol. Assoc. UK 71, 425–436.

Jonsson, B., Jonsson, N., Hansen, L.P., 2003. The marine survival and growth of wild and hatchery-reared Atlantic salmon. *J. Appl. Ecol.*, 2003 vol. 40, 900–911.

Kristoffersen, A.B., Qviller, L., Hellgesen, K.O., Vollset, K.W., Viljugrein, H., 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., Morton, A., Volpe, J.P., Lewis, M.A., 2009. Sea lice and salmon population dynamics: effects of exposure time for migratory fish. Proc. Biol. Sci. 276 (1668), 2819–2828. https://doi.org/10.1098/rspb.2009.0317.

Malcolm, I.A., Millar, C.P., Millidine, K.J., 2015. Spatio-temporal variability in Scottish smolt emigration times and sizes. Scott. Mar. Freshw. Scienc*e* 6 (2). https://doi.org/10.7489/1590-1.

Marine Scotland 2021 ⟨https://www.gov.scot/publications/salmon-fishing-proposed-river-gradings-for-2021-season/⟩.

Marshall, S., 2003. The incidence of sea lice infestations on wild sea trout compared to farmed salmon. Bull. Eur. Assoc. Fish. Pathol. 23, 72–79.

Mcilvenny, J., Youngson, A., Williamson, B.Jm, Gauld, N.R., Goddijn- Murphy, L., Del Villar-Guerra, D., 2021. Combining acoustic tracking and hydrodynamic modelling to study migratory behaviour of Atlantic salmon (Salmo salar) smolts on entry into high-energy coastal waters. ICES J. Mar. Sci. 78 (7) https://doi.org/10.1093/icesjms/fsab111.

Middlemas, S., Stewart, D., Henry, J., Wyndham, M., Ballantyne, L., Baum, D., 2017. Dispersal of post-smolt Atlantic salmon and sea trout within a Scottish sea loch system. p339-353. In: Harris, G. (Ed.), Sea Trout – Science and Management: Proceedings of the 2nd International Sea Trout Symposium. Inland Fisheries Ireland, Dundalk, Ireland.

Middlemas, S.J., Fryer, R.J., Tulett, D., Armstrong, J.D., 2013. Relationship between sea lice levels on sea trout and fish farm activity in western Scotland. Fish. Manag. Ecol. 20, 68–74.

Moriarty, P.E., Byron, C.J., Pershing, A.J., Stockwell, J.D., Xue, H., 2016. Predicting migratory paths of post-smolt Atlantic salmon (Salmo salar). Mar. Biol. 163 (4) https://doi.org/10.1007/s00227-016-2847-5.

Moriarty M., Gillibrand P., Garnier S., O'Hara Murray R., Rabe B., Brain S, Gallego A. (2023) Work Package 4 Final Report: Model inter-comparison and validation in Inner and Outer Loch Linnhe. *Supporting Document* Marine Scotland. 2023. Salmon Parasite Interactions in Linnhe, Lorn and Shuna (SPILLS) Final Project doi: 10.7489/12443-1.

Mork, K.A., Gilbey, J., Hansen, L.P., Jensen, A.J., Jacobsen, J.A., Holm, M., Holst, J.C., Maoiléidigh, Ó., Vikebo, N., McGinnity, F., Melle, P., Thomas, W., Verspoor, E, K., Wennevik, V., 2012. Modelling the migration of post-smolt Atlantic salmon (Salmo salar) in the Northeast Atlantic. ICES J. Mar. Sci. 69 (9), 1616–1624. https://doi.org/10.1093/icesjms/fss108.

Morris, D.J., Gauld, N.R., Raynard, R.S., Armstrong, J.D., 2019. A pilot study to determine the effect of an anti - sea lice agent on the marine survival of Atlantic salmon on the West coast of Scotland. Scott. Mar. Freshw. Sci. 10, 15. https://doi.org/10.7489/12212-1.

Munro L.A. 2022. Scottish finfish production survey (2021). The Scottish Government, Edinburgh file://scotland.gov.uk/dc1/fs3_home/U206422/scottish-fish-farm-production-survey-2021.pdf.

Murray, A.G., Moriarty, M., 2021. A simple modelling tool for assessing interaction with host and local infestation of sea lice from salmonid farms on wild salmonids based on processes operating at multiple scales in space and time. Ecol. Model. 443, 109459.

Murray, A.G., Ives, S.C., Smith, R.J., Moriarty, M., 2021. A preliminary assessment of indirect impacts on aquaculture species health and welfare in Scotland during COVID-19 lockdown. Vet. Anim. Sci. 11, 100167 https://doi.org/10.1016/j.vas.2021.100167.

Murray, A.G., Ives, S.C., Murphy, J., Moriarty, M., 2022b. Modelling parasite-driven impacts of aquaculture on wild fish: the case of the Salmon Louse (*Lepeophtheirus salmonis*). p103-114 in K.A. In: Robinson, McIntyre, K.M. (Eds.), Proceedings of the Society for Veterinary Epidemiology and Preventive Medicine annual meeting held in Belfast.

Murray, A.G., Amundrud, T.L., Penston, M.J., Pert, C.C., Middlemas, S.J., 2011. Abundance and distribution of larval sea lice in Scottish coastal waters. In: Jones, S., Beamish, R. (Eds.), Salmon Lice: An Integrated Approach to Understanding Parasite Abundance and Distribution. Wiley-Blackwell.

Murray, A.G., Shephard, S., Asplin, L., Adams, T., Gallego, A., Hartnett, M., Askeland, I., Jones, S.R.M., Moriarty, M., Nash, S., Pert, C.C., Rabe, B., Gargan, P.G., 2022a. A standardised generic framework of sea lice model components for application in coupled hydrodynamic-particle models. In: Treasurer, J., Bricknell, I., Bron, J. (Eds.), Sea Lice Biology and Control. 5M Books, pp. 167–187.

Ounsley, J.P., Gallego, A., Morris, D.J., Armstrong, J.D., 2020. Regional variation in directed swimming by Atlantic salmon smolts leaving Scottish waters for their oceanic feeding grounds - a modelling study. ICES J. Mar. Sci. 77 (1), 315–325. https://doi.org/10.1093/icesjms/fsz160.

Penston, M.J., McKibben, M.A., Hay, D.W., Gillibrand, P.A., 2004. Observations on open water densities of sea lice larvae in Loch Sheidaig, western Scotland. Aquac. Res. 35, 793–805.

Pert, C.C., Fryer, R.J., Cook, P., Kilburn, R., McBeath, S., McBeath, A., Matejusova, I., Urquhart, K., Weir, S.J., McCarthy, U., Collins, C., Amundrud, T., Bricknell, I.R., 2014. Using sentinel cages to estimate infestation pressure on salmonids from sea lice in Loch Shieldaig, Scotland. Aquac. Environ. Interact. 5, 49–59.

R Core Team , 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL 〈https://www.R-project.org/〉.

Rabe, B., Hindson, J., 2017. Forcing mechanisms and hydrodynamics in Loch Linnhe, a dynamically wide Scottish estuary. Estuar. Coast. Shelf Sci. 196, 159–172.

Rabe, B., Gallego, A., Wolf, J., O'Hara Murray, R., Stuiver, C., Price, D., Johnson, H., 2020. Applied connectivity modelling at local to regional scale: The potential for sea lice transmission between Scottish finfish aquaculture management areas. Est. Coast. Shelf Sci. 238, 106716 https://doi.org/10.1016/j.ecss.2020.106716.

Salama, N.K.G., Murray, A.G., Rabe, B., 2016. Simulated environmental transport distances of Lepeophtheirus salmonis in Loch Linnhe, Scotland, for informing aquaculture area management structures. J. Fish. Dis. 39, 419–428. https://doi.org/10.1111/jfd.12375.

Salama, N.K.G., Dale, A.C., Ivanov, V.V., Cook, P.F., Pert, C.C., Collins, C.M., Rabe, B., 2018. Using biological–physical modelling for informing sea lice dispersal in Loch Linnhe, Scotland. J. Fish. Dis. 41, 901–919. https://doi.org/10.1111/jfd.12693.

Samsing, F., Solstorm, D., Oppedal, F., Solstorm, F., Dempster, T., 2015. Gone with the flow: current velocities mediate parasitic infestation of an aquatic host. Int. J. Parasitol. 45, 559–565.

Samsing, F., Oppedal, F., Dalvin, S., Johnsen, I., Vågseth, T., Dempster, T., 2016. Salmon lice (*Lepeophtheirus salmonis*) development times, body size, and reproductive outputs follow universal models of temperature dependence. Can. J. Fish. Aquat. Sci. 73 (12) https://doi.org/10.1139/cjfas-2016-0050.

Sandvik, A.D., Johnsen, I.A., Myksvoll, M.S., Sævik, P.N., Skogen, M.D., 2020. Prediction of the salmon lice infestation pressure in a Norwegian fjord. ICES J. Mar. Sci. 77 (2), 746–756. https://doi.org/10.1093/icesjms/fsz256.

Skarđhamar, J., Albretsen, J., Sandvik, A.D., Lien, V.S., Myksvoll, M.S., Johnsen, I.A., Asplin, L., Ådlandsvik, B., Halttunen, E., Bjørn, P.A., 2018. Modelling salmon lice dispersion and infestation patterns in a sub-artic fjord. ICES J. Mar. Sci. 75, 1733–1747.

Stien, A., Bjørn, P.A., Heuch, P.A., Elston, D.A., 2005. Population dynamics of salmon lice *Lepeophtheirus salmonis* on Atlantic salmon and sea trout. Mar. Ecol. Prog. Ser. 290, 263–275.

Stige, L.C., Helgessen, K.O., Viljugrein, H., Qviller, L., 2021. A statistical mechanistic approach including temperature and salinity effects to improve salmon lice modelling of infestation pressure. Aquac. Environ. Interact. 13, 339–361. https://doi.org/10.3354/aei00410.

Taranger, G.L., Karlsen, Ø., Bannister, R.J., Glover, K.A., Husa, V., Karlsbakk, E., Kvamme, B.O., Boxaspen, K.K., Bjørn, P.A., Finstad, B., Madhun, A.S., Morton, H.C., Svåsand, T., 2015. Risk assessment of the environmental impact of Norwegian Atlantic salmon farming. ICES J. Mar. Sci. 72, 997–1021. https://doi.org/10.1093/icesjms/fsu132.

Thorstad, E.B., Whoriskey, F., Uglem, I., Moore, A., Rikardsen, A.H., Finstad, B., 2012. A critical life stage of the Atlantic salmon Salmo salar: behaviour and survival during the smolt and initial post-smolt migration. J. Fish. Biol. 81 (2), 500–542. https://doi.org/10.1111/j.1095-8649.2012.03370.x.

Tucker, C.S., Norman, R., Shinn, A., Bron, J., Sommerville, C., Wootten, R., 2002. A single cohort time delay model of the life-cycle of the salmon louse Lepeophtheirus salmonis on Atlantic salmon Salmo salar. Fish. Pathol. 37, 107–118.

Vollset, K.W., 2019. Parasite induced mortality is context dependent in Atlantic salmon: insights from an individual-based model. Sci. Rep. 9 (17377), 2019. https://doi.org/10.1038/s41598-019-53871-2.

Vollset, K.W., Krontveit, R.I., Jansen, P.A., Finstad, B., Barlup, B.T., Skilbrei, O.T., Krkosek, M., Romstad, P., Jensen, A.J., Dohoo, I., 2016. Impact of parasites on marine survival of Atlantic salmon: a meta-analysis. Fish Fish. 17, 714–730.

Vollset, K.W., Dohoo, I., Karlsen, Ø., Halttunen, E., Kvamme, B.O., Finstad, B., Wennevik, V., Diserud, O.H., Bateman, A., Friedland, K.D., Mahlum, S., Jørgensen, C., Qviller, L., Krkošek, M., Åtland, Å., Barlaup, B.T., 2018. Disentangling the role of sea lice on the marine survival of Atlantic salmon. ICES J. Mar. Sci. 75, 50–60. https://doi.org/10.1093/icesjms/fsx104.

Wagner, G.N., Fast, M.D., Johnson, S.C., 2008. 'Physiology and immunology of Lepeophtheirus salmonis infections of salmonids'. Trends Parasitol. 24 (4), 176–183. https://doi.org/10.1016/j.pt.2007.12.010.

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Sea-lice regulation in salmon-farming countries: how science shape policies for protecting wild salmon

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Abstract
The proliferation of sea lice from aquaculture may substantially aggravate the decline in marine survival of wild salmons. In some countries, this risk has motivated regulators to adopt more precautionary policies; in other countries, however, regulators have disputed the need for stricter regulation. This article compares the sea-lice regulations of Norway, Scotland, Ireland, and Canada (British Columbia), showing how varying interpretations of the science on farm–wild interactions have shaped efforts to scale up regulatory measures for mitigating health hazards and mortality risks for wild salmon. In Norway and Scotland, scientific consensus has expedited cooperation between research and governing institutions and facilitated ambitious policy reforms. In Ireland and Canada, by contrast, scientific controversy around the scale of farm-lice impacts on wild salmon populations has led to conflict and disagreement between researchers and policymakers, and to failure of reform attempts desired by wild salmon stakeholders.

Keywords Salmon aquaculture · Wild salmon · Sea-lice regulation · Science–policy interactions

Introduction

The abundance of wild salmon has declined dramatically since the 1980s (Kellogg 1999, Noakes, Beamish et al. 2000, Torrissen, Jones et al. 2013, NASCO 2019). This global decline is due mainly to poor marine survival (ICES 2016) caused by the complex interaction of anthropogenic, natural biological, and physical factors, including sea-temperature change, pollution, susceptibility to predators, and post-smolt growth (Fig. 1) (Friedland, Reddin et al. 1993, Parrish, Behnke et al. 1998, Jonsson and Jonsson 2004, Friedland, MacLean et al. 2009, Chaput 2012, Friedland, Shank et al. 2014, Vollset, Krontveit et al. 2015).

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A growing body of scientific evidence indicates that the sea-lice parasite *Lepeophtheirus salmonis*, which thrives in salmon farms and spreads to infest surrounding salmon populations, can significantly aggravate marine mortality among wild salmon (Hilborn 2006, Costello 2009, Krkosek, Connors et al. 2011, Vollset, Krontveit et al. 2015, Johnsen, Harvey et al. 2021, Stige, Helgesen et al. 2022). However, the precise extent to which sea-lice infestations reduce adult salmon returns has been subject to scientific debate. Some studies find that farm sea lice represent a minor and irregular component of marine mortality, with insignificant population-level effects (Marty, Saksida et al. 2010, Jackson, Cotter et al. 2011, Jackson, Cotter et al. 2013a, Jackson, Kane et al. 2013b, Skilbrei, Finstad et al. 2013). However, others, using similar data, find that the presence of sea lice fuels the decline in populations (Otero, Jensen et al. 2011, Gargan, Forde et al. 2012, Krkosek, Revie et al. 2013, Shepard and Gargan 2017, Shepard and Gargan 2021).

This lack of scientific consensus around the scale of farm-lice impacts has been accompanied by political controversy around what policies are needed to protect wild salmons adequately. This is a common feature of “wicked” policy problems, which are often riddled with scientific uncertainties that fuel disagreement as to appropriate regulatory responses (Rittel and Webber 1973, Osmundsen, Almklow et al. 2017). Scientific uncertainty often spurs conflict between institutional and political players with differing values, interests, and policy preferences (Sarewitz 2004, Hoppe 2005, Lackey 2007). In the case of salmon aquaculture, disputes around the need for stricter sea-lice regulation have emerged between, on the one hand, researchers, stakeholders, and government actors that believe the available scientific knowledge on lice-induced health hazards and mortality risks for wild salmons justifies more stringent regulations, and, on the other hand, those who stress the lack of a statistically proven association between lice infestations and population declines, and thus dispute the need for reform.

This study examines the role of science in shaping aquaculture policymaking towards enhanced protection of wild salmon. It does so by conducting a comparison of sea-lice regulation in four major salmon-farming jurisdictions that have a stated responsibility to protect wild populations: Norway, Canada, Scotland, and Ireland. The article first provides an overview of sea-lice regulations in each country, focusing on farm sea-lice limits or management thresholds during periods of out-migration for juvenile salmons, the rules of threshold enforcement, and reporting and public disclosure of on-farm lice levels, and new, area-based management systems that regulate farm biomass (production volumes) based on estimated mortality risks for wild salmon. Second, it considers whether the regulations have been designed and revised to provide improved protection of wild salmons. Third, it assesses how variations in regulatory approaches relate to differences in the governments’ interpretation of the scientific basis. Notwithstanding other factors that may contribute to explaining whether or not a country has significantly revised its on-farm thresholds or adopted new regimes for area-based sea lice management—including institutional, political, cultural, or ecological factors—the article finds that the existence of consensus or controversy around the science on farm–wild interactions has shaped regulatory actions toward reform. In Norway and Scotland, the emergence of a near-consensus around the science that justifies policy change has enabled reformist political forces to adopt and implement more precautionary and strict regulation to protect wild salmon. By contrast, the persistence of controversy in Canada and Ireland appears to have hindered reformists in their calls for change and led to a lack of political commitment. The emergence of scientific agreement within the government may be an important prerequisite for significant policy reforms related to farm–wild interactions.

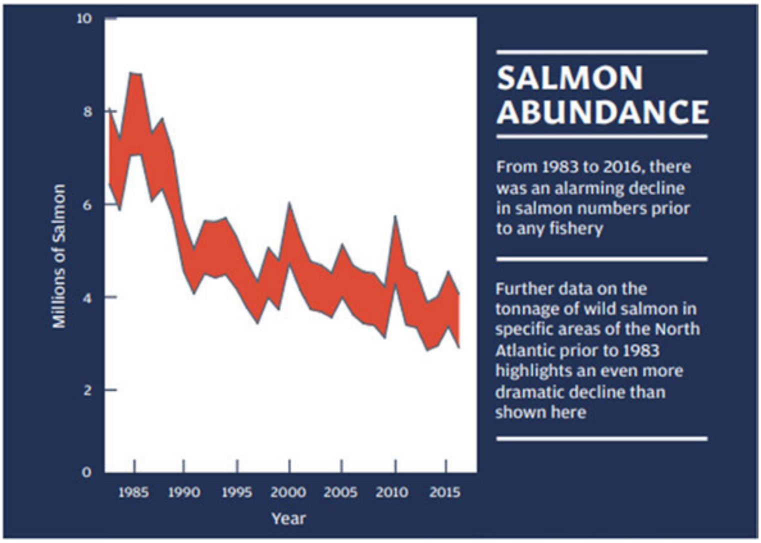

Fig. 1 Decline in salmon abundance, 1983–2016 (NASCO 2019)

Methodology and data collection

The research employs a qualitative, case-study approach. The cases were selected on the basis of two criteria: that the jurisdictions have a national salmon-farming industry and have native, wild salmon populations for which they have a stated responsibility to protect. These criteria excluded Chile, a large salmon producer with no wild salmons, and the Faroe Islands, a substantial producer but with no native wild salmons—only a small population of native trout. As for Canada, the Atlantic East Coast region was excluded due problems of access: aquaculture and sea-lice regulations are worked out on an individual basis through farm management plans by the province-level government. Such farm management plans are private, protected by corporate confidentiality agreements, which hindered efforts to assess their regulatory schemes for this study.

The research draws upon a range of written sources, including peer-reviewed literature, government reports and presentations, policy and legislative documents, and written correspondence and semi-structured interviews with a total of 23 key informants. Informants were selected from relevant government bodies (the main bodies responsible for regulating aquaculture, sea lice, and wild salmon), stakeholder organizations (NGOs or corporate organizations involved in sea-lice regulation), and research (scientists and researchers studying farm sea lice on wild salmon, either from government research or key monitoring bodies, public universities, or private research institutions). The aim was to find at least one informant from each of these sectors in each jurisdiction and to select informants who were deemed particularly resourceful, knowledgeable, and experienced in their region (see Kumar, Stern et al. 1993: 1634). In the case of Ireland, the wild salmon NGO declined the request for an interview due to its strong opposition to aquaculture (and thus any aquaculture-related research). However, this NGO provided information about its positions through written correspondence.

A snowball method was used to locate additional, highly knowledgeable persons by asking all interviewees to identify other relevant informants. The Aquaculture Stewardship Council's (ASC) Head of Standards played a facilitating role, helping to scope out, contact, and convince key informants to participate in interviews.

Interviews were conducted according to a semi-structured model, whereby the researcher prepares a set of prepared themes, issues, and questions to be covered during the interview but leaves space and time open to adjust the sequence and nature of the questions throughout (Kvale 1997, Rubin and Rubin 2005: 4). This enables the researcher to pursue relevant but unanticipated issues and information raised by informants (Kvale 1997: 72, Bauer 2000). The strategy resembles a conversational interview, in which data are gathered through a dynamic interplay and exchange of knowledge and information between informant and interviewer (Pawson 1996: 298, Kvale 1997: 29, Holstein and Gubrium 2002: 113).

All interviews were based on a common interview guide that was adjusted to the specific national or local circumstances of each case. Desk research was conducted prior to scripting the interview guides, to establish the context and an understanding of the historical and current regulations in each jurisdiction. Interviews covered the following topics: (i) politics (the positions of various actors and interests in public/political debates around salmon aquaculture, farm lice, and wild salmon protection and the focus and role of science in such debates); (ii) regulation (specific regulatory requirements and bodies, regulatory updates or lack thereof); (iii) research and stakeholders (the role of science and stakeholders in government decision-making toward reform, consensus, or controversy within government and with stakeholders); (iv) data transparency (farm reporting requirements, monitoring of wild salmon, publication of real-time data).

Interviews lasted between 45 and 90 min. All were transcribed and subjected to systematic analysis, where the content was organized according to key themes and coding words. Information provided by informants was supplemented and triangulated (see Denzin 1978, Miles and Huberman 1994) using documentary analysis, including reports, presentations, policy documents, and newspaper articles.

Due largely to the controversies surrounding views on aquaculture sea-lice regulation and wild salmon, most informants requested anonymity. Thus, the presentation of the research findings does not refer directly to individual statements made or information provided by informants during interviews or written correspondence. An anonymized list of the interview informants is provided in Table 1.

Sea-lice regulation and the role of science in salmon-farming countries

Norway

Norway has sought to reduce sea lice-induced health hazards and mortality risks for its wild salmon populations by setting increasingly strict limits as to on-farm sea lice. During the period of out-migration for juvenile wild salmons (weeks 16–21 in southern Norway; weeks 21–26 in Northern Norway), all holders of government permits to produce salmon in specific locations are required to keep lice levels below a maximum average of 0.2 adult female *L. salmonis* per fish on their farm sites. When this absolute limit was adopted in 2017, it represented a tightening of the previous requirement from 2012 to keep levels below 0.5.[1] The 0.2 limit was intended to be precautionary, but the decision-making process prior to its adoption was also partly anchored in research. The Institute for Marine Research (IMR)—a neutral knowledge-provider and advisor on farm and wild fish interactions associated with

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[1] The absolute sea-lice limits in the sensitive period replaced the previous requirement to conduct "spring delousing." Certain licenses have stricter sea-lice limits, such as "green licenses" (limits between 0.1 and 0.25), and for sites that were granted capacity increases in 2015, conditional on keeping sea-lice levels below 0.2

Table 1 Anonymized list of the informants

Informant	Organization	Position
1	Department of Fisheries and Oceans (DFO), Aquaculture Management Division, Canada	Regional manager
2	DFO, Aquaculture Management Division, Canada	Veterinarian
3	Maaqutusiis Hahoulthee Stewardship Society (MHSS), Ucluelet, BC (British Columbia), Canada	Stewardship Biologist
4	Dept. of Biology, Dalhousie University, Canada	Senior Researcher
5	Cedar Coast Field Station, BC, Canada	Executive Director and Director of Research
6	Living Oceans Society, West Vancouver, BC, Canada	Executive Director
7	Living Oceans Society, Canada	Sustainable Food Campaigner
8	Uu-a-thluk Fisheries, Nuu-chah-nulth Tribal Council, BC, Canada	Regional Fisheries Biologist
9	Mainstream Biological Consulting Inc., Campbell River, BC, Canada	Co-founder, researcher, RPBio. CPESC
10	West Coast Aquatic, Port Alberni, BC, Canada	Director of Development
11	Inland Fisheries Ireland, Dublin, Ireland	Fishery Biologist and Senior Research Officer
12	The Marine Institute, Galway, Ireland	FEAS Aquaculture Manager
13	Salmon Watch, Dublin, Ireland	Founder and Chair of the Board
14	The Food Safety Authority (FSA), Norway	Senior Advisor
15	Norske Lakseelver (association, Norwegian Salmon Rivers), Norway	Chief Advisor
16	The Veterinary Institute (VI), Norway	Veterinarian and Senior Researcher
17	Institute for Marine Research (IMR), Norway	Senior Researcher
18	Fisheries Management Scotland, Edinburgh, UK	CEO
19	Fisheries Management Scotland, Edinburgh, UK	Aquaculture Interactions Manager
20	Scottish Salmon Producers' Organization (SSPO), UK	Head of Standards
21	Ecology Action Center, Nova Scotia, Canada	Marine Conservation Officer
22	The Scottish Government, UK.	Head of Aquaculture Development
23	Fish Health Inspectorate (FHI), Marine Scotland Science, UK	Technical Manager

the Ministry of Trade, Industry, and Fisheries—ran models simulating the effects of different thresholds. However, setting the limit at 0.2 (and not 0.1) was also a decision based on farm data, where consideration was given to what was possible, given existing sampling/counting techniques, and without necessitating excessive delousing, to minimize welfare concerns.[2] The Food Safety Authority (FSA) is responsible for enforcing compliance with the limit.[3]

Since 2012, license-holders have been required to conduct weekly counts and file weekly reports to the FSA that include the average number of motile lice, mature female lice, and sedentary stages of *L. Salmonis* per fish in all production cages.[4] In addition, they must report the type of delousing measures used to keep levels below the set limits. The FSA publishes lice data close to real time and shares the data on a weekly basis with the industry and NGOs. Full public access is provided through two sites, lakselus.no and Barentswatch.no. Every week, the IMR, on behalf of the FSA, also compiles a sea lice and biomass report from each Norwegian production area (PA), which is shared with the industry.

Norway has adopted an area-based system for regulating aquaculture production volumes according to mortality risks for wild salmon. The Traffic Light System (TLS) from 2017 models mortality risk based on sea-lice infestation pressure within 13 delineated production areas, which are then attributed a red, yellow, or green “traffic light” based on their respective risk levels, on a biannual basis. In green areas, salmon producers are allowed to increase their biomass; in yellow areas, they are requested to maintain current production volumes; and in red areas, they are required to reduce their total salmon biomass.

Area-based, mortality risk levels are set by an expert group composed of scientists from the IMR, the Veterinary Institute (VI), and the Norwegian Institute of Nature Research (NINA).[5] These levels are based on a combination of hydrodynamic dispersion models, which predict the spread of lice larvae from production sites from reported lice levels, sea temperature, and water currents—as well as data from the national surveillance program for salmon lice on wild salmon (NALO), which are used to verify the models.[6] The conclusions of the expert group are considered by a steering group, who advise the Ministry on the final decision on traffic lights for each PA.[7] The TLS system is also linked to on-farm thresholds, as farmers within red PA may apply for an increase in site biomass if they can demonstrate compliance with the 0.1 limit.

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[2] Due to increasing resistance to therapeutants, farmers must rely primarily on mechanical delousing methods, which often cause increased farm-fish mortality. The FSA is currently considering how better to incorporate farm-fish welfare into the lice regulation.

[3] Until 2012, the government set a trigger level for treatment at 0.5 average mature female lice per fish. The maximum limit was established with the regulation on combating sea lice in aquaculture facilities, implemented in 2013, and amended in 2017/2018.

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[4] When water temperatures fall below 4 °C, reporting may be conducted every other week.

[5] The VI is a public-sector research institute that conducts monitoring and risk assessment related to fish health, associated with the Ministry of Agriculture and Food, and provides advice to the Ministry of Industry and Fisheries. NINA is an independent research institution that conducts research related to coastal marine environments.

[6] NALO is conducted by the IMR on behalf of the Norwegian Food Safety Authority. The aim of the program is to obtain robust data on salmon-lice infestation on wild salmonids in all production areas. Field surveys are conducted from late April till early August; quality assured data are published annually. See: https://www.hi.no/hi/nettrapporter?query=&fast_serie=overvaking-lakselus

[7] License-holders within a PA deemed to have an “acceptable” impact on wild salmon (“green light”) may buy a set percentage increase in production volume at a fixed price from the government (2% in 2018 and 1% in 2020). They may also participate in auctions where allowances to increase production volumes by up to 6% are sold, after added volumes bought at fixed price have been deducted. License-holders within a PA deemed to have a “moderate” impact (“yellow light”) are allowed to maintain current production volumes; license-holders within a PA deemed to have an “unacceptable” impact will be required to reduce production volumes by 6%.

This increasingly strict regulatory regime has been anchored in the growing scientific knowledge-base concerning the negative impact of sea lice on the health and survival of wild salmonids in Norway (see Skilbrei, Finstad et al. 2013, Svåsand, Boxaspen et al. 2015, Nilsen, Bjørn et al. 2016, Thorstad and Finstad 2018, Vollset, Dohoo et al. 2018). In 2011, the Norwegian Parliament acknowledged that sea lice from salmon farms could be a serious hazard to the country's wild salmonids, and that it constituted a potential threat their survival[8] (White Paper 1 S, chapter 4.1). This was reiterated by the Office of the Auditor General in its 2012 evaluation of Norwegian aquaculture, which concluded that current regulations were insufficient to combat the proliferation of sea lice, in view of the substantial growth and farm expansions. Thus, the growth of a scientific knowledge-base and related political concerns were they key drivers behind the adoption of more stringent sea-lice regulation. The emergence of a near-consensus between national research institutes and the government that farm sea lice may have hazardous, sub-lethal, and potentially lethal effects on wild salmonids also facilitated the institutionalization of researchers as regulators within the TLS.

Although industry actors have disputed the scientific justification for stricter regulation, an evaluation conducted by an independent expert committee has concluded that the regulatory system fails to communicate scientific uncertainties satisfactorily—in particular, regarding the modelled estimations of mortality thresholds (Revie, Eliasen et al. 2021)—there has been little major controversy around the evidence base for regulatory action. Research institutes, policymakers employed in the Ministry, and other bodies such as the FSA and the Fisheries Directorate, as well as the executive government, have largely agreed that sea lice represent a threat to wild populations, and thus on the need for scaling up regulatory actions.

Scotland

Scotland has set comparatively lenient thresholds for on-farm sea lice. Until recently, its sea-lice policy[9] was not designed to address interactions between farms and wild fish, but to protect the health of caged salmon. The scientific justification for on-farm thresholds did thus not relate to emerging data and evidence of farm-lice impacts on wild populations.

Scotland requires all license-holders to inform the Fish Health Inspectorate (FHI)—which is responsible for monitoring and enforcing the policy—upon exceeding an average of 2.0 adult female *L. salmonis* per fish. Reports of reaching the 2.0 "trigger limit" prompt increased FHI monitoring. When sea-lice levels reach or exceed an average of 6.0 adult females per fish, license-holders are required to meet the Scottish Salmon Producer Organization's voluntary Code of Good Practices (CoGP) criteria for the period of out-migration (February 1st to June 30th).[10] They must then bring levels down to 0.5 adult female *L. salmonis* per fish.

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[8] White Paper 1S, URL: Prop. 1 S (2010–2011) (regjeringen.no)

[9] The policy regime is anchored in the Aquaculture and Fisheries (Scotland) Act of 2007, in legislative requirements of The Fish Farming Businesses (Record Keeping) (Scotland) Order 2008, and more recently also in The Fish Farming Businesses (Reporting) (Scotland) Order 2020. Significant exceedance of thresholds set also requires farmers to follow the Scottish Salmon Producer Organization's voluntary Code of Good Practice (CoGP). See "The Regulation of Sea Lice in Scotland," Marine Scotland, 2021. URL: 71+The+Regulation+of+Sea+Lice+in+Scotland+2021.pdf (www.gov.scot)

[10] If the farm does bring levels down but not below the CoGP criteria, an advisory letter will be issued to alert of the breech; after 4 more weeks, if levels do not continue to reduce below 2.0, an enforcement notice will be issued. If the farm does not reduce below 6.0 within 4 weeks, a warning letter will be issued, and after two more weeks, an enforcement notice will follow.

These trigger levels have been updated once since their adoption in 2007. The notification threshold of 2.0 has remained unchanged, but the intervention limit was lowered from 8.0 to 6.0 in 2019. This was the result of public and political debate around the welfare of farmed fish, and not the potential hazards for wild populations.

Scotland's sea-lice reporting regime was recently tightened with the adoption of the new Fish Farming Businesses (Reporting) order—which requires mandatory reporting for *all* aquaculture-production businesses. After the order entered into force in 2021, sea-lice counts must be reported on a weekly basis, irrespective of the average levels per fish; if no count is conducted, a reason must be provided. Fish farmers must report the average number of adult female (gravid and non-gravid) *L. salmonis* counted per fish per site in the reporting week. The government publishes sea-lice data within 2 weeks of receiving the weekly reports.[11] Furthermore, all sea-lice data are made publicly available through the Scotland Aquaculture Website.[12]

Furthermore, an ongoing policy reform process has now been instigated to establish an area-based system for regulating sea-lice levels based on modelled infestation pressures in the wild. The scientific basis and justification for adopting this new regulatory scheme is the explicit acknowledgement of the need to address potentially hazardous impacts of farm sea lice on wild populations. The reform was triggered by two parliamentary inquiries by the Environment, Climate Change, and Land Reform Committee (ECCLR) and the Rural Economy and Connectivity (REC) committee in 2018, which led the government to make a political commitment to reforming the existing system. It established the Salmon Interactions Working Group (SIWG), which in April 2020 published 40 reform recommendations; in October 2021, the government issued its formal response to them. Meanwhile, the ruling Scottish National Party (SNP) pledged to thoroughly reform the regulatory framework for salmon aquaculture, with one government authority made responsible for managing farm–wild interactions.[13]

Although the final outcome of this process is still undetermined, responsibility for managing risks to wild salmonids from sea lice emitted from fish farms has been assigned to the Scottish Environmental Protection Agency (SEPA). SEPA also has responsibility for issuing licenses "to pollute" under the Water Environment Controlled Activities Regulations of 2011. These "CAR licenses" set the limits for levels of pollutants that fish farms may discharge to the water environment; although they currently cover the use of sea-lice therapeutants, they do not regulate sea lice or emissions of sea-lice larvae into the wild. SEPA was instructed to build on the work of the Regulators Technical Working Group and worked closely with scientists from Marine Scotland to develop the technical details of a proposal for "a spatially based risk-assessment framework for regulating the interaction between sea lice from marine finfish farms and wild Atlantic salmon." In 2022, SEPA consulted stakeholders on the proposal, and in 2023, it will consult on how the framework will operate in practice, before it is implemented through the CAR licensing regime.[14]

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[11] Fish Health Inspectorate: sea lice information-gov.scot (www.gov.scot)

[12] Scotland's Aquaculture|Home

[13] To this end, the SNP commissioned an independent review of the Scottish regulatory framework for aquaculture. A report with recommendations was published in Feb. 2022. See: URL: A Consenting and Framework System for the Future-Aquaculture regulatory process: review-gov.scot (www.gov.scot)

[14] See: Proposals for a risk-based framework for managing interaction between sea lice from marine finfish farm developments and wild Atlantic salmon in Scotland - Scottish Environment Protection Agency-Citizen Space (sepa.org.uk)

There have been fewer scientific studies of interactions between wild fish and farms in Scotland than in Norway and Ireland. However, the scientific knowledge-base relevant to assessing risks for Scottish wild salmonids has grown in recent decades (Butler 2002, Butler and Watt 2003, McKibben and Hay 2004, Middlemas, Fryer et al. 2013, Susdorf, Salama et al. 2018).[15] As in Norway, a near-consensus among research institutes, politicians, and policymakers around the science of wild-farm interactions and the conclusion that sea lice represent a hazard and potential threat to wild populations have enabled political commitment to reform. Government bodies have also increasingly turned to the scientific knowledge-base to justify reform. For instance, Marine Scotland has conducted regular literature reviews, which resulted in the 2021 publication of a Summary of the Science. This has been publicly referred to by the government as the basis for its official acknowledgement of the need to reform the Scottish regime to deal effectively with hazards to wild salmonids.[16]

Ireland

As in Norway, the objective of Ireland's on-farm sea-lice threshold is to mitigate potential health hazards and mortality risks for wild salmonids. Its sea-lice policy has since 2008 required license-holders to instigate treatment or management action to reduce sea-lice levels on salmon farms when these reach or exceed an average level of 0.5 ovigerous (egg-bearing) *L. salmonis* per fish in the period of out-migration (March 1 to May 31). This requirement was added to an existing year-round trigger level for treatment set at an average of 2.0 lice per fish. The adoption of a 0.5 "trigger limit" was the result of processes instigated by the government, which had requested an examination and review of the existing system for sea-lice control in marine finfish farms. However, the commissioned "Sea Lice Monitoring and Control Working Group" (with representatives from the Department of Communications, Marine and Natural Resources, the Marine Institute, the Fisheries Boards, and the Irish Seafood Federation) was unable to reach consensus on recommendations for moving forward. The responsibility for aquaculture licensing was then transferred to the Department of Agriculture, Fisheries, and Food (now AFM). In 2008, they developed a pest-control strategy and worked closely with the Marine Institute (MI) on updating the treatment trigger level in the out-migration period. The 0.5 trigger level for treatment was intended to be precautionary, to ensure mitigation of potentially negative effects of farm sea lice. However, setting the level at 0.5 was also a pragmatic decision anchored in farm data, taking into consideration what was achievable. There was no scientific evidence-base or analysis conducted to justify the threshold level.[17]

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[15] See: Impacts of lice from fish farms on wild Scottish sea trout and salmon: summary of science-gov.scot (www.gov.scot)

[16] Impacts of lice from fish farms on wild Scottish sea trout and salmon: summary of science-gov.scot (www.gov.scot)

[17] License conditions are anchored in the Fisheries (Amendment) Act of 1997. Additionally, several associated regulations have been amended to give effect to various EU Environmental "Protection Directives." See gov.ie-Aquaculture & Foreshore Management (www.gov.ie)

Single Bay Management also facilitates coordinated lice management, with synergistical stocking, fallowing, and treatment regimes for neighboring farms. See https://www.marine.ie/Home/site-area/areas-activity/aquaculture/sea-lice/single-bay-management

Independent inspectors from the Marine Institute (MI) are responsible for monitoring and enforcing the treatment threshold. Bi-weekly sampling is conducted in the sensitive period; for the rest of the year, sampling is conducted on a monthly basis. The MI compiles monthly reports of farm sea-lice levels, which include counts of the average level of ovigerous and mobile *L. salmonis* and *Caligus elongatus* per fish.[18] These reports are shared with the Department of Agriculture, Food and the Marine, and a range of other stakeholders, including the IFI and the regional fisheries board. However, live, real-time data are not publicly available. The results are reported back to farms within 5 days of inspection; if a fish farm is found to exceed the 0.5 threshold, MI will aim to report back to the farm as soon as possible.

The sea-lice threshold has not been revised since 2008, although a reform was considered in 2016, when the Department of Agriculture, Fisheries, and the Marine requested a review of the aquaculture licensing process.[19] That led to discussions between the Department and the Marine Institute (MI); however, according to the latter, there is no new scientific evidence on optimal sea-lice thresholds; whether the threshold requires an update would be a political decision.

The lack of reform thus relates to the MI's position that the current threshold is adequately precautionary, and the ongoing scientific controversy between actors within and outside the Irish government concerning the basis for scientific evidence and the scale of farm-lice impacts. Various governmental bodies, as well as scientists studying farm–wild interactions, do not agree on how and the extent to which farm sea lice have population-level effects. MI scientists are the main knowledge providers and advisors on aquaculture to the Department; they have developed a substantial body of research,[20] concluding that farm lice represent only a small and irregular component of the marine mortality of wild populations (Jackson, Cotter et al. 2011, Jackson, Cotter et al. 2013a, Jackson, Kane et al. 2013b). On the other hand, scientists at the Inland Fisheries Ireland (IFI), responsible for protecting wild salmons and working under the Department of Environment, Climate, and Communications, conclude otherwise. They have found that sea lice-induced mortality affects Atlantic salmon returns, and that farm lice represent a serious hazard for sea-trout populations (Gargan, Forde et al. 2012, Shepard and Gargan 2017, Shepard and Gargan 2021). Moreover, the results of studies conducted by MI scientists have been disputed by independent researchers not associated with IFI (Krkosek, Revie et al. 2013).

Similarly, wild salmon stakeholders see the Irish regulation as unsuccessful in mitigating the effects of farm sea lice on wild salmonid survival. They hold that this has led to extinction of sea trout as well as significant reductions in wild salmon populations in fish-farming areas.

Moreover, there is disagreement on the need for stricter regulation: while the MI holds that no new research or analysis on optimal sea-lice thresholds has indicated the need for regulatory change, the IFI argues that the current 0.5 trigger level leads to inadequate protection of wild salmonids, and that Ireland must set stricter on-farm thresholds to ensure that sea-lice levels are closer to zero in the period of out-migration. They also argue for absolute enforcement limits for both mobile *L. salmonis* and *Caligus elongatus* and want a "total bay cap" setting a total lice load limit in aquaculture bays during spring migration. However, as the IFI has neither a formal nor informal role as advisor to the Department of Agriculture Food and the Marine, its suggestions have not been taken into consideration.

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[18] *Irish Fisheries Bulletin*, No. 52, 2020: 125853 Marine Institute Irish Fisheries Bulletin 52.indd

[19] See: http://www.fishingnet.ie/media/fishingnet/content/ReviewoftheAquacultureLicensingProcess310517 pdf

[20] See Sea Lice|Marine Institute

Thus, the lack of regulatory reform since 2008 appears to be anchored in the circumstance whereby a scientific knowledge-base represents only side of the debate.

Canada, British Columbia

The federal government in Canada, which is responsible for both the protection of wild salmonids and for managing salmon aquaculture in British Columbia (BC), has also set on-farm sea-lice thresholds to mitigate risks for wild populations. Licensing conditions require salmon farmers to undertake delousing actions when on-farm sea-lice levels reach or exceed an average of 3.0 *motile L. salmonis* per fish (equals about 0.64–1.65 adult females)[21] in the period of out-migration (March 1 to June 30). Although a literature review was conducted prior to setting the 3.0 threshold, the figure arrived at was not based on research or BC-specific knowledge, but was a "best guess" of what might be precautionary at the time.

In 2020, the regulation was updated to strengthen the enforceability of the 3.0 threshold. Since then, farmers have been required to bring lice levels below 3.0 within 42 days of having exceeded the threshold. They must also notify the authorities about planned delousing measures in the pre-migration period (February 1 to 28/29), to ensure that they will be under the threshold by the first day of out-migration. The conditions apply to farmers of Atlantic and Pacific salmon (chinook and coho) and are monitored and enforced by the Department of Fisheries and Oceans (DFO).[22] These revisions were triggered by heightened political attention to sea lice-induced hazards for wild salmon in 2018, after reports of a sea-lice outbreak in Clayoquot Sound on the west coast of Vancouver Island following the emergence of resistance to SLICE (a treatment for all parasitic stages of sea lice) and the lack of alternative chemotherapeutics or mechanical delousing equipment.[23] After independent biologists and wild-salmon NGOs had alerted the media, bringing the issue to the DFO Minister's attention, the aquaculture management division was asked to update the conditions of licensing to improve the enforceability of the threshold.

Atlantic salmon farms are required to conduct bi-weekly sampling in the pre-migration and out-migration windows and to report the average level of motile, chalimus-stage, and adult female *L. salmonis*, as well as the average level of adult and preadult *Caligus clemensi* per fish. For the rest of the year, license-holders are to report monthly. For Pacific salmon farmers, quarterly sampling is required. The DFO publishes an Industry Sea Lice Abundance Counts report (per farm), updated on a monthly basis.[24] However, there is a significant time-lag between reporting and publication. Although they must perform bi-weekly counting, license-holders are required to submit the counts to the DFO only on a monthly basis. The DFO receives the reports on the 15th of the following month, upon which they conduct a quality control, including a comparison of data with DFO-performed audits, which may take between 2 and 4 weeks. In practice, however, the reviews of reports are often bundled together quarterly, so there is a significant time-lag of up to several months in data publication.

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[21] Motile includes adult *L. salmonis* females (with or without egg strings) and other motile *L. salmonis* (including adult males and preadults). "Mobile" is considered a synonym of "motile."

[22] The DFO is responsible for both the protection of wild salmonids and the management of salmon aquaculture in British Columbia. The responsibility for aquaculture was transferred from the province level to the federal government in 2010, after a federal court case challenged the authority of the provincial government to be the lead regulator of salmon aquaculture in 2008.

[23] See, for example Sea lice outbreak threatens Clayoquot salmon–Today In BC

[24] https://open.canada.ca/data/en/dataset/3cafbe89-c98b-4b44-88f1-594e8d28838d

The lack of a substantial tightening of the 3.0 threshold also appears associated with an ongoing controversy around the science of farm–wild interactions. There are opposing views among researchers working within the DFO science branch, and some DFO studies show that the physiological impact of *L. salmonis* on Pacific salmon species, particularly sockeye salmon, may be greater than for Atlantic salmon (Long, Garver et al. 2019). However, most DFO scientists argue that the risks to wild populations have been exaggerated (e.g. Brooks and Jones 2008). The views of in-house scientists reflect the position of the DFO aquaculture management, who argue that farm sea lice do not represent a significant threat to the abundance and population productivity of wild salmonids.[25] Thus, continuation of the 3.0 threshold is anchored in a belief shared by many DFO researchers and policymakers that the threshold remains precautionary in nature and that the population-level effects of farm sea lice are low to negligible.

However, a substantial body of research developed by independent scientists concludes otherwise, stressing the importance of sub-lethal and indirect effects of farm lice on the health of wild populations (Mages and Dill 2010, Godwin, Dill et al. 2017). These have also demonstrated the existence of significant population-level impacts, albeit through correlational studies (Krkosek, Connors et al. 2011, Connors, Braun et al. 2012). However, non-DFO scientists do not have a formal advisory role as do their in-house scientists and have historically not influenced the regulatory decision-making.

When sea-lice conditions were up for renewal in 2022, the DFO was considering arguments for stricter and more extensive regulation advocated by the independent research community and wild salmon stakeholders.[26] These have long argued that lice levels should not be allowed to remain above 3.0 for as long as 6 weeks, resulting in volatile levels in the period of out-migration.[27] Second, they have argued for setting thresholds related to the total lice load of a farm or farming area. As the size and thus biomass of many farms has grown over time, so has the abundance of sea lice—irrespective of the license-holders' ability to keep average levels per fish below 3.0. Thirdly, they have pressed for the adoption of a management system for farms based on monitoring of salmonids and sea-lice levels in the wild. However, the DFO has remained skeptical to area-based regulation of farms on the basis of wild salmonid monitoring or modeling of risks based on sea-lice infestation levels.

Regulatory differences and how science shaped policy (in)action to enhance protection of wild salmons

This study finds substantial variations in the national regulatory regimes governing on-farm sea-lice levels in periods of wild salmonid out-migration, as well as efforts towards adopting area-based regulation of total lice loads in production areas based on sea-lice infestation levels in the wild and the estimated mortality risks for wild salmons.

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[25] One example is the DFO's response to Recommendation 19 of the 2012 Cohen Commission, on the impact of pathogens from Atlantic salmon farms on the health of Fraser River (BC) sockeye salmon. After completing nine risk assessments, the DFO concluded that pathogens, including sea lice, posed at most a minimal risk to the abundance and diversity of Fraser River sockeye salmon under current regulatory practices. See Response to Cohen Commission (dfo-mpo.gc.ca)

[26] Under the National Fisheries Act, the DFO may issue multi-year licenses of up to 9 years; in practice, however, salmon aquaculture licenses are issued for 6 years at a time. In line with the principle of adaptive management, the DFO considers a reassessment of license conditions upon renewal.

[27] The 42 days was originally based on an estimate of how much time was needed for therapeutants such as SLICE or other delousing measures to be effective. However, the DFO is considering whether this can be shortened based on data of treatment time using other delousing technologies.

Scotland has historically not designed its sea-lice regulations for the purpose of mitigating impacts of farm lice on wild populations: until recently, the aim has been to protect farmed-fish welfare. This explains the use of a higher trigger level for treatment for adult females compared to the other countries. In Norway, Ireland, and Canada (British Columbia), on the other hand, on-farm sea-lice thresholds have been adopted for the stated purpose of minimizing potential hazards to wild salmonids. Norway enforces the most stringent, absolute sea-lice limit of 0.2 mature female lice per fish. Ireland does not regulate so strictly, setting a trigger level for treatment at 0.5 ovigerous lice per fish, and Canada (BC) sets a trigger level for delousing actions at 3.0 motile lice per fish (equaling ca. 0.64–1.65 adult females).[28]

As regards sea-lice reporting requirements, these countries differ considerably with respect to data-sharing arrangements and the timing of publication. In Scotland, sea-lice data are published no later than 2 weeks after recording. In Norway, the data are published close to real time; in addition, the government arranges regular industry data-sharing through meetings and report distribution. In Ireland and Canada, sea-lice reports are shared with industry and stakeholders, but the considerable time-lags in publication give rise to concerns about real-time data transparency.

Norway stands out as the only country that has implemented area-based sea-lice regulation. However, Scotland is moving in the same direction, seeking to reform its salmon farming regime thoroughly, and adopting a spatially based, risk-assessment framework. This appears to be partly influenced by Norway's red/yellow/green "traffic light" system. While there is strong political commitment to reform in Scotland, uncertainties remain as to how on-farm lice thresholds will be updated.

However, an in-depth comparative evaluation of the different sea-lice limits and trigger-level thresholds with the aim of assessing their robustness or effectiveness in protecting the health of wild salmonids is beyond the scope of this assessment (Table 2). The various threshold levels are not directly comparable, as the jurisdictions have varying ecological and biological conditions, different wild salmonid species, lice species and sub-species, as well as highly varying aquaculture production outputs and farm-area densities. For instance, Norway has set the strictest absolute thresholds but is also the by far largest producer of farmed salmon. Ireland's trigger levels are less stringent, but Ireland has a comparatively small-scale fish-farming industry. Canada's BC threshold is set to protect wild populations of Pacific salmon, which are genetically distinct from Atlantic salmon.

A comparative analysis of sea-lice regulation in these jurisdictions shows that two countries have revised or are in the process of revising their sea-lice regulations with the aim of enhancing wild salmon protection: Norway has adopted strict on-farm limits and a new, area-based management system, and Scotland is in the process of adopting a similar system. A near-consensus around the scientific knowledge-base of farm–wild interactions has also emerged. Although many aquaculture industry actors have disputed the need for stricter sea-lice management, most scientists, national research institutes, politicians, and policymaking bodies have acknowledged and largely agreed that sea lice from salmon-farm lice represent a major health hazard and potentially threat to the reproductivity of wild salmonids. The absence of pronounced conflict around scientific uncertainties appears to have enabled political efforts to adopt stricter regulation to mitigate the risks for wild salmon populations.

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[28] Aquaculture Management Division, DFO. "Technical report: Sea lice threshold equivalency assessment for policy change."

Ireland and B.C. Canada have not conducted substantial regulatory revisions in response to calls for improving wild salmon protection, and in these jurisdictions, there has also been pronounced political controversy around the science of farm-wild fish interactions. Indeed, the deviating positions of the various national research institutes and independent scientists on both the sub-lethal and the population-level effects of farm sea lice appear to have limited the scope for regulatory reform. In both countries, the governmental departments responsible for aquaculture management have relied largely on research, analysis, and advice from scientists who represent only one side of the scientific debate, leading them to conclude that population-level effects are small to negligible. Other research institutes or scientists have concluded differently and stressed the need to incorporate sub-lethal effects of lice on salmonids to a greater extent. However, this research has not had a significant impact on government decision-making. This is most clearly seen in Ireland, where sea-lice regulations have not been updated since 2008, despite considerable pressure from wild salmonid knowledge providers. Thus, a lack of consensus around the science involved appears to have hindered political agreement on the need for regulatory change.

Conclusions

This study has conducted a comparative evaluation of aquaculture sea-lice regulations in major salmon-farming countries with wild salmon populations they are tasked to protect. This includes an assessment of their on-farm limits/thresholds, systems for data monitoring and reporting, and area-based management. The aim has been to establish how and the extent to which the jurisdictions have implemented regulatory reforms to meet growing concerns that protection of the health and survival of their wild salmon populations has been inadequate.

Norway has the by far most stringent and extensive regime for sea-lice management, combining strict absolute on-farm limits and reporting with area-based regulation. Scotland is headed in this direction, having embarked on a thorough reform toward area-based sea-lice management. The regulatory reforms of these jurisdictions, involving significant updates towards more precautionary measures to protect wild salmonids, have been made possible by the emergence of consensus around the science of farm–wild interactions. In contrast, Ireland and Canada's British Columbia have not seriously considered or embarked on any substantial policy reforms. The lack of significant regulatory updates in these jurisdictions appears related to the persistence of controversy

Table 2 Comparison of regulatory regimes for aquaculture sea lice

	Stringency	Scope	Purpose and scientific understanding
Norway	Maximum limit: 0,2 adult female	On-farm and area-based (AB) regulation	Protect wild salmon *Consensus*
Scotland	Trigger limit: 2.0 adult female	On-farm and AB reform	Protect wild salmon *Consensus*
Ireland	Trigger limit: 0.5 ovigerous female	On-farm	Protect wild salmon *Disagreement*
Canada (West Coast)	Trigger limit: 3.0 motile	On-farm	Protect wild salmon *Disagreement*

around the knowledge-basis for reform. Here, scientists and policymakers still disagree on the extent of the impact of farm sea lice on wild populations, which has hindered reformist forces and led to a lack of political commitment.

This illustrates a more general phenomenon related to "wicked" policy problems (Rittel and Webber 1973): that uncertainties related to available data and knowledge become a political battleground between actors with competing policy preferences (Sarewitz 2004, Van Enst, Driessen et al. 2014). It suggests that the emergence of consensus between key actors around the knowledge-base for regulatory change may serve to facilitate reforms to deal with wicked policy problems such as aquaculture sea lice. Conversely, when scientific disparity and political conflict exist or persist, reform may be difficult. Thus, broader consensus around the science of farm–wild interactions may be an important prerequisite for the adoption of more precautionary policies for mitigating risks to wild salmon populations.

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Data availability The primary data, which consists of transcribed interviews with informants, cannot be made publicly available due to anonymity and ethical concerns. However, the records can be made available on request.

Declarations

Ethical approval All interviewees have consented to participating and being named as informants in the published study.

Competing interests The author declares no competing interests.

References

Bauer MW (2000) In: Bauer MW, Gaskell G (eds) Individual and group interviewing. Qualitative researching with text, image and sound. Sage Pulications, London

Brooks KM, Jones SRM (2008) Perspectives on pink salmon and sea lice: scientific evidence fails to support the extinction hypothesis. Rev Fish Sci 16(4):403–412

Butler JRA (2002) Wild salmonids and sea louse infestations on the West Coast of Scotland: sources of infection and implications for the management of marine salmon farms. Pest Manag Sci 58:595–608

Butler JRA, Watt J (2003) Assessing and managing the impacts of marine salmon farms on wild atlantic salmon in western Scotland: identifying priority rivers for conservation. Salmon at the Edge:93–118

Chaput G (2012) Overview of the status of Atlantic salmon (Salmo salar) in the North Atlantic and trends in marine mortality. ICES J Mar Sci 69(9):1538–1548

Connors BM, Braun DC, Peterman AB, Cooper JD, Reynolds JD, Dill LM, Ruggerone GT, Krkosek M (2012) Migration links ocean-scale competition and local ocean conditions with exposure to farmed salmon to shape wild salmon dynamics. Conserv Biol 5(4):304–312

Costello MJ (2009) How sea lice from salmon farms may cause wild salmonid declines in Europe and North America and be a threat to fishes elsewhere. Proc R Soc B 276:3385–3394

Denzin NK (1978) The Research Act. Aldine, Chicago

Friedland KD, MacLean JC, Hansen LP, Peyronnet AJ, Karlsson L, Reddin DG, Maoiléidigh NÓ, McCarthy JL (2009) The recruitment of Atlantic salmon in Europe. National Marine Fisheries Service, US Government

Friedland KD, Reddin DG, Kocik JF (1993) Marine survival of North American and European Atlantic salmon: effects of growth and environment. ICES J Mar Sci 50:481–492

Friedland KD, Shank BV, Todd CD, McGinnity P, Nye JA (2014) Differential response of continental stock complexes of Atlantic salmon (Salmo salar) to the Atlantic Multidecadal Oscillation. J Mar Syst 133:77–87

Gargan PG, Forde G, Hazon N, Russell DJF, Todd CD (2012) Evidence for sea lice-induced marine mortality of Atlantic salmon (Salmo salar) in western Ireland from experimental releases of ranched smolts treated with emamectin benzoate. Can J Fish Aquat Sci 69:343–353

Godwin SC, Dill LM, Krkosek M, Price MHH, Reynolds JD (2017) Reduced growth in wild juvenile sockeye salmon Oncorhynchus nerka infected with sea lice. J Fish Biol 91(41-57):41–57

Hilborn R (2006) Salmon-farming impacts on wild salmon. Proc Natl Acad Sci 103(42):15277

Holstein JA, Gubrium JF (2002) In: Wienberg D (ed) Active interviewing qualitative research methods. Blackwell Publishers, Malden, Massachusetts

Hoppe R (2005) Rethinking the science-policy nexus: from knowledge utilization and science technology studies to types of boundary arrangements. Poiesis & praxis 3:199–215

ICES (2016) Advice on fishing opportunities, catch and effort: North Atalntic Salmon Stocks. In: Report on the ICES Advisory Committee to the NASCO., 10th edn

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

Jackson D, Cotter D, ÓMaoiléidigh N, O'Donohoe P, White J, Kane F, Kelly S, McDermott T, McEvoy S, Drumm A, Cullen A (2011) An evaluation of the impact of early infestation with the salmon louse Lepeophtheirus salmonis on the subsequent survival of outwardly migrating Atlantic salmon, Salmo salar L., smolts. Aquaculture 320:159–163

Jackson D, Kane F, O'Donohoe P, Mc Dermott T, Kelly S, Drumm A, Newell J (2013b) Sea lice levels on wild Atlantic salmon, Salmo salar L., returning to the coast of Ireland. J Fish Dis 36:293–298

Johnsen IA, Harvey A, Sævik PN, Sandvik AD, Ugedal O, Ådlandsvik B, Wennevik V, Glover KA, Karlsen Ø (2021) Salmon lice-induced mortality of Atlantic salmon during post-smolt migration in Norway. ICES J Mar Sci 78:142–154

Jonsson B, Jonsson N (2004) Factors affecting marine production of Atlantic salmon (Salmo salar). Can J Fish Aquat Sci 61:2369–2383

Kellogg KA (1999) Salmon on the edge. Trends Ecol Evol 14(1):45–46

Krkosek M, Connors BM, Morton A, Lewis MA, Dill LM, Hilborn R (2011) Effects of parasites from salmon farms on productivity of wild salmon. Proc Natl Acad Sci 108(35):14700–14704

Krkosek M, Revie CW, Finstad B, Todd CD (2013) Comment on Jackson et al. 'Impact of Lepeophtheirus salmonis infestations on migrating Atlantic salmon, Salmo salar L., smolts at eight locations in Ireland with an analysis of lice-induced marine mortality'. J Fish Dis 37(4):415–417

Kumar N, Stern LW, Anderson JC (1993) Conducting interorganizational research using key informants. Acad Manage J 36(6):1633–1651

Kvale S (1997) Det kvalitative forskningsintervju. Gyldendal Norsk Forlag, Oslo

Lackey RT (2007) Science, Scientists, and Policy Advocacy. Conserv Biol 21(1):12

Long A, Garver KA, Jones SRM (2019) Differential effects of adult salmon lice Lepeophtheirus Salmonis on Physiological responses of sockeye salmon and Atlantic salmon. J Aquat Anim Health 31:75–87

Mages P, Dill LM (2010) The effect of sea lice (Lepeophtheirus salmonis) on juvenile pink salmon (Oncorhynchus gorbuscha) swimming endurance. Can J Fish Aquat Sci 67(12):2045–2051

Marty GD, Saksida SM, Quinn TJ (2010) Relationship of farm salmon, sea lice, and wild salmon populations. Proc Natl Acad Sci 107(52):22599–22604

McKibben MA, Hay DW (2004) Distributions of planktonic sea lice larvae Lepeophtheirus Salmonis in the inter-tidal zone in Loch Torridon, western Scotland in relation to salmon farm production cycles. Aquacult Res 35:742–750

Middlemas SJ, Fryer RJ, Tulett D, Armstrong JD (2013) Relationship between sea lice levels on sea trout and fish farm activity in western Scotland. Fish Manag Ecol 20:68–74

Miles MB, Huberman AM (1994) Qualitative data analysis. Sage Publications, London

NASCO (2019) State of North Atlantic Salmon. NASCO, Edinburgh

Nilsen R, Bjørn PA, Serra-Llinares RM, Asplin L, Sandvik AD, Johnsen IA, Karlsen Ø (2016) Lakselus-infesksjonen på vill laksefisk langs norskekysten i 2015. Havforskningen.

Noakes DJ, Beamish RJ, Kent ML (2000) On the decline of Pacific salmon and speculative links to salmon farming in British Columbia. Aquaculture 183:363–386

Osmundsen TC, Almklow P, Tveterås R (2017) Fish farmers and regulators coping with the wickedness of aquaculture. Aquac Econ Manag 21(1):163–183

Otero J, Jensen AJ, L'Abée-Lund JH, Stenseth NC, Storvik GO, Vøllestad LA (2011) Quantifying the ocean, freshwater and human effects on year-to-year variability of one-sea-winter atlantic salmon angled in multiple Norwegian rivers. PLoS 6(8):e24005

Parrish DL, Behnke RJ, Gephard SR, McCormick SD, Reeves GH (1998) Why aren't there more Atlantic salmon (Salmo salar)? Can J Fish Aquat Sci 55(Suppl. 1):281–287

Pawson R (1996) Theorizing the interview. Br J Sociol 47(2):295–314

Revie C, Eliasen K, Jackson D, Koed A, Swanson HA, Turnbull J, Vanhatalo J, Visser A (2021) An evaluation of the scientific basis of the traffic light system for Norwegian salmonid aquaculture. Research Council of Norway (RCN), Lysaker, Norway

Rittel HW, Webber MM (1973) Dilemmas in a General Theory of Planning. Pol Sci 4(2):155–169

Rubin HJ, Rubin IS (2005) Qualitative interviewing: the art of hearing data. Sage Publications, Inc, Thousand Oaks

Sarewitz D (2004) How science makes environmental controveries worse. Environ Sci Policy 7:385–403

Shepard S, Gargan PG (2017) Quantifying the contribution of sea lice from aquaculture to declining annual returns in a wild Atlantic salmon population. Aquac Environ Interact 9:181–192

Shepard S, Gargan PG (2021) Wild Atlantic salmon exposed to sea lice from aquaculture show reduced marine survival and modified response to ocean climate. ICES J Mar Sci 78(1):368–376

Skilbrei OT, Finstad B, Urdal K, Bakke G, Kroglund F, Strand R (2013) Impact of early salmon louse, Lepeophtheirus salmonis, infestation and differences in survival and marine growth of sea-ranched Atlantic salmon, Salmo salar L., smolts 1997–2009. J Fish Dis 36:249–260

Stige LC, Helgesen KO, Viljugrein H, Qviller L (2022) Modelling salmon lice-induced mortality of wild salmon post-smolts is highly sensitive to calibration data. Aquac Environ Interact 14:263–277

Susdorf R, Salama NGK, Lusseau D (2018) Influence of body condition on the population dynamics of Atlantic salmon with consideration of the potential impact of sea lice. J Fish Dis 41:941–951

Svåsand, T., K. K. Boxaspen, Ø. Karlsen, B. O. Kvamme, L. H. Stien and G. L. Taranger (2015). Risikovurdering norsk fiskeoppdrett.

Thorstad EB, Finstad B (2018) Impacts of salmon lice emanating from salmon farms on wild Atlantic salmon and sea trout. 1-22. Report 1449. NINA, Trondheim, Norway

Torrissen O, Jones S, Asche F, Guttormsen A, Skilbrei OT, Nilsen F, Horsberg TE, Jackson D (2013) Salmon lice–impact on wild salmonids and salmon aquaculture. J Fish Dis 36:171–194

Van Enst WI, Driessen PPJ, Runhaar HAC (2014) Towards productive science-policy interfaces: a research agenda. JEAPM 16(1):1450007

Vollset KW, Dohoo I, Karlsen Ø, Halttunen E, Kvamme BO, Finstad B, Wennevik V, Diserud OH, Bateman A, Friedland KD, Mahlum S, Jørgensen C, Quiller L, Krkosek M, Åtland Å, Baralaup BT (2018) Disentangling the role of sea lice on the marine survival of Atlantic salmon. ICES J Mar Sci 75(1):50–60

Vollset KW, Krontveit RI, Jansen PA, Finstad B, Torgeir BB, Skilbrei OT, Krkôsek M, Romunstad P, Aunsmo A, Jensen AJ, Dohoo I (2015) Impacts of parasites on marine survival of Atlantic salmon: a meta-analysis. Fish Fish 17(3):714–730