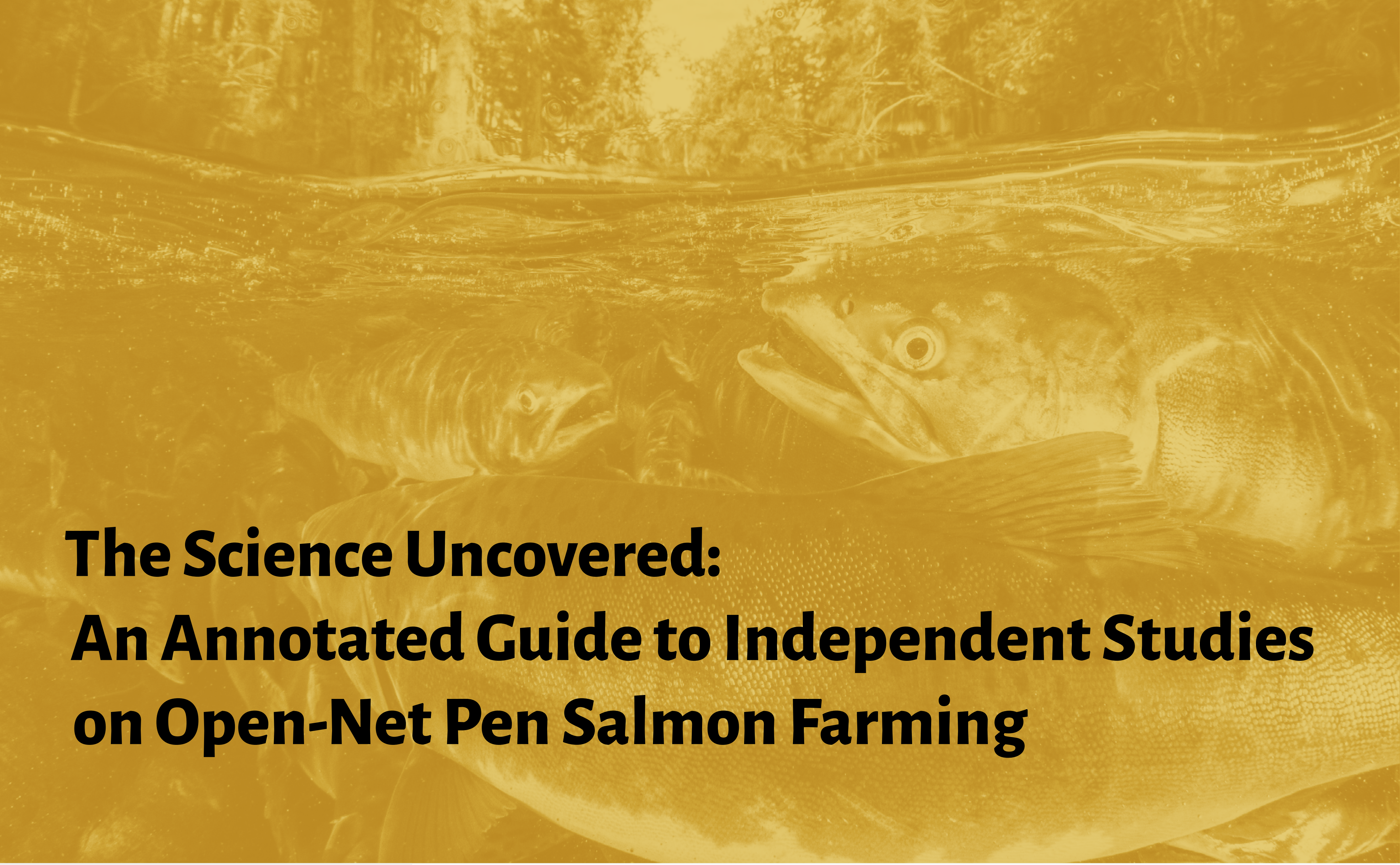

The Science Uncovered: An Annotated Guide to Independent Studies on Open-Net Pen Salmon Farming

PACIFIC WILD

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Note to the reader:

This annotated resource list was developed through a combination of file and literature reviews. It presents a curated collection of research articles, records, and resources focused on the risks that open-net salmon farming poses to wild Pacific salmon populations. Its primary focus is the transmission of diseases and parasites from farmed fish to wild stocks. While this compilation is not an exhaustive exploration of all topics related to Pacific salmon—acknowledging financial and other constraints—it serves as a substantial foundation. This document is intended as a starting point that can be refined and expanded over time.

Contents

1 Disease

1.1 Distribution of Infectious Agents

1.1.1 Intrinsic and extrinsic factors associated with the spatio-temporal distribution of infectious agents in early marine Chinook and coho salmon

Bass, A., Anderson, S. C., Bateman, A. W., Connors, B. M., Peña, M. A., Li, S., Kaukinen, K., Patterson, D., Hinch, S., & Miller, K. (2024). Intrinsic and extrinsic factors associated with the spatio-temporal distribution of infectious agents in early marine Chinook and coho salmon. *Marine Ecology Progress Series*, 736, 107-127. https://doi.org/10.3354/meps14581.

In this study, Bass et al. (2024) investigate how various intrinsic (internal) and extrinsic (external) factors influence the distribution of infectious agents in Chinook *(Oncorhynchus tshawytscha)* and coho salmon *(Oncorhynchus kisutch)* along the British Columbia (B.C.) coast during their early marine phase when they are at one of their most vulnerable life stages. The study found that proximity to open-net pen salmon farms was associated with higher pathogen loads in both Chinook and coho salmon. This suggests that the farms are a significant source of infectious agents. Evidence indicates that pathogens from farmed salmon could spill over to wild salmon populations. This spillover effect contributes to the spread and increased prevalence of infectious agents in areas near salmon farms. Open-net pen farms are identified as key extrinsic factors influencing the spatio-temporal distribution of pathogens. The farms create localized environments where pathogens can thrive and spread more easily, impacting surrounding wild salmon populations. The interaction between farmed and wild salmon populations highlights species-specific differences in susceptibility to certain pathogens, with some pathogens being more prevalent in farmed salmon and then affecting nearby wild salmon populations. These results contribute to existing evidence assessing the risk of infectious agent transmission from net pen aquaculture to free-ranging salmon and emphasize the importance of considering the role of open-net pen salmon farms in managing the health of both farmed and wild salmon populations.

1.1.2 Environmental DNA dispersal from Atlantic salmon farms

Shea, D., Frazer, N., Wadhawan, K., Bateman, A., Li, S., Miller, K., Short, S., & Krkošek, M. (2022). Environmental DNA dispersal from Atlantic salmon farms. *Canadian Journal of Fisheries and Aquatic Sciences*, 79,1377–1388. https://doi.org/10.1139/cjfas-2021-0216.

Shea et al. (2022) aimed to understand how environmental DNA (eDNA) from Atlantic salmon farms is distributed in the surrounding environment and the factors influencing its spread. The authors observed Atlantic salmon eDNA within 5 km from the nearest salmon farm with the most detectable eDNA being concentrated within 3 km of its source. These results indicate the potential for dispersal of biological material originating from farm sites. Water currents, tides, and other hydrodynamic factors played a significant role in the dispersal patterns of eDNA. Areas with stronger currents showed more widespread distribution of eDNA. The physical structure and operational practices of the salmon farms, such as feeding regimes and waste management, also influenced eDNA levels in the surrounding water. The dispersal of eDNA from salmon farms can affect local biodiversity and ecosystem dynamics. The presence of farm-derived eDNA in the environment may have implications for local biodiversity, disease management, and ecosystem dynamics for wild salmon populations and other marine organisms. EDNA analysis can provide valuable ecological information about the spread of farm-related genetic material and these insights can inform management strategies for salmon aquaculture.

1.2 *Tenacibaculum maritimum*

1.2.1 Atlantic salmon farms are a likely source of *Tenacibaculum maritimum* infection in migratory Fraser River sockeye salmon

Bateman, A. W., Teffer, A. K., Bass, A., Ming, T., Kaukinen, K., Hunt, B. P. V., Krkošek, M., & Miller, K. M. (2022). Atlantic salmon farms are a likely source of Tenacibaculum maritimum infection in migratory Fraser River sockeye salmon. *Canadian Journal of Fisheries and Aquatic Sciences*, 79(8), 1225–1240. https://doi.org/10.1139/cjfas-2021-0164.

Bateman et al. (2022) analyzed patterns of molecular detection in juvenile sockeye (*Oncorhynchus nerka*) for the bacterium *Tenacibaculum maritimum*, known to cause disease in fish globally and to cause mouthrot disease in farmed Atlantic salmon in British Columbia. The data show a clear peak in *T. maritimum* detections in the Discovery Islands region of B.C., where sockeye migrate close to open-net salmon farms. The authors noted a higher incidence of *T. maritimum* infections in areas with intensive aquaculture activities, suggesting a potential link between fish farming practices and the spread of the pathogen. Environmental factors such as water temperature, salinity, and habitat conditions also influence the prevalence and impact of the bacteria. The report underscores the significant threat that *T. maritimum* poses to sockeye salmon populations. By understanding the factors influencing the spread and impact of this pathogen, better management and conservation strategies can be developed to protect these important fish populations.

1.2.2 Identification of infectious agents in early marine Chinook and coho salmon associated with cohort survival

Bass, A. L., Bateman, A. W., Connors, B. M., Staton, B. A., Rondeau, E. B., Mordecai, G. J., Teffer, A. K., Kaukinen, K. H., Li, S., Tabata, A. M., Patterson, D. A., Hinch, S. G., & Miller, K. M. (2022). Identification of infectious agents in early marine Chinook and coho salmon associated with cohort survival. *FACETS*, 7, 742–773. https://doi.org/10.1139/facets-2021-0102

Researchers hypothesize that depressed early marine survival primarily drives declines in coho and Chinook salmon abundance across much of their southern range in British Columbia. At the same time, there is a growing appreciation within the scientific community for the potential for infectious agents to cause mass mortality events. Bass et al. (2022) consistently identified *Tenacibaculum maritimum* and PRV as pathogens negatively associated with mass deviation. Negative associations with Chinook salmon survival are strongest in the fall–winter for both pathogens. *Tenacibaculum maritimum*, PRV, and Myxobolus arcticus show negative associations with survival for Chinook salmon and corresponding mass deviations. Furthermore, the authors warned that *T. maritimum* may become a greater issue for wild Pacific salmon growth and survival as water temperatures rise and antibiotic resistance evolves.

1.2.3 Experimental induction of mouthrot in Atlantic salmon smolts using *Tenacibaculum maritimum* from Western Canada

Frisch, K., Småge, S. B., Vallestad, C., & et al. (2018). Experimental induction of mouthrot in Atlantic salmon smolts using Tenacibaculum maritimum from Western Canada. *Journal of Fish Diseases*, 41, 1247–1258. https://doi.org/10.1111/jfd.12818.

Frisch et al. (2018) examined the incidence and impact of tenacibaculosis, a disease caused by the bacterium *Tenacibaculum*, on Atlantic salmon during their transfer from freshwater to seawater in B.C. aquaculture operations. The onset of tenacibaculosis symptoms typically occurred within the first few weeks after the salmon were transferred to seawater. This period is critical as the fish adapt to the new environment. The authors affirmed *T. maritimum* as the causative agent of mouthrot and noted that horizontal transfer occurs easily for Western Canadian *T. maritimum* strains. This raises concern for the potential for cross-species transmission of *Tenacibaculum* between Atlantic and Pacific salmon, especially in regions where both species are farmed or share habitats. The paper underscores the importance of monitoring and managing bacterial infections in aquaculture to prevent widespread outbreaks.

1.3 *Piscine orthoreovirus-1*

1.3.1 The same strain of Piscine orthoreovirus (PRV-1) is involved in the development of different, but related, diseases in Atlantic and Pacific salmon in British Columbia

Di Cicco, E., Ferguson, H. W., Kaukinen, K. H., Schulze, A. D., Li, S., Tabata, A., & et al. (2018). The same strain of Piscine orthoreovirus (PRV-1) is involved in the development of different, but related, diseases in Atlantic and Pacific salmon in British Columbia. *FACETS*, 3, 599–641. https://doi.org/10.1139/facets-2018-0008.

Di Cicco et al. (2018) established a significant relationship between the localization of *Piscine orthoreovirus* (PRV-1) in salmon tissues and the development of histological lesions, affirming the virus's etiological role in causing both heart and skeletal muscle inflammation (HSMI) in Atlantic salmon and jaundice/anemia in Chinook salmon. This connection extends to other PRV strains, with PRV-2 causing erythrocytic inclusion body syndrome (EIBS) in coho salmon and PRV-3 being associated with HSMI-like disease in rainbow trout and coho salmon in different geographical regions. Through full viral genome sequencing, the study found that PRV-1 variants in B.C. salmon farms show high genetic similarity to those in Norway and Chile.

1.3.2 *Piscine orthoreovirus* sequences in escaped farmed Atlantic salmon in Washington and British Columbia

Kibenge, M. J. T., Wang, Y., Gayeski, N., Morton, A., Beardslee, K., McMillan, B., & Kibenge, F. (2019). Piscine orthoreovirus sequences in escaped farmed Atlantic salmon in Washington and British Columbia. *Virology Journal*, 16, https://doi.org/10.1186/s12985-019-1148-2.

Kibenge et al. (2019) investigated the prevalence and genetic characteristics of *Piscine orthoreovirus* (PRV) in farmed Atlantic salmon that escaped from a commercial aquaculture site in Puget Sound, Washington State, USA. Nearly all of the escaped Atlantic salmon sampled tested positive for PRV (72 out of 73 tissue samples from 27 fish), indicating a prevalence close to 100% in the farm population. The PRV strain found in the escaped salmon was identified as sub-genotype Ia, which is very similar to strains from farmed Atlantic salmon in Iceland. This suggests that the source of the infected fish was the hatchery in Iceland. The findings highlight concerns about the impact of PRV on wild Pacific salmon populations, given that farmed Atlantic salmon are often reared in proximity to wild salmon.

1.3.3 Aquaculture mediates global transmission of a viral pathogen to wild salmon

Mordecai, G. J., Miller, K. M., Bass, A. L., Bateman, A. W., Teffer, A. K., Caleta, J. M., & et al. (2021). Aquaculture mediates global transmission of a viral pathogen to wild salmon. *Science Advances*, 7(22), https://doi.org/10.1126/sciadv.abe2592.

Mordecai et al. (2021) found that PRV is widespread in farmed Atlantic salmon. They detected the virus in farmed fish from multiple locations, indicating a high prevalence within aquaculture environments. There is strong evidence that PRV is transmitted from farmed Atlantic salmon to wild Pacific salmon. The genetic analysis of PRV from farmed and wild fish showed that the virus strains are highly similar, suggesting that farmed fish are a significant source of infection in wild populations. The PRV strains found in different regions and species (both farmed and wild) are genetically homogeneous. This implies that the virus has a common origin and supports the hypothesis of aquaculture-mediated transmission. The study concludes that aquaculture is a major driver of PRV transmission to wild salmon, posing a significant threat to their health and conservation.

1.3.4 Detection and phylogenetic assessment of PRV-1 via sampling of biological materials released from salmon farms in British Columbia

Mordecai, G., Beardslee, K., Glambeck, B., Frazer, N., Routledge, R., & Morton, A. (2022). Detection and phylogenetic assessment of PRV-1 via sampling of biological materials released from salmon farms in British Columbia. *Canadian Journal of Fisheries and Aquatic Sciences*, 80, https://doi.org/10.1139/cjfas-2022-0019.

In this 2022 study, Mordecai et al. sought to understand the potential impact of PRV-1 on both farmed and wild salmon populations. Authors collected biological samples adjacent to 56 marine net-pens from five different companies, and 25 from two farmed salmon processing plants. The study found that 70% of the samples collected near salmon farms tested positive for PRV-1. This indicates a significant presence of the virus in the vicinity of these farms. Sequencing of PRV-1 genome segments revealed that the virus present in the region is monophyletic, meaning it likely originated from a single introduction event. The virus detected in the samples was closely related to the PRV-1a sub-strain, which is commonly found in both farmed and wild salmon in the area. The similarity in the PRV-1 sequences within samples from different companies suggests that the virus may be originating from Atlantic salmon freshwater hatcheries, which are a probable source of PRV-1 to the marine environment. The study reinforces concerns about the potential transmission of PRV-1 from farmed to wild salmon, especially given the high rates of infection found near salmon farms. This could pose a risk to wild salmon populations, which are already in decline in the region.

1.3.5 The effect of exposure to farmed salmon on *Piscine orthoreovirus* infection and fitness in wild Pacific salmon in British Columbia, Canada

Morton, A., Routledge, R., Hrushowy, S., Kibenge, M., & Kibenge, F. (2017). The effect of exposure to farmed salmon on Piscine orthoreovirus infection and fitness in wild Pacific salmon in British Columbia, Canada. *PLoS ONE*, 12, Article e0188793. https://doi.org/10.1371/journal.pone.0188793.

Morton et al. (2017) found a significant correlation between the exposure of wild Pacific salmon to farmed salmon and the prevalence of PRV infection. The researchers detected PRV in 95% of farmed Atlantic salmon, 37–45% of wild salmon in regions highly exposed to salmon farms, and only 5% in wild salmon from regions farthest from salmon farms. The infection was observed to be lower in wild salmon that underwent a strenuous return migration to high-elevation spawning habitats. This suggests that the arduous journey may reduce the likelihood of PRV-infected fish completing the migration. The data suggests that PRV transmission occurs from farmed Atlantic salmon to wild Pacific salmon, indicating a potential epidemiological link. Overall, the infection in farmed salmon appears to influence infection rates in wild salmon. These findings raise concerns about the health and sustainability of wild salmon.

1.4 Infectious salmon anaemia virus (ISAV)

1.4.1 Discovery of variant Infectious Salmon Anaemia Virus (ISAV) of European genotype in British Columbia, Canada

Kibenge, M., Iwamoto, T., Wang, Y., Morton, A., Routledge, R., & Kibenge, F.S.B. (2016). Discovery of variant Infectious Salmon Anaemia Virus (ISAV) of European genotype in British Columbia, Canada. *Virology Journal*, 13(3), https://doi.org/10.1186/s12985-015-0459-1

Infectious Salmon Anaemia (ISA) virus (ISAV) is an economically important pathogen of marine-farmed Atlantic salmon. ISAV belongs to the genus Isavirus in the family *Orthomyxoviridae* and occurs in two basic genotypes—North American and European. The European genotype is more widespread and shows greater genetic variation and virulence variation compared to the North American genotype. This study provides evidence of the presence of ISAV variants of the European genotype in British Columbia, Canada, which may have gone undetected previously due to the limitations of the standard diagnostic methods designed to detect virulent ISAV strains causing disease outbreaks. Improved detection methods are needed to better understand the prevalence and evolution of ISAV in the region.

1.4.2 Infectious Salmon Anaemia Virus: The political power of a small infectious agent

Bega, A. (2016). Infectious Salmon Anaemia Virus: The political power of a small infectious agent [Master's research project, Simon Fraser University]. https://summit.sfu.ca/item/16736

Bega (2016) analyzed the scientific controversy over the presence of ISAV in British Columbia. Bega focused on the last three days of the Cohen Commission of Inquiry, which was established to investigate the decline of wild sockeye salmon in the region. The paper explores the possibility of government and industry influence in the decision-making process, as well as the limitations of science as the sole knowledge producer in resource management. The key findings are: (1) The scientific controversy over ISAV is highly politicized, with the possibility of government and industry influence in the decision-making process. Government labs and those affiliated with the industry reported negative results for the presence of the virus, while independent labs found positive evidence. (2) Science alone has been unable to resolve the controversy, as different methodologies and choices in analyzing the virus have led to contradictory results between labs. This points to the limitations of science as the sole institutionalized knowledge producer in resource management. (3) Bega recommends greater collaboration with First Nations and the inclusion of their traditional ecological knowledge as scientifically valid. First Nations' participation in the management of natural resources was limited during the Cohen Commission, despite their deep cultural and economic ties to the salmon.

2 Parasites

2.1 Sea Lice

2.1.1 Academic scientists' critique of DFO Science Response Report 2022/045

Bateman, A., Darimont, C., Dill, L., Frommel, A., Frazer, N., Godwin, S., Hinch, S., Krkošek, M., Lewis, M., Moore, J., Mordecai, G., Otto, S., Peacock, S., Price, M., Reynolds, J., & Routledge, R. (2023, January 30). Letter to The Honourable Joyce Murray.

This letter from academic scientists to the Minister of Fisheries, Oceans, and the Canadian Coast Guard raises several serious concerns regarding the DFO Science Response Report 2022/045, which addresses the issue of sea lice on salmon farms and their impact on wild salmon populations in British Columbia. The key points of concern and findings are:

1. **Flawed Conclusion**: Even a simple analysis of the report's own data shows a significant association between sea lice from Atlantic salmon farms and infestations on wild juvenile salmon.

2. **Lack of Independent Peer Review:** The report was authored by DFO employees with a mandate to support aquaculture development, and it was externally reviewed by only one industry-associated professor.

3. **Selective Reporting:** Only analyses that showed no significant association were included, while other analyses that indicated significant associations were omitted.

4. **Disregard for Existing Research:** The report is said to downplay a large body of peer-reviewed research that demonstrates the relationship between salmon farms and sea lice on wild salmon, both in British Columbia and internationally.

5. **Inadequate Statistical Analysis:** The report lacks a power analysis, which is necessary to determine the reliability of the findings. It also uses inappropriate statistical methods that could lead to misleading conclusions.

6. **Data Transparency Issues:** The underlying data used in the report were not provided, preventing independent validation of the analyses and conclusions.

Unvalidated Infestation Model: The report relies on an unvalidated model for infestation pressure that contradicts established scientific knowledge and fails to account for important factors such as the migratory patterns of wild salmon.

The report fails to meet widely accepted scientific standards and should not be used to inform policy decisions regarding salmon farming in British Columbia.

2.1.2 Migration links ocean-scale competition and local ocean conditions with exposure to farmed salmon to shape wild salmon dynamics

Connors, B. M., Braun, D. C., Peterman, R. M., Cooper, A. B., Reynolds, J. D., Dill, L. M., Ruggerone, G. T., & Krkošek, M. (2012). Migration links ocean-scale competition and local ocean conditions with exposure to farmed salmon to shape wild salmon dynamics. *Conservation Letters*, 5(2012), 304–312. https://doi.org/10.1111/j.1755-263X.2012.00244.x

The primary driver of the long-term decline in the productivity of Fraser River sockeye salmon is competition with pink salmon (*Oncorhynchus gorbuscha*), which can be further exacerbated by exposure to farmed salmon early in the sockeye's marine life. Additionally, there is an interaction between coastal ocean temperature and farmed-salmon exposure that also contributes to this decline. The findings suggest that large-scale oceanic processes, which are beyond the control of current regulatory bodies, may intensify local ecological challenges and make it difficult for fisheries and aquaculture to coexist sustainably in coastal regions.

2.1.3 Coho salmon productivity in relation to salmon lice from infected prey and salmon farms

Connors, B. M., Krkošek, M., Ford, J., & Dill, L. M. (2010). Coho salmon productivity in relation to salmon lice from infected prey and salmon farms. *Journal of Applied Ecology*, 47, 1372–1377. https://doi.org/10.1111/j.1365-2664.2010.01889.x

Coho salmon populations exposed to salmon louse infestations had significantly lower productivity—about seven times lower—compared to populations that were not exposed. This indicates that salmon lice have a detrimental effect on coho salmon, which is likely exacerbated by interactions with infected prey (juvenile pink salmon). The study suggests that salmon lice are transmitted not only directly from salmon farms but also through trophic transmission, where coho salmon become infected by preying on louse-infected juvenile pink salmon. The transmission of pathogens from farmed to wild salmon can propagate through the food web, affecting predator-prey relationships and potentially leading to broader ecological consequences. The study highlights the need for salmon aquaculture management to consider these species interactions to ensure ecological sustainability.

2.1.4 Predation intensifies parasite exposure in a salmonid food chain

Connors, B. M., Hargreaves, N. B., Jones, S. R. M., & Dill, L. M. (2010). Predation intensifies parasite exposure in a salmonid food chain. *Journal of Applied Ecology*, 47, 1365–1371. https://doi.org/10.1111/j.1365-2664.2010.01887.x

Connors et al. (2010) found that louse infections increase the susceptibility of juvenile pink salmon to predation. Predators, such as juvenile coho salmon, that feed on infected pink salmon, acquire the lice, leading to a trophic transmission of the parasites. The results showed that coho salmon had higher abundance and a more adult male-biased population of lice compared to their pink salmon prey. This suggests that predation on infected prey significantly increases the lice burden on the predator. The study estimated that trophic transmission accounts for 53–67% of the pre-adult and adult louse infection in coho salmon. This indicates that a significant portion of the lice infestation in predators comes from consuming infected prey rather than passive exposure to larvae in the environment. The findings suggest that predation can intensify parasite exposure within food webs, potentially undermining the natural protection against ectoparasites that larger body size in predators would normally confer. This has important implications for managing marine environments, particularly in regions with intensive salmon aquaculture where the risk of parasite transmission might be greater than previously understood.

2.1.5 Sea lice, sockeye salmon, and foraging competition: Lousy fish are lousy competitors

Godwin, S. C., Dill, L. M., Reynolds, J. D., & Krkošek, M. (2015). Sea lice, sockeye salmon, and foraging competition: Lousy fish are lousy competitors. *Canadian Journal of Fisheries and Aquatic Sciences*, 72, 1113–1120. https://doi.org/10.1139/cjfas-2014-0284

Godwin et al. (2015) found that highly infected sockeye were 20% less successful at consuming food, on average, than lightly infected fish. Competitive ability also increased with fish body size. These results provide the first evidence that parasite exposure may have negative indirect effects on the fitness of juvenile sockeye salmon and suggest that indirect effects of pathogens may be of key importance for the conservation of fish.

2.1.6 Heavy sea louse infection is associated with decreased stomach fullness in wild juvenile sockeye salmon

Godwin, S. C., Krkošek, M., Reynolds, J. D., Rogers, L. A., & Dill, L. M. (2018). Heavy sea louse infection is associated with decreased stomach fullness in wild juvenile sockeye salmon. *Canadian Journal of Fisheries and Aquatic Sciences*, 75, 1587–1595. https://doi.org/10.1139/cjfas-2017-0267

Godwin et al. (2018) found that juvenile sockeye salmon with heavy sea louse infections had significantly lower stomach fullness compared to those with lighter infections. Specifically, highly infected fish had, on average, 17% lower relative stomach fullness. The decreased stomach fullness in heavily infected fish suggests that sea lice infection impairs the foraging success of juvenile salmon. This is particularly concerning in a food-limited environment, where competition for food is intense. Early marine growth, which is influenced by foraging success, is often a predictor of survival in juvenile salmon. Therefore, the negative impact of sea lice on stomach fullness could have significant implications for the survival and population dynamics of these fish.

2.1.7 Reduced growth in wild juvenile sockeye salmon *Oncorhynchus nerka* infected with sea lice

Godwin, S. C., Dill, L. M., Krkošek, M., Price, M. H. H., & Reynolds, J. D. (2017). Reduced growth in wild juvenile sockeye salmon Oncorhynchus nerka infected with sea lice. *Journal of Fish Biology*, 91, 41–57. https://doi.org/10.1111/jfb.1332

Godwin et al. (2017) examined the impact of sea lice infection on the growth of wild juvenile sockeye salmon through otolith microstructure analysis in British Columbia. Statistical analyses found that sea lice infection is negatively correlated with the speed of host body growth and, subsequently, host survival. These results highlight the importance of understanding the effects of marine pathogens on salmon populations. Given the implications for wild salmonid populations, the study recommends a comprehensive management plan for sea lice on farmed sockeye salmon to improve survival and conservation efforts. These results contribute to existing evidence characterizing the significant risks presented by sea lice infestation towards the health of wild salmon species.

2.1.8 Development of the salmon louse, *Lepeophtheirus salmonis* and its effects on juvenile sockeye salmon Oncorhynchus nerka.

Jakob, E., Sweeten, T., Bennett, W., & Jones, S. (2013). Development of the salmon louse, *Lepeophtheirus salmonis*, and its effects on juvenile sockeye salmon *Oncorhynchus nerka*. *Diseases of Aquatic Organisms*, 106, 217–227. https://doi.org/10.3354/dao02642

Jakob et al. (2013) investigated the effects of salmon lice (*Lepeophtheirus salmonis*) infections on juvenile sockeye salmon under controlled laboratory conditions. All salmon in the trials became infected, with infection levels varying depending on the number of copepodids (larval stage of lice) they were exposed to. Higher infection levels (19.5 to 60.7 lice per fish) in Trial 3 led to a cumulative mortality of 24.4%. The authors observed significant physiological and histopathological changes in the infected salmon affecting gills, fins, plasma, and cortisol levels. The study suggests that juvenile sockeye salmon exhibit patterns of infection and physiological response to salmon lice similar to those observed in Atlantic and Chinook salmon. However, it notes that natural resistance to lice, such as that observed in coho and pink salmon, does not appear to be present in juvenile sockeye salmon. This study highlights potential vulnerabilities in sockeye salmon populations relevant to strengthening management practices in aquaculture.

2.1.9 Early development of resistance to the salmon louse, *Lepeophtheirus salmonis* (Krøyer), in juvenile pink salmon, Oncorhynchus gorbuscha (Walbaum)

Jones, S., Kim, E., & Bennett, W. (2008). Early development of resistance to the salmon louse, *Lepeophtheirus salmonis* (Krøyer), in juvenile pink salmon *Oncorhynchus gorbuscha* (Walbaum). *Journal of Fish Diseases*, 31, 591–600. https://doi.org/10.1111/j.1365-2761.2008.00933.x

Jones et al. (2008) examined the effect of fish weight on the susceptibility of post-emergent pink salmon to the salmon louse through trials using two pink salmon stocks in British Columbia. Fish of varying weight were exposed to salmon louse copepodids at varying levels. For fish weighing 0.3 g, mortality was around 37% regardless of exposure to copepodids. Fish weighing 0.7 g had 5% mortality and there was no mortality with the 2.4 g fish. Histological analysis showed that the larger fish developed thicker epidermis and eventually the development of scales. These developments increase resistance to the salmon louse. These findings suggest that early migrating pink salmon are at an elevated risk from salmon louse infections.These results contribute to existing evidence characterizing the impacts of sea lice on the ecological health of wild salmon populations.

2.1.10 Infection threshold to estimate *Lepeophtheirus salmonis* associated mortality among juvenile pink salmon

Jones, S. R. M., & Hargreaves, B. (2009). Infection threshold to estimate *Lepeophtheirus salmonis* associated mortality among juvenile pink salmon. *Diseases of Aquatic Organisms*, 84, 131–137. https://doi.org/10.3354/dao02043

Jones et al. (2009) investigate the infection threshold of *Lepeophtheirus salmonis* in juvenile pink salmon. The study establishes a threshold of lethal infection at 7.5 lice per gram of fish weight for pink salmon averaging less than 0.7 grams. This threshold was used to assess the risk of mortality from *L. salmonis* among juvenile pink salmon in the Broughton Archipelago, Canada, between 2005 and 2008. The prevalence and intensity of *L. salmonis* infections, as well as the proportion of salmon exceeding the lethal infection threshold, significantly declined from 2005 to 2008, suggesting a reduced mortality risk from *L. salmonis* over time. In 2005, 4.5% of small salmon were infected at or above the lethal threshold, which decreased to 0% by 2008. The infections generally coincided with the early stages of ocean migration, when the fish are most vulnerable. The reduction in infection levels may be attributed to changes in ocean conditions, improvements in parasite management practices on salmon farms, and possible changes in the abundance or distribution of non-farmed hosts.

2.1.11 Large scale modelling of salmon lice *(L. salmonis)* infection pressure based on lice monitoring data from Norwegian salmonid farms

Kristoffersen, A. B., Jimenez, D., Viljugrein, H., Grøntvedt, R., Stien, A., & Jansen, P. A. (2014). Large scale modelling of salmon lice (*L. salmonis*) infection pressure based on lice monitoring data from Norwegian salmonid farms. *Epidemics*, 9, 31–39. https://doi.org/10.1016/j.epidem.2014.09.007

Kristoffersen et al. (2014) investigated how salmon lice populations in Norwegian salmon farming impact wild salmonid populations. The study integrates monitoring data with a deterministic model to estimate the production of infectious lice stages in salmonid farms and the external infection pressure from neighboring farms. External infection pressure is identified as a main predictor of salmon lice population dynamics in newly stocked cohorts of salmonids. This emphasizes the importance of keeping the production of infectious lice stages at low levels within local networks of salmon farms. It is suggested that improvements to lice monitoring methods could be made through the addition of a real-time estimation system for infestation pressure. This paper underscores the need for rigorous industry standards that enhance predictability.

2.1.12 Declining wild salmon populations in relation to parasites from farm salmon

Krkošek, M., Ford, J. S., Morton, A., Lele, S., Myers, R. A., & Lewis, M. A. (2007). Declining wild salmon populations in relation to parasites from farm salmon. *Science*, 318, 1772–1775. https://doi.org/10.1126/science.1148744

Krkošek et al. (2007) investigated the impact of sea lice infestations, originating from salmon farms, on wild pink salmon populations in the Broughton Archipelago, British Columbia. The study demonstrated that sea lice infestations significantly reduced the population growth rate of exposed wild pink salmon compared to unexposed populations. The infestation led to a marked decline in salmon populations during the infestation years. The implementation of the Pink Salmon Action Plan in 2003, which involved fallowing (removing farmed salmon from areas along migration routes), was associated with a reduction in sea lice abundance and an improvement in wild salmon survival rates. The paper suggests that continued management interventions, like fallowing and better control of sea lice, are crucial for the recovery and conservation of wild salmon populations. The study emphasizes that without such interventions, wild salmon populations are at risk of extirpation.

2.1.13 Sea lice and salmon population dynamics: Effects of exposure time for migratory fish

Krkošek, M., Morton, A., Volpe, J., & Lewis, M. (2009). Sea lice and salmon population dynamics: Effects of exposure time for migratory fish. *Proceedings of the Royal Society of London Series B*, 276, 2819–2828. https://doi.org/10.1098/rspb.2009.0317

The duration of exposure to sea lice is critical. Short exposure periods result in low parasite-induced mortality, similar to laboratory experiments. However, when exposure is extended, as in the wild where juvenile salmon migrate past salmon farms, lice populations accumulate, leading to significant increases in salmon mortality and declines in salmon populations. Krkošek et al. (2009) developed a mathematical model to simulate lice population dynamics and their effect on salmon mortality. The model showed that lice experience high mortality during the early motile stages, but prolonged exposure to lice results in higher mortality rates for salmon, especially when exposed to salmon farms over several weeks. The research indicates that sustained exposure to sea lice can severely depress salmon populations, potentially leading to population collapse if not managed properly. This highlights the importance of minimizing exposure time to sea lice in coastal management, particularly in areas where salmon farms are located along migration routes.

2.1.14 Effects of parasites from salmon farms on productivity of wild salmon

Krkošek, M., Connors, B. M., Morton, A., Lewis, M. A., Dill, L. M., & Hilborn, R. (2011). Effects of parasites from salmon farms on productivity of wild salmon. *Proceedings of the National Academy of Sciences of the United States of America*, 108, 14700–14704. https://doi.org/10.1073/pnas.1101845108

Krkošek et al. (2011) reanalyzed previous data published by Marty et al. (2010) to resolve conflicting conclusions regarding whether sea lice from salmon farms negatively affect wild salmon productivity. The study found a significant negative association between the abundance of sea lice on salmon farms and the productivity of wild pink and coho salmon in the Broughton Archipelago. Higher sea lice levels on farms correlated with lower survival rates of wild salmon. The findings contradict results published by Marty et al. (2010) that claimed no significant impact of sea lice on wild salmon, suggesting that the earlier analysis might have lacked sufficient statistical power and overlooked spatial and temporal factors. The analysis highlighted variability in the impact of sea lice across different regions and years. Mortality due to sea lice varied, sometimes reaching as high as 92% for coho salmon when lice were abundant. The study suggests that effective management practices, such as the fallowing of farms and use of parasiticides, could mitigate the negative effects of sea lice on wild salmon populations. The authors argue against the previous study's recommendation that downplayed the need for such interventions. The paper concludes that sea lice from salmon farms pose a significant threat to wild salmon populations in the Broughton Archipelago. The authors advocate for continued and enhanced management measures to protect wild salmon from the detrimental effects of parasites associated with aquaculture.

2.1.15 Fish farms, parasites, and predators: Implications for salmon population dynamics

Krkošek, M., Connors, B., Mages, P., Peacock, S., Ford, H., Ford, J., Morton, A., Volpe, J., Hilborn, R., Dill, L., & Lewis, M. (2011). Fish farms, parasites, and predators: Implications for salmon population dynamics. *Ecological Applications*, 21, 897–914. https://doi.org/10.1890/09-1861.1

Krkošek et al. (2011) examined how sea lice from salmon farms impact the population dynamics of wild salmon, particularly pink and chum salmon (*Oncorhynchus keta*). The study found that juvenile salmon infected with sea lice were more likely to engage in riskier behavior, such as resuming feeding more quickly after a simulated predator attack, making them more vulnerable to predators. Infected salmon were observed to take positions on the periphery of schools, making them more susceptible to predation. Predators, such as cutthroat trout (*Oncorhynchus clarkii*) and coho salmon, were found to selectively target infected juvenile salmon over uninfected ones. This selective predation was observed both in controlled experiments and in natural group settings. A mathematical model developed in the study suggests that sea lice infestation can significantly increase predation rates, leading to higher mortality in juvenile salmon. The findings of the paper highlight the complex interactions between parasites and predators and their significant implications for wild salmon populations. The study suggests that sea lice from fish farms, combined with natural predation, can have severe impacts on wild salmon productivity, calling for more nuanced management and conservation strategies.

2.1.16 Epizootics of wild fish induced by farm fish

Krkošek, M., Lewis, M. A., Morton, A., Frazer, L. N., & Volpe, J. P. (2006). Epizootics of wild fish induced by farm fish. *Proceedings of the National Academy of Sciences USA*, 103, 15506–15510. https://doi.org/10.1073/pnas.0603525103

Sea lice from salmon farms caused significant mortality in wild juvenile pink and chum salmon populations in B.C., with mortality rates ranging from 9% to 95%. This varied across different salmon populations and migration routes. Under natural conditions, the migratory life cycle of wild salmon typically prevents young salmon from encountering parasites carried by adult salmon. However, salmon farms disrupt this natural protection by introducing large numbers of parasites to juvenile salmon during their early marine life, leading to high rates of infection. Models indicated that farmed salmon were the primary source of lice, significantly increasing the density of infectious larvae along the migration routes of wild salmon. This effect was observed up to 80 km from the farm locations. The paper suggests that this mechanism of disease transmission could affect other species and ecosystems as aquaculture continues to expand globally. The study emphasizes the need for better management practices to protect wild fish populations from the impacts of farm-origin parasites.

2.1.17 Transmission dynamics of parasitic sea lice from farm to wild salmon

Krkošek, M., Lewis, M. A., & Volpe, J. P. (2005). Transmission dynamics of parasitic sea lice from farm to wild salmon. *Proceedings of the Royal Society of London Series B*, 272, 689–696. https://doi.org/10.1098/rspb.2004.3027

Krkošek et al. (2005) studied pink and chum salmon as they migrated through two narrow corridors near an isolated salmon farm in British Columbia. The farm significantly increased the infection pressure on the wild salmon, with infection levels near the farm being 73 times higher than ambient levels. This heightened infection pressure extended for up to 30 km along the salmon migration routes. The lice that initially infected the juvenile salmon from the farm matured and produced a second generation, further increasing the infection pressure by an order of magnitude. This secondary infection pressure affected up to 75 km of the migration routes. The study found that both the farm-origin lice and the secondary lice from infected juvenile salmon were the primary contributors to the observed infection dynamics. The amplified sea lice infestations due to the farm could be a significant limiting factor for the conservation of wild salmon populations. The findings suggest that salmon farms may pose a serious threat to wild salmon populations by dramatically increasing sea lice infestations, particularly during the vulnerable early marine phase of the salmon's life cycle.

2.1.18 Effects of host migration, diversity and aquaculture on sea lice threats to Pacific salmon populations

Krkošek, M., Gottesfeld, A., Proctor, B., Rolston, D., Carr-Harris, C., & Lewis, M. A. (2007). Effects of host migration, diversity, and aquaculture on sea lice threats to Pacific salmon populations. *Proceedings of the Royal Society B*, 274, 3141–3149. https://doi.org/10.1098/rspb.2007.1122

In this 2007 study, Krkošek et al. highlight the concept of migratory allopatry, where the spatial separation between juvenile and adult salmon due to migration prevents the transmission of *L. salmonis* from adults to juveniles during the first two to three months of the juveniles' marine life. This reduces *L. salmonis* prevalence in juvenile salmon during this critical period. While *L. salmonis* prevalence was low due to migratory allopatry, *Caligus clemensi* was more prevalent (8–20%) among juvenile salmon due to the presence of diverse host species (e.g., herring, sandfish) that were sympatric with the juveniles. However, *C. clemensi* infections appeared to be short-lived and less pathogenic compared to *L. salmonis*. The study models the potential impact of salmon aquaculture on wild salmon populations, predicting that the introduction of farmed salmon could increase sea lice exposure for wild juveniles, potentially leading to population collapse if lice abundance exceeds 1.5–5 motile lice per fish. This underscores the sensitivity of wild salmon populations to early life-stage parasitism. The findings suggest that salmon aquaculture, by augmenting host abundance and diversity, can undermine the natural protective effect of migratory allopatry and increase the threat of sea lice to wild salmon populations. The study emphasizes the need for careful management of aquaculture to protect wild salmon stocks, particularly in regions like the Skeena River estuary, which is home to some of Canada's largest salmon populations.

2.1.19 Sea lice infestations and productivity of pink salmon populations in the Broughton Archipelago

Krkošek, M., & Hilborn, R. (2011). Sea lice infestations and productivity of pink salmon populations in the Broughton Archipelago. *Canadian Journal of Fisheries and Aquatic Sciences*, 68, 17–29. https://doi.org/10.1139/F10-137

Krkošek and Hilborn (2011) examined the impact of salmon lice infestations from salmon farms on wild pink salmon populations in British Columbia through the analysis of stock-recruit data. Analysis reveals trends in fishing mortality, spatial covariation, and lice infestation impacts on pink salmon population dynamics. Overall, populations exposed to salmon farms decline in productivity during years with sea lice infestations. Population growth rates declined and showed a 90% drop in survival. Comparatively, populations that were not exposed did not experience a change in productivity. The results suggest that sea lice infestations lead to declines in wild pink salmon populations. This paper joins a body of research with similar conclusions and reinforces the existing recommendations for strengthening policies that protect wild juvenile salmon from sea lice exposure.

2.1.20 Impact of parasites on salmon recruitment in the Northeast Atlantic Ocean

Krkošek, M., Revie, C. W., Gargan, P. G., Skilbrei, O. T., Finstad, B., & Todd, C. D. (2013). Impact of parasites on salmon recruitment in the Northeast Atlantic Ocean. *Proceedings of the Royal Society B*, 280(1750), 20122359. https://doi.org/10.1098/rspb.2012.2359

Krkošek et al. (2013) examined the impact of parasitic crustaceans, particularly *L. salmonis*, on the survival of Atlantic salmon in the Northeast Atlantic Ocean. This meta-analysis synthesizes 24 field experiments where tagged salmon smolts are released as paired control and parasiticide-treated groups. Then, the proportion of each group that returns as adults is compared. Parasitic crustaceans contribute to an estimated 39% loss of adult salmon recruitment. It is suspected that these parasites were acquired during early marine migration in areas with large aquaculture populations of domesticated salmon. With consistency, the results show that the parasiticidal treatment had a positive effect on survival to recruitment. Strengthened regulations are recommended to reduce and prevent mortalities in adult salmon populations.

2.1.21 Relationship of farm salmon, sea lice, and wild salmon populations

Marty, G. D., Saksida, S. M., & Quinn, T. J. (2010). Relationship of farm salmon, sea lice, and wild salmon populations. *Proceedings of the National Academy of Sciences*, 107(52), 22599–22604. https://doi.org/10.1073/pnas.1009573108

Marty et al. (2010) explored the relationship between farm salmon, sea lice, and wild salmon populations through the analysis of 10–20 years of fish farm data and 60 years of pink salmon data from the Broughton Archipelago. The writers observe that the number of returning adult pink salmon predicts the number of female sea lice on farm fish the following spring. This accounts for 98% of the annual variability in sea lice prevalence on juvenile wild salmon. However, the data highlights that productivity of wild salmon populations are not negatively associated with the number of farm fish production or sea lice. Because other variables, like disease, may be relevant contributors, medical analysis is recommended to better understand the complexities surrounding aquaculture, sustainability, and salmon conservation.

2.1.22 Relationship between sea lice levels on sea trout and fish farm activity in western Scotland

Middlemas, S., Fryer, R., Tulett, D., & Armstrong, J. (2013). Relationship between sea lice levels on sea trout and fish farm activity in western Scotland. *Fisheries Management & Ecology*, 20(1), 68-74. https://doi.org/10.1111/fme.12010

Middlemas et al. (2013) examined the relationship between Atlantic salmon farming and sea lice infestations in wild sea trout populations of western Scotland. They used longitudinal analysis across multiple farm cycles to determine if the sea lice impacted the second year of production cycles in salmon farms. The findings indicate a significant increase in lice in wild sea trout populations during the second year of these cycles and suggests a critical link between infestations and wild sea trout health. These results emphasize the threat sea lice pose to wild sea trout populations and underscores the importance of considering the role of salmon farms in managing the health of both farmed and wild salmon populations.

2.1.23 First report of a sea louse, *Lepeophtheirus salmonis*, infestation on juvenile pink salmon, *Oncorhynchus gorbuscha*, in nearshore habitat

Morton, A., & Williams, R. (2003). First report of a sea louse, *Lepeophtheirus salmonis*, infestation on juvenile pink salmon *Oncorhynchus gorbuscha*, in nearshore habitat. *Canadian Field-Naturalist*, 117, 634–641. https://doi.org/10.22621/cfn.v117i4.834

In this paper, Morton and Williams (2003) document the first recorded infestation of *L. salmonis* on juvenile pink salmon in the Broughton Archipelago. The study found high infestation rates of *L. salmonis* on juvenile pink salmon, with an average of 11.3 sea lice per fish and 6.1 sea lice per gram of host weight. Approximately 75% of the fish were infected at levels equal to or higher than the lethal limit reported for larger post-smolts. The study revealed that the abundance and intensity of sea lice infestations were significantly higher in juvenile pink salmon collected near salmon farms compared to those collected from sites further away from the farms. The high levels of infestation likely compromised the growth and survivorship of the juvenile pink salmon, raising concerns about the health and viability of the stock when 98% of the examined juvenile salmon failed to return to spawn in 2002. It is suggested that the source of the sea lice infestation was local, likely originating from the nearby salmon farms, as juvenile salmon with heavy infestations were found in close proximity to these farms. The findings highlight the potential threat of salmon farming to wild salmon populations, suggesting that salmon farms could be contributing to the spread of sea lice and subsequent declines in wild salmon stocks..

2.1.24 Sea louse infestation in wild juvenile salmon and pacific herring associated with fish farms off the east-central coast of Vancouver Island, British Columbia

Morton, A., Routledge, R., & Krkošek, M. (2008). Sea louse infestation in wild juvenile salmon and pacific herring associated with fish farms off the east-central coast of Vancouver Island, British Columbia. *North American Journal of Fisheries Management*, 28, 523–532. https://doi.org/10.1577/M07-042.1

Morton et al. (2008) used field surveys to investigate the abundance of sea lice in larval Pacific herring and wild juvenile pink, chum, and sockeye salmon along eastern Vancouver Island. Among variables like temperature, salinity, sampling period, and host species, farm exposure was the most consistent predictor for sea louse abundance across all data sets. The study highlights the lethality of sea lice on pink and chum salmon and emphasizes the potential for high mortality in wild juvenile salmon populations due to sea louse transmission from farmed salmon. The authors recommend that conservation policies be strengthened to protect these species from sea lice infestations. This paper contributes to existing evidence characterizing the risks of sea lice transmission towards the health of both farmed and wild fish populations.

2.1.25 Sea lice *(Lepeophtheirus salmonis)* infection rates on juvenile pink *(Oncorhynchus gorbuscha)* and chum *(Oncorhynchus keta)* salmon in the nearshore marine environment of British Columbia, Canada

Morton, A., Routledge, R., Peet, C., & Ladwig, A. (2004). Sea lice (*Lepeophtheirus salmonis*) infection rates on juvenile pink (*Oncorhynchus gorbuscha*) and chum (*Oncorhynchus keta*) salmon in the nearshore marine environment of British Columbia, Canada. *Canadian Journal of Fisheries and Aquatic Sciences*, 61, 147–157. https://doi.org/10.1139/f04-016

Morton et al. (2004) found that sea lice were significantly more abundant on wild salmon near fish farms. Sea lice were 8.8 times more abundant near farms with adult salmon and 5 times more abundant near farms with smolts than in areas distant from farms. Of the juvenile pink and chum salmon sampled near salmon farms, 90% were infected with sea lice at levels above the proposed lethal limit (1.6 lice per gram of host mass). The authors found that the most immature life stages dominated the lice population, indicating that the source of lice was likely a stationary, local salmonid population such as a salmon farm. Sea lice abundance was near zero in areas without salmon farms, suggesting that the higher infestation rates were not due to environmental factors like salinity or temperature.

2.1.26 Sea lice dispersion and salmon survival in relation to salmon farm activity in the Broughton Archipelago

Morton, A., Routledge, R., McConnell, A., & Krkošek, M. (2011). Sea lice dispersion and salmon survival in relation to salmon farm activity in the Broughton Archipelago. *ICES Journal of Marine Science*, 68, 144–156. https://doi.org/10.1093/icesjms/fsq146

Morton et al. (2011) found that sea lice were more abundant near active salmon farms compared to fallowed farms or areas without farms. Planktonic lice, particularly nauplii and copepodites, were primarily found near active farms, suggesting that these farms were the primary sources of lice in the environment. Fallowing salmon farms significantly reduced the abundance and spatial distribution of sea lice to levels similar to areas without salmon farms. Chemical treatment (using emamectin benzoate) on active farms reduced lice transmission by about 100 times compared to previous epizootics, but active farms still remained a significant source of lice. Juvenile salmon migrating past active farms exhibited higher lice infestation rates, with up to 50% showing surface tissue damage. The estimated direct mortality of juvenile salmon due to lice on the active migration route was less than 10%, a figure that did not account for indirect effects such as increased predation risk. The study found no significant difference in the survival rates of pink salmon cohorts from the Broughton Archipelago compared to those from a reference region without salmon farms. However, the variability in survival data made it difficult to detect the precise impact of sea lice on overall salmon survival. These findings highlight the complexities of managing sea lice in relation to salmon farming practices and are relevant to understanding implications for wild salmon populations.

2.1.27 The effect of exposure to farmed salmon on *Piscine orthoreovirus* infection and fitness in wild Pacific salmon in British Columbia, Canada

Morton, A., Routledge, R., Hrushowy, S., Kibenge, M., & Kibenge, F. (2017). The effect of exposure to farmed salmon on *Piscine orthoreovirus* infection and fitness in wild Pacific salmon in British Columbia, Canada. *PLoS ONE*, 12(12), e0188793. https://doi.org/10.1371/journal.pone.0188793

Morton et al. (2017) investigated the prevalence of PRV infection in farmed Atlantic salmon and wild Pacific salmon in British Columbia. Atlantic salmon, wild Pacific salmon, and British Columbia-reared steelhead were tested for PRV infection. Tests found PRV in 95% farmed Atlantic salmon, 37–45% of wild salmon from regions near salmon farms, and 5% of wild salmon from regions furthest from salmon farms. Furthermore, the study observed a negative correlation between increased migratory challenge and PRV-positive proportions in salmon return-migrating adult salmon. This suggests that PRV infection reduces the capacity to complete a challenging migration and, subsequently, reduces reproductive success. Additionally, this suggests that low elevation salmonid populations are more susceptible to viral disease. Further research into the fitness impacts of farmed salmon pathogens on wild fish populations is needed.

2.1.28 Can reduced predation offset negative effects of sea louse parasites on chum salmon?

Peacock, S., Connors, B., Krkošek, M., Irvine, J., & Lewis, M. (2014). Can reduced predation offset negative effects of sea louse parasites on chum salmon? *Proceedings of the Royal Society B*, 281, 20132913. https://doi.org/10.1098/rspb.2013.2913

Sea lice physically damage individual salmon leading to increased mortality, especially in juvenile pink and chum salmon. Despite the negative impact of sea lice on chum salmon, Peacock et al. found no significant decrease in chum salmon productivity in areas exposed to sea louse infestations. This was surprising given the high statistical power of the analysis. The researchers hypothesized that reduced predation might offset the negative effects of sea lice on chum salmon. Predators, such as coho salmon, show a preference for pink salmon over chum salmon, and this preference may become more pronounced when pink salmon are compromised by sea lice infestations. This shift in predation pressure could reduce the overall impact of sea lice on chum salmon populations. Using a mathematical model, the study indicates that under certain conditions, parasite-induced changes in predation dynamics could lead to higher survival rates for chum salmon, despite the presence of sea lice. This is because the predation pressure shifts towards pink salmon, which are more affected by the sea lice. The findings highlight the importance of considering the broader ecological context when evaluating the impact of parasites on host populations. In some cases, the expected negative effects of parasites may be mitigated or even reversed due to complex interactions with other ecological factors like predation.

2.1.29 Parasitism and food web dynamics of juvenile Pacific salmon

Peacock, S., Krkošek, M., Bateman, A., & Lewis, M. (2015). Parasitism and food web dynamics of juvenile Pacific salmon. *Ecosphere*, 6(12), art264. https://doi.org/10.1890/ES15-00337.1

Coho salmon preferentially prey on pink salmon over chum salmon. This preference slightly increases when prey are parasitized by sea lice, although the effect size is small and uncertain. Peacock et al. (2015) found that sea lice infestations make pink salmon more vulnerable to predation. However, under certain conditions, the presence of sea lice could lead to a reduction in predation on chum salmon due to a shift in predator preference towards the more affected pink salmon. A mathematical model suggests that there is a critical abundance of pink salmon above which predation on chum salmon decreases with increasing sea lice. This threshold depends on the number of pink salmon, the predators' handling time, and the base attack rate on pink salmon. The findings highlight the importance of considering species-selective predation and parasite-mediated interactions when assessing the impact of parasites on host populations. Even small changes in predator preference due to parasites can have significant ecological consequences, potentially altering population dynamics and survival rates.

2.1.30 Cessation of a salmon decline with control of parasites

Peacock, S., Krkošek, M., Proboszcz, S., Orr, C., & Lewis, M. (2013). Cessation of a salmon decline with control of parasites. *Ecological Applications*, 23, 606–620. https://doi.org/10.1890/12-0519.1

In this 2013 study, Peacock et al. documented a decline in wild pink salmon populations coinciding with sea lice epizootics from 2001 to 2005. High levels of sea lice on farmed salmon were linked to increased infestations on wild juvenile salmon, contributing to the population decline. In response to the decline, salmon farms began applying parasiticides (specifically emamectin benzoate, known as "SLICE") during the winter months before the juvenile wild salmon out-migration. This strategic timing helped to reduce sea lice levels on farmed salmon before the wild salmon migrated through farming areas, thereby lowering the transmission of lice to wild populations. The implementation of winter treatments led to a significant reduction in sea lice levels on wild juvenile salmon, which correlated with a recovery in wild pink salmon populations. By 2006, this change in management marked a turning point, with subsequent years showing improved survival and productivity of wild salmon. While the adaptive management approach has been successful in the short term, the study raises concerns about the long-term sustainability of relying on parasiticides. There is potential for the development of resistance in sea lice and unknown ecological impacts from continued chemical use.

2.1.31 Evidence of farm-induced parasite infestations on wild juvenile salmon in multiple regions of coastal British Columbia, Canada

Price, M. H. H., Morton, A., & Reynolds, J. D. (2010). Evidence of farm-induced parasite infestations on wild juvenile salmon in multiple regions of coastal British Columbia, Canada. *Canadian Journal of Fisheries and Aquatic Sciences*, 67, 1925–1932. https://doi.org/10.1139/F10-105

Louse prevalence and abundance were significantly higher in areas with high exposure to salmon farms compared to areas with low exposure and regions without farms (e.g., Bella Bella). This suggests that salmon farms are a major source of sea lice that infect wild salmon. *L. salmonis* was more prevalent at high-exposure sites, while *C. clemensi* was more common in areas with lower exposure to farms. This shift in louse species composition further indicates that salmon farms are altering the natural parasite dynamics. Although factors such as salinity and temperature were found to have some influence on louse prevalence, exposure to salmon farms was the most significant factor. The study found that louse abundance was correlated with the amount of salmon produced in a given farm region. The findings highlight the potential threat that salmon farms pose to wild salmon populations, particularly through the transmission of sea lice. The paper underscores the need for better management practices, such as reducing farm densities and relocating farms away from wild salmon migration routes, to mitigate these impacts.

2.1.32 Sea louse infection of juvenile sockeye salmon in relation to marine salmon farms on Canada's west coast

Price, M. H. H., Proboszcz, S. L., Routledge, R. D., Gottesfeld, A. S., Orr, C., & Reynolds, J. D. (2011). Sea louse infection of juvenile sockeye salmon in relation to marine salmon farms on Canada's west coast. *PLoS ONE*, 6, e16851. https://doi.org/10.1371/journal.pone.0016851

Juvenile sockeye migrating from the Fraser river through areas with salmon farms had significantly higher levels of sea lice compared to those from the Skeena River, which migrated through areas without farms. The study identified two main species of lice: *C. clemensi* and *L. salmonis*. *C. clemensi* was more prevalent, particularly downstream of salmon farms, indicating that farms may be a source of infection. The abundance of L. salmonis was also higher downstream of farms, with variations between years corresponding to changes in lice levels on the farms. While environmental factors like salinity and temperature influenced lice levels, the study found that proximity to salmon farms was the most significant factor affecting lice abundance on juvenile sockeye. The findings suggest that salmon farms could be contributing to the transmission of sea lice to wild sockeye salmon, which may have implications for the health and survival of these populations, particularly those already under stress from other environmental factors.

2.1.33 Spatial patterns of sea lice infection among wild and captive salmon in western Canada

Rees, E., St-Hilaire, S., Jones, S., Krkošek, M., DeDominicis, S., Foreman, M., Patanasatienkul, T., & Revie, C. (2015). Spatial patterns of sea lice infection among wild and captive salmon in western Canada. *Landscape Ecology*, 30, 989–1004. https://doi.org/10.1007/s10980-015-0188-2

Sea lice infection levels in wild juvenile salmon (chum and pink) were found to be correlated with infection levels in farmed salmon within a 30 km radius. This suggests that salmon farms contribute significantly to the spread of sea lice to wild salmon populations within this distance. The study identified several factors that strongly influenced sea lice infection levels in wild salmon, including fish length, salinity, and the year of sampling. Higher infection levels were associated with larger fish, higher salinity, and certain years with favorable conditions for lice survival. The analysis revealed that the infection pressure from farms, even when sea lice levels were below regulatory limits, still had a measurable impact on the infection levels in wild salmon. This highlights the importance of farm management practices in controlling lice levels. The study also found that environmental factors, like salinity and the spatial distribution of farms and wild salmon, play critical roles in the transmission dynamics of sea lice. Areas with higher salinity and closer proximity to farms showed higher infection levels.

2.1.34 Effect of government removal of salmon farms on sea lice infection of juvenile wild salmon in the Discovery Islands

Routledge, R., & Morton, A. (2023). Effect of government removal of salmon farms on sea lice infection of juvenile wild salmon in the Discovery Islands. *Canadian Journal of Fisheries and Aquatic Sciences*, 80, 1984–1989. https://doi.org/10.1139/cjfas-2023-0039

In December 2020, the Canadian government banned the restocking of salmon farms in the Discovery Islands, leading to the gradual removal of active farms. By 2022, only one farm remained in operation, compared to eight in 2020. This study provides compelling evidence that the removal of salmon farms led to a significant decrease in sea lice infections on juvenile wild salmon in the Discovery Islands. This suggests that salmon farms are a major source of sea lice, and their removal can help reduce parasitic infections on wild fish, potentially aiding in the recovery of salmon populations. Over the three years since the removal of the farms, the average number of sea lice per fish decreased by 96%, from 5.15 lice/fish in 2020 to 0.198 lice/fish in 2022. This significant decline in sea lice infection was not seen in nearby regions like the Broughton Archipelago, where no farm removal occurred. The reduction could not be explained by changes in environmental factors like salinity and temperature. The study also found that during the transition year (2021), higher sea lice levels were recorded near the remaining active farms, suggesting those farms were still contributing to infection levels.

2.1.35 Impacts of parasites on marine survival of Atlantic salmon: a meta-analysis

Vollset, K. W., Krontveit, R. I., Jansen, P., Finstad, B., Barlaup, B. T., Skilbrei, O. T., Krkošek, M., Romunstad, P., Aunsmo, A., Jensen, A. J., & Dohoo, I. (2016). Impacts of parasites on marine survival of Atlantic salmon: A meta-analysis. *Fish and Fisheries*, 17(3), 714–730. https://doi.org/10.1111/faf.12141

In this 2016 paper, Vollset et al. deliver a systematic review and meta-analysis evaluating the impacts of anti-parasitic treatment on Atlantic salmon in Norway from 1996 to 2011. The study uses 118 release groups with 657,624 fish released and 3,989 fish recaptured. While outcomes are variable, 70% of trends are explained by released location, time period, and baseline survival. Of these variables, baseline survival is most significant. The anti-parasitic treatment appears to protect smolts from parasites during outward migration, but treatment effect was modulated by other risk factors and there were data limitations. The authors recommend a more comprehensive data set to improve comprehension on lice exposure and the migratory routes of smolts.

3 Additional Reading

3.1 Ecosystem

3.1.1 Ecosystemic effects of salmon farming increase mercury contamination in wild fish

Debruyn, A. M., Trudel, M., Eyding, N., Harding, J., McNally, H., Mountain, R., Orr, C., Urban, D., Verenitch, S., & Mazumder, A. (2006). Ecosystemic effects of salmon farming increase mercury contamination in wild fish. *Environmental Science & Technology*, 40(11), 3489–3493. https://doi.org/10.1021/es0520161

Debruyn et al. (2006) examined the impacts of open-net salmon farms on the cycling of mercury contamination in coastal ecosystems in British Columbia by sediment and biota sampling. The study reveals that nearby demersal rockfish contain elevated levels of mercury. This is likely due to prey-based mercury-loading from waste feed/feces and mercury in sediment from farm-induced anoxia. Even with fallowing periods, mercury levels in rockfish remain elevated and mercury-based sediment promotes long-term contaminant cycling. Given the long lifespan of rockfish and the persistence of sediment anoxia, this study reveals that mercury-cycling is not transitory like other ecosystem impacts of salmon farming and suggests that aquaculture management practices be improved to account for long-term contaminant cycling. This paper underscores the long-term ecosystem effects driven by salmon farming.

3.1.2 A global assessment of salmon aquaculture impacts on wild salmonids

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

Ford and Myers (2008) examined the survival of wild salmonids near salmon farms in Scotland, Ireland, Atlantic Canada, and Pacific Canada through a meta-analysis of existing stock data from the late 1980s. Analysis reveals a significant negative correlation between the production of farmed salmon and the survival and abundance of the five species studied (Atlantic salmon, sea trout, pink salmon, chum salmon, and coho salmon). In some instances, reductions in survival and abundance surpass 50%. It is estimated that wild salmonid populations will continue to shrink as aquaculture production increases. The study emphasizes the need to prioritize salmon farming measures that promote wild salmon survival.

3.2 Economics

3.2.1 Dead Loss: The high cost of poor farming practices and mortalities on salmon farms

Just Economics. (2021). *Dead loss: The high cost of poor farming practices and mortalities on salmon farms*. Aquaculture Report V5. https://www.justeconomics.co.uk/uploads/reports/Aquaculture-Report-v5.pdf

This report provides an overview of the economic, environmental, and social aspects of the salmon aquaculture industry. Norway, Chile, Canada, and Scotland account for 96% of global farmed salmon production. The report identifies mortalities (through parasites, disease, and pollution) as the biggest cost to the industry. Other major costs are allocated towards parasite control and the use of wild-caught salmon in fish feed. The cost of parasite control is estimated at over $4 billion since 2013. The cost of wild-caught salmon in fish feed is estimated to cost $8 billion. The cost of pollution abatement is estimated at over $4 billion. The loss of ecosystem services from declines in wild salmon stocks are estimated at $308 million. Consumer willingness to pay for higher fish welfare standards is estimated at $4.6 billion. Overall, this analysis estimates that salmon aquaculture generates private and external costs of almost $50 billion since 2013. It is recommended that decision makers shift to support a transition to more sustainable aquaculture. This report is consistent with other literature raising concern for the significant economic, environmental, and social risks within the aquaculture industry.

3.2.2 Fished or farmed: Life cycle impacts of salmon consumer decisions and opportunities for reducing impacts

Ziegler, F., & Hilborn, R. (2023). Fished or farmed: Life cycle impacts of salmon consumer decisions and opportunities for reducing impacts. *Science of The Total Environment, 854*, 158591. https://doi.org/10.1016/j.scitotenv.2022.158591

Ziegler and Hilborn (2023) conducted a Life Cycle Assessment (LCA) of the environmental impacts of fresh and frozen salmon products from two major salmon fisheries in Alaska (one for pink salmon, one for sockeye) and Norwegian aquaculture. The LCA includes impact categories (e.g. greenhouse gas emissions, marine eutrophication, marine ecotoxicity, land use) to provide insights into the sustainability of different salmon products. Compared to Norwegian farmed salmon, wild salmon products in Alaska show 46–86% and 12–71% lower greenhouse gas emissions for American and European consumers, respectively, depending on species and product form. The study recommends that aquaculture improve the sustainability of the supply chains to reduce greenhouse gas emissions as salmon consumption continues to increase globally.

3.3 Sustainability

3.3.1 Feeding global aquaculture

Roberts, S., Jacquet, J., Majluf, P., & Hayek, M. N. (2024). Feeding global aquaculture. *Science Advances*, 10(42). https://doi.org/10.1126/sciadv.adn9698

In this paper, Roberts et al. (2024) assess the sustainability of aquaculture by examining data on feed composition. The authors identify a farmed output ratio ranging from 0.36 to 1.15, which exceeds the previous estimate (0.28) by 27% to 307%. The authors conclude that wild fish mortality in aquaculture has been underestimated and has had a significant environmental impact. Additionally, the study shows that the growth in aquaculture has been accompanied by a fivefold increase in the use of feed crops from 1997 to 2017. These insights challenge current claims about the sustainability of aquaculture and its role in food security. Overall, there is a need for greater transparency within this industry and a necessity for rigorous evaluation of aquaculture's environmental footprint.