Vol. 14: 181–188, 2022
https://doi.org/10.3354/aei00436
AQUACULTURE ENVIRONMENT INTERACTIONS
Aquacult Environ Interact
Published July 14

OPINION PIECE

Considering elements of natural strategies to control salmon lice infestation in marine cage culture

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ABSTRACT: Salmon lice are a severe problem in salmonid aquaculture and also affect wild salmon smolts migrating through fjord systems in spring. To keep the lice burden within acceptable limits, frequent use of chemical delousing has resulted in the parasite becoming resistant to these treatments. Alternative thermal and mechanical delousing practices induce welfare problems and loss of farmed fish. To avoid losing the constant arms race with the parasite, we need a new approach to the problem. Inspired by the natural host–parasite balance, we propose a change in salmonid aquaculture practices by combining and improving existing management strategies for a more holistic and sustainable vision of the industry. Before salmonids were farmed in open cages, few hosts were available for salmon lice during winter, which reduced the salmon lice populations to a minimum when the wild smolts were migrating to sea. Thus, the natural strategy is to decrease host availability for a sufficient period of time to allow salmon lice nauplii to die of starvation. Due to the long survival and drift of the nauplii, it is important to significantly increase the distance between open farming units, either by organising and aggregating farms in extensive fallowing areas with significant distance to other corresponding areas or by controlling water flow through active production units during extensive fallowing. Here we primarily address environmental interactions. Economic and juridical implications of the proposed strategy are not discussed in detail. However, we do briefly suggest relevant current regulations and possible costs and benefits of reducing delousing treatment intensity.

KEY WORDS: *Lepeophtheirus salmonis* · Salmon lice infection pressure · Farmed/wild salmonid interactions · Arms race

1. THE PROBLEM

A generalised problem in intensive animal husbandry is that high animal densities benefit parasites due to the high host availability (Colvin et al. 2012, Aaen et al. 2015, Børretzen Fjørtoft et al. 2019). Salmonid aquaculture is no exception. In the North Atlantic Ocean, salmon lice *Lepeophtheirus salmonis* are specialized in infesting salmonids. Severe infestations can lead to sores, osmoregulatory failure, stress, and immunosuppression (Tveiten et al. 2010).

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Publisher: Inter-Research · www.int-res.com

Increased production of salmonids in open sea cages has boosted the availability of hosts for salmon lice, leading to an extensive and sustained production of lice larvae throughout the year (Heuch & Mo 2001, Dempster et al. 2021). The nauplii produced by adult lice on farmed fish also infest wild salmonids, reducing their marine survival. This, combined with anthropogenic pressures, such as agriculture, climate change, and road construction, which change the riverine environment, can result in population declines in wild stocks (Børretzen Fjørtoft et al. 2014).

To address this problem, regulations exist to limit the number of lice on farmed fish. To keep salmon lice infestations within mandatory low limits, treatment intensity is increasing, which also drives resistance among the salmon lice not only to chemicals, but possibly also to freshwater exposure, thermal and biological treatments, and selective breeding methods (Ljungfeldt et al. 2017, Børretzen Fjørtoft et al. 2021, Coates et al. 2021, Dempster et al. 2021). Treatment can also induce a reduction in welfare and, ultimately, the loss of farmed fish and thereby income and reputation of the industry. Furthermore, treatment-related complex logistics result in additional expenses for the farmers (Abolofia et al. 2017, Greaker et al. 2020). This raises serious questions about the sustainability of the current production systems (Overton et al. 2019).

The infection pressure from the parasite remains high at some sites regardless of treatment protocols (Nelson et al. 2018, Vollset et al. 2018b). Delousing fish in just 1 to 2 cages and transferring them back adjacent to non-deloused fish will lead to instant reinfection. Moreover, contact with nearby farms and tidal currents transporting the nauplii back and forth in the farm environment may cause frequent reinfection of deloused fish. The vertical migration of the nauplii between different layers with different current direction may also sustain the nauplii population on site, inducing the reinfection of deloused fish (Johnsen et al. 2014).

Since salmon lice have hosts in the natural environment that interact with the hosts inside the cages, it will be impossible to eliminate this parasite. The strategy in the current official management system is to control the infection pressure in the marine environment. However, rules and regulations are complex, sometimes short-sighted, and open to different interpretations (Wold Sund & Mestad 2021). Technological innovations may also constitute quick fixes, rather than prioritizing long-term solutions with high public acceptance and sustainable results (Fauchald 2020, Greaker et al. 2020, Wold Sund & Mestad 2021).

This paper presents an alternative management strategy that incorporates different available technologies and management practices for more holistic problem-solving and a sustainable future of the industry, with less impact on wild salmonid stocks.

2. OFFICIAL MANAGEMENT GUIDELINES

The official Norwegian strategy is to promote the growth of the aquaculture sector under sustainable and satisfactory environmental conditions. The problems with lice on wild salmon smolts during outmigration has limited sustainable growth in parts of Norway. The 'traffic light system' (NMTIF 2015) regulates the production capacity allowed in defined production areas along the coast according to a model that predicts the risk of salmon lice-induced mortality on wild salmon smolts migrating out of the fjords in the spring. The production is then stabilised ('yellow'), adjusted upward ('green'), or adjusted downward ('red') (Vollset et al. 2018a). The intention is that the farmers are collectively responsible for the salmon lice pressure and thereby for potential growth in their production area (NMTIF 2017a).

There is also mandatory registration of mean salmon-louse burden on salmon in all marine farms to protect wild salmonids and to assure acceptable animal welfare standards in the cages. The louse-burden limit is <0.2 adult female lice per fish prior to wild smolt migration, and <0.5 adult female lice per fish for the rest of the year (NMTIF 2017b). Despite these strict regulations on infestation limits, 4 out of the 13 production areas in Norway are currently assigned to 'red' and 'yellow' based on the traffic light system. These are areas with high production intensities, large fjord systems, and rivers with local wild salmon stocks, which suggests that the mandatory louse limit of <0.2 adult females per fish is not sufficient during wild smolt outmigration (Johnsen et al. 2021).

Furthermore, to assure high environmental standards in the production of salmonids, related measures are implemented: a maximal allowed biomass determined per farming site, monitoring the seabed condition for organic wastes and fallowing of the farming sites for about 2 mo to allow the seabed to clean itself from pollution generated by the previous production. In addition, nearby farms are aggregated into zones with geographical separation to adjacent zones. These farm aggregations are termed 'generation zones', having coordinated fallowing, smolt transfer (same generation), and slaughter. A 2–5 km distance between farms and generation zones is mandatory.

The aim is to try to keep pathogen numbers under control (Guarracino et al. 2018, NMTIF 2021).

Based on verbal information provided by the Norwegian Seafood Authorities, the size of each generation zone and the number of farms in each zone may vary, depending on the number of farmers and farming sites involved. Generally, the number ranges between 3 and 7 sites (range: 1–15). A distance of 5 km between generation zones is recommended, meaning that farming sites >5 km away from any adjacent farms may function as 1 generation zone. This also means that many newly fallowed areas will still have close water contact and may incur extensive infection pressure from adjacent generation zones.

3. TREATMENTS

The use of chemotherapeutants has been an effective way of keeping lice infestations below the mandatory limit. However, the reliance on just a few chemicals has resulted in the widespread evolution of salmon lice resistance to most active compounds (Aaen et al. 2015, Børretzen Fjørtoft et al. 2019, Dempster et al. 2021), which has caused a shift in the treatment strategies of salmon lice in the Norwegian aquaculture industry (Fig. 1).

Various mechanical, including thermal, delousing methods have been developed to replace chemical treatment. Although these methods can be effective in removing lice, they induce stress and mortality in the salmon (Overton et al. 2019). Cleaner fish such as lumpsucker and various wrasse species that pick pre-adult and adult lice off the farmed salmonids are commonly used; however, catching wild wrasses may disturb and diminish local stocks. Cleaner fish can also transmit diseases to the farmed fish, and the efficiency of the cleaner fish and their welfare in the cages are also questionable (Murray 2016, Bui et al. 2020, Geitung et al. 2020, Overton et al. 2020).

4. ALTERNATIVE TECHNOLOGIES

Long-term resistance to salmon lice can be achieved in salmonids using selective breeding (Houston 2017). Ten generations of family-based selective breeding are predicted to reduce the frequency of delousing events in salmonid farming, assuming lice do not adapt to the changing host population over this period of time (Gharbi et al. 2015). Functional feeds and vaccines might also be an option, but no effective product has yet been developed (Barrett et al. 2020).

To minimize host–parasite contact, swimming depth manipulation using light, feeding depth, and net pens such as 'snorkels' or 'skirts' have been implemented with good results. Completely enclosed cages and land-based production either in recirculating aquaculture systems or flow-through systems are alternatives to control water-borne transmission of pathogens (Stien et al. 2016, Oppedal et al. 2017, Barrett et al. 2020).

Offshore aquaculture has gained increased attention as a way of expanding the production of commercially important fish, but few farms are active. Large hull-based salmon farms are under construction, which make it possible not only to move, but also to close and thereby control the quality and depth of the water inlet and utilise optimal water quality for salmon production (Soltveit 2018).

From an environmental point of view, it could be argued that, in future, salmonid aquaculture should be in closed cages or in land-based containers with

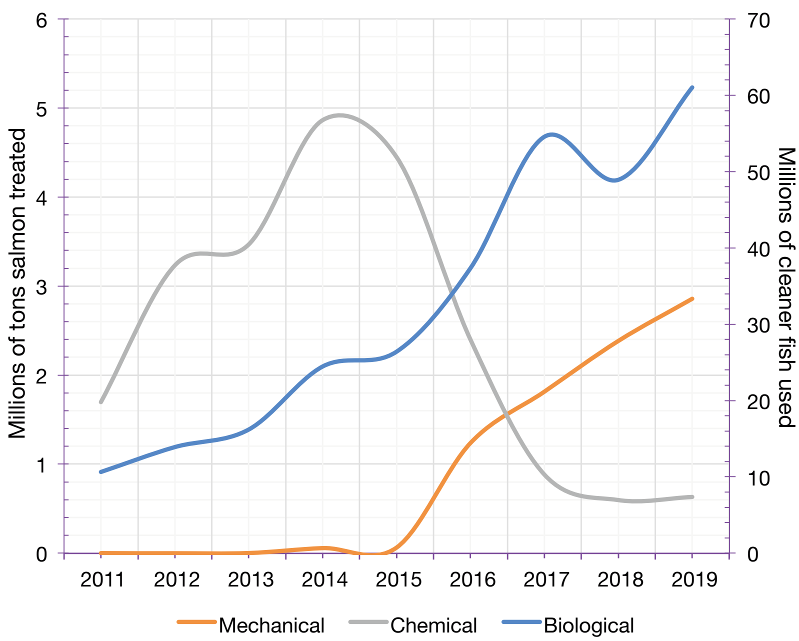

Fig. 1. Sea lice treatments used by the Norwegian aquaculture industry between 2011 and 2019. Mechanical treatments include thermal application of Thermolicer and Optilicer. Chemical and mechanical treatments are expressed in millions of tonnes of salmon treated, while biological treatments are expressed in millions of cleaner fish used (for references and statistics, see the Supplement at www.int-res.com/articles/suppl/q014p181_supp.pdf)

the possibility of controlling and cleaning the water flowing in and out of the production units in order to avoid pollution and pathogens and to control the salmon-lice problem. However, the Norwegian coastline offers a water quality perfect for fish farming without using energy, technology, or labor for pumping, cleaning, and monitoring water systems. Another aspect is that shore areas are attractive for stakeholders and for purposes other than aquaculture, e.g. recreation, ports, urban development (Hersoug et al. 2021). Moving large quantities of biomass on land would also generate an increase in the carbon footprint of the industry (MacLeod et al. 2020).

5. NATURAL HOST–PARASITE BALANCE

Before the introduction of salmonid aquaculture along the Norwegian coast, wild Atlantic salmon *Salmo salar*, sea trout *S. trutta*, and sea-going Arctic charr *Salvelinus alpinus* were infested with salmon lice only during their seawater phase. Fresh and brackish water had a natural delousing effect on the spawners when they returned from their marine feeding grounds (Børretzen Fjørtoft et al. 2014). In the winter, wild Atlantic salmon were either on their feeding grounds in the North Atlantic or in rivers, while sea trout concentrated near fresh and brackish waters, making short migrations into the fjord for feeding (Thorstad et al. 2016).

From the moment they hatch until their energy reserve is spent, salmon lice larvae have approximately 140 degree days (e.g. 20 d at 7°C) to localise a host before starvation (Samsing et al. 2016). During the winter months, the lack of available hosts in the absence of aquaculture reduced the population of salmon lice in the fjords significantly. As a result, the seaward-migrating smolts could reach their feeding grounds without encountering high levels of salmon lice, which increased their chances of growing and surviving to contribute positively to the stocks of the different rivers (Johnsen et al. 2021).

6. THE SOLUTION: A COMBINATION OF STRATEGIES

To control the salmon lice infection pressure upon wild salmonids, and at the same time increase farmed salmonid production volumes, new sustainable strategies are needed. As the overall aim is to deprive the parasite from access to hosts from the moment the nauplii hatch until death from starvation, a fallowing period of a maximum of 30 d is required. Here, we describe 2 main strategies for controlling salmon lice through the implememtation of elements in the natural host–parasite balance: (1) the creation of larger generation zones with much longer distances between adjacent zones than used today; and (2) by closing production units and controlling the water flow when production needs to remain in a generation zone during fallowing, or alternatively, moving the fish out of the area.

The current mandatory fallowing period of 2 mo is generally long enough to exceed the timespan for the survival of nauplii without a host for any water temperature relevant to the Norwegian coast throughout the year. However, with a mandatory distance between farms and generation zones of only 2–5 km and given the speed of sea currents required for cage-based salmon production, pathogens may be transported from farm sites and slaughter facilities for extensive distances before acquiring a host (Asplin et al. 2011, Kristoffersen et al. 2013, Price et al. 2013, Stene et al. 2014, Kragesteen et al. 2019). Based on related studies, more than 50 km between farms and generation zones with open cages would be more likely to decrease host availability for the lice (Brooks 2005, Middlemas et al. 2013, Salama et al. 2016).

Official regulations are intended to control the salmon lice infection pressure by reducing the number of hosts in production areas under stress and limiting the maximum lice burden per farmed fish (NMTIF 2017a,b). However, with the substantial number of hosts constantly available for the lice, a general reduction of biomass density per farm and production area would not be sufficient to reduce the infection pressure to a level that will not affect out-migrating smolts (Heuch & Mo 2001, Kristoffersen et al. 2013, van Walraven et al. 2021). Coordinated fallowing will also fail if the distance between generation zones is not extended.

Fig. 2 illustrates how extensive and coordinated fallowing of a generation zone might be achieved in a fjord system with many farming sites in different stages of their production cycle. The aim is to protect wild local salmonid populations from severe salmon-lice infestation. To obtain this effect it is crucial that no salmon is produced in open cages during fallowing and that the distance to the next generation zone is substantial. The most complete barrier technologies are fully enclosed production units supplied with louse-free water either filtered or pumped from depths below the typical depth range of copepodites (Nilsen et al. 2017, Barrett et al. 2020). Closed sea-based or land-based systems must be available to

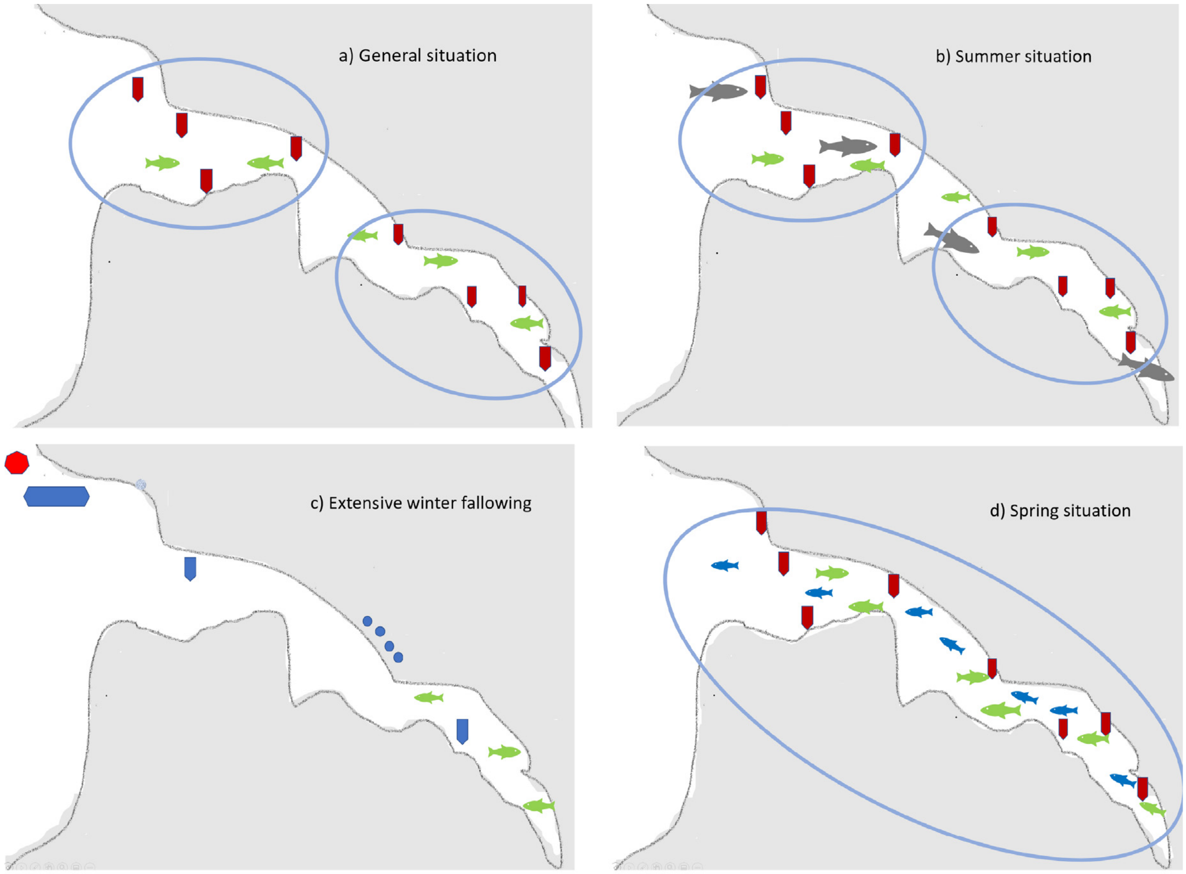

Fig. 2. Interactions between farmed and wild salmonids in a fjord system. (a) General situation: farmed salmonids in production (red cages) are in close interaction with wild sea trout (green fish) feeding in the fjord. The production is divided into 2 generation zones (blue ellipses). (b) Summer: full production on farming sites. Wild salmon (grey fish) migrate towards rivers to spawn and have limited contact with farmed fish. Wild sea trout (green fish) feed within the fjord. (c) Winter: fallowing the whole fjord for 1 mo by emptying cages (slaughtering fish), closing units that need to be in production (blue cages), producing fish offshore (red heptagon), and moving fish out of the fjord (blue hexagon). Autumn smolt are kept in cages or tanks onshore (blue circles). Sea trout (green fish) migrate toward more brackish and fresh water. (d) Spring: autumn and spring smolt are transferred to open (red) cages. Fish produced in closed cages are slaughtered. Wild smolt begin migrating from rivers (blue fish). Sea trout (green fish) feed in the fjord. The whole fjord system is organised in 1 generation zone (blue ellipse), with large distances between nearby zones

keep the autumn smolt for on-growing under controlled conditions before transfer to cages at sea. Barriers of various types such as ‘skirts’, ‘snorkels’, or ‘tarpaulins’ may also prevent copepodites from entering the cages. Such equipment and technology must be shared between farmers and be available if salmon need to be in production during fallowing. Local wild sea trout will make short migrations into the fjord in this period and thus can act as a host for salmon lice (Serra-Llinares et al. 2014).

Water transport models are available and should be considered when defining larger generation zones and to obtain maximum control and impact of fallowing and treatment (Asplin et al. 2020). The geographical sequence of de-lousing at farms and fallowing of generation zones should be performed according to the dominating water current direction along the coast.

One aspect to consider regarding extensive fallowing is the size of salmonids demanded by the market. Another aspect is to control and reduce infection pressure from adjacent zones. Farmed salmon in the second spring of production are the primary hosts for salmon lice (Butler 2002). Large fish (≥2 kg) are also more susceptible to increased mortality during de-lousing (Overton et al. 2019). Therefore, the number of large salmon should be adjusted through slaughter at relevant size for the market even if the optimal price is not obtained. Keeping the salmon for a longer time in controlled systems before sea transfer is also an option to reduce production time in the sea and to adjust production according to the market.

7. IMPLICATIONS OF EXTENSIVE FALLOWING

Common threats require common efforts. The strategy and the extensive intervention we propose will affect the logistics, production, and profits, as well as laws and regulations. Production costs are likely to increase due to the slaughter of fish at sub-optimal market sizes. Similar for requirements for barrier technologies and site-flexible systems (Soltveit 2018). Keeping smolts in closed systems before sea transfer and using larger smolts to reduce production time at sea will also require expensive facilities. A completely closed cage system may cost 10- to 50-fold more than an open cage. Land-based systems will cost even more (NF 2021, 2022). However, our suggestion is not to replace open cages with closed production units, but to have closed systems available if needed during fallowing. The costs of such infrastructure may be shared between farmers in generation zones or production areas under bio-secure conditions, financed by farmers or their industrial bodies, with incentives from the authorities.

Although costs related to extensive fallowing will increase, they are likely to decrease in the long run by saving on delousing practices. Indeed, in Norway, where some production sites are forced to reduce their production capacity due to salmon lice, large sums are spent on delousing activities. The cost of salmon lice for Norwegian farmers is over 5 billion NOK (510 million USD), plus significant indirect costs (McDonagh 2019). In 2019, more than 50 million salmon died in cages (Nedrejord 2021). One way of increasing production is to keep more farmed salmonids alive. Another way is to better control the lice infection pressure upon wild and farmed salmonids.

Production in a shared environment requires close cooperation among farmers but also with management authorities to achieve optimal fallowing. In addition, unequivocal laws and regulations providing long-term predictability for stakeholders are crucial. These regulations must apply to every farmer, and enforcement may be needed (Kragesteen et al. 2019).

The traffic light system was designed to give farmers incentives to collaborate in their efforts against lice and to increase the production of farmed salmonids in their production area (Hersoug et al. 2021). However, by introducing interregional biomass limits, companies could move some of their allowed production volume from one production area to another. This, combined with new research and innovation licenses for testing new innovations in marine salmon production, may result in an unwanted increase in production in 'yellow' and 'red' areas that initially are not allowed to increase production. This may undermine the original intent of the system (NMTIF 2017a, Fauchald 2020). Regulations susceptible to differences in interpretation are contrary to the stringent intentions behind the traffic light system (NMTIF 2015).

This may result in laws and regulation that, for some farmers, seem unjust, and may also be compounded with the number of different administrative bodies operating at different levels in the decision process (Wold Sund & Mestad 2021), leading to an increased risk for decisions to be perceived as arbitrary. The main priority should be to draft a new aquaculture law that improves and simplifies the comprehensive and at times short-term regulatory framework (Wold Sund & Mestad 2021). This is also the priority of the Norwegian government (Norwegian Government 2021).

Changing and coordinating fallowing regimes at the national level, not only in each extensive generation zone but also in adjacent generation zones, will be complex, but possible and necessary to solve an urgent problem in a long-term perspective. The aquaculture industry is adding pressure on wild salmonid stocks in Norwegian rivers — especially on out-migrating smolts if they encounter high levels of salmon lice produced at salmonid farming sites along their migration route. It is our responsibility to (take some of the cost to) develop and implement long-term strategies against sea-lice infection pressure to improve their survival.

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Editorial responsibility: Tim Dempster, Melbourne, Victoria, Australia;
Christine Paetzold, Oldendorf/Luhe, Germany
Reviewed by: S. Murray and 2 anonymous referees and previous version reviewed in AEI by S. Murray and 2 anonymous referees

Submitted: November 18, 2021
Accepted: May 18, 2022
Proofs received from author(s): July 5, 2022