R E V I E W An aquaculture risk model to understand the causes and consequences of Atlantic Salmon mass mortality events: A review

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REVIEW

REVIEWS IN Aquaculture

An aquaculture risk model to understand the causes and consequences of Atlantic Salmon mass mortality events: A review

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Abstract

Mass mortality events (MMEs) are defined as the death of large numbers of fish over a short period of time. These events can result in catastrophic losses to the Atlantic salmon aquaculture industry and the local economy. However, they are challenging to understand because of their relative infrequency and the high number of potential factors involved. As a result, the causes and consequences of MMEs in Atlantic salmon aquaculture are not well understood. In this study, we developed a structural network of causal risk factors for MMEs for aquaculture and the communities that depend on Atlantic salmon aquaculture. Using the Interpretive Structural Modeling (ISM) technique, we analysed the causes of Atlantic salmon mass mortalities due to environmental (abiotic), biological (biotic) and nutritional risk factors. The consequences of MMEs were also assessed for the occupational health and safety of aquaculture workers and their implications for the livelihoods of local communities. This structural network deepens our understanding of MMEs and points to management actions and interventions that can help mitigate mass mortalities. MMEs are typically not the result of a single risk factor but are caused by the systematic interaction of risk factors related to the environment, fish diseases, feeding/nutrition and cage-site management. Results also indicate that considerations of health and safety risk, through pre- and post-event risk assessments, may help to minimize workplace injuries and eliminate potential risks of human fatalities. Company and government-assisted socio-economic measures could help mitigate post-mass mortality impacts. Appropriate and timely management actions may help reduce MMEs at Atlantic salmon cage sites and minimize the physical and social vulnerabilities of workers and local communities.

KEYWORDS
aquaculture, aquaculture system designing, environmental stressors, mass mortality event (MME), risk assessment, salmon disease

1 | INTRODUCTION

In 2022, the Food and Agriculture Organization (FAO) of the United Nations estimated that global seafood production in 2020 was 178 million metric tonnes (MMT) with an estimated total sale value of $406 billion US; of which $265 billion US (88 MMT of fish production) came from aquaculture.[1] Thus, animal aquaculture accounted for nearly 49% of total seafood production globally in 2020. The growth of the industry and its sustainability are seen as critical to future seafood (food) security, given that the projected demand for seafood may increase by 44 MMT by 2050 (up to a 50% increase compared to the current production level),[2] and because commercial seafood fishery landings have plateaued. Expanded production can also reduce global seafood trade deficits in some countries, create local employment opportunities, and enhance community prosperity in often isolated rural regions.[3] One of the possible constraints on expanded aquaculture production is an increase in the frequency and magnitude of large-scale farmed fish mass mortality events (MMEs) in many jurisdictions, as shown in Supporting Information: Table 1. Such events threaten the sector's sustainability.[4–7]

Any given MME can vary in magnitude from a few thousand to over a million organisms.[8] MMEs are defined differently in different jurisdictions and by various authors, who stress diverse aspects of their causes and effects. For example, Fey and colleagues define MMEs as 'catastrophic demographic events that can affect all life stages of an animal and have the potential to eliminate a substantial portion of a marine population in a short period'.[9] Another study defines MMEs as 'large environmental perturbations that produce sudden major reductions in population size'.[10] Another work on die-offs defines an MME as 'a decrease of 50% or more of a population in one year'.[11] Finally, Kibria defines an MME as the sudden death of a large number of fish over a short period in a defined area.[8] In this study, we adopt an MME definition specifically related to aquaculture operations: an event that results in the loss of a considerable proportion of a farmed marine population over a period of days to weeks.

In the world's leading Atlantic salmon-producing countries, including Norway, Chile, the United Kingdom (UK) and Canada, recorded mass die-offs of salmon are of concern to industry and regulators.[12,13] For example, in 2019, the Norwegian aquaculture industry lost 59.3 million farmed salmon,[7] of which 52.8 million salmon died in MMEs.[14]

In 2016, nearly 12% of Chilean salmon production (more than 40,000 MT) was lost due to harmful algal blooms (HABs), resulting in an economic loss of more than $800 million US.[15] In 2020 in the UK, the Scottish aquaculture industry lost 27,000 MT of salmon due to MMEs—a production loss almost four times higher than the loss in 2010.[6,16] At Scottish sea farms, post-smolt mass mortality due to MMEs is estimated to be approximately 14.5%.[17] Finally, in 2020, Mowi Canada East experienced an MME at their farm sites on the south coast of Newfoundland, where an estimated 450,000 Atlantic salmon died due to high sustained water temperatures, in combination with hypoxia and the effects of sea lice and corresponding treatment interventions.[18] These MMEs are also common for other salmonid species, such as coho salmon and trout. For example, on 2 January 2024, an MME in Chile caused the loss of approximately 3800 MT of Atlantic and coho salmon.[19] On 20 November 2023, a similar MME resulted in the loss of ~500 MT of coho salmon and rainbow trout. The common cause for both MMEs was HABs.[20]

There have been several lab-based studies on the effects of one or a combination of two factors (e.g., temperature, hypoxia, a combination of hypoxia and temperature, or a combined effect of temperature and sea lice) that contribute to the risk of salmon MMEs (e.g., see reference 21). Further, a study recently explored the correlation between 65 different causes of salmon mortality through linear models,[22] and another detailed the putative determinants of 'baseline mortality' among Norwegian populations of farmed Atlantic salmon.[13] However, these analyses often consider limited risk factors (and limited interactions between risk factors), and thus, describe a simplified view of the causes of salmon mortalities at sea farms. They do not consider the complex interaction of causes of MMEs and appropriate management tools to mitigate them (i.e., see fig. 7 in reference 13). A more holistic understanding that considers the simultaneous impacts of multiple stressors on salmon health/welfare and mass mortality is needed if the industry is to adapt to factors such as climate change and the complex and interrelated causes of MMEs (e.g., see reference 23). This can only be achieved when we understand the roles and interrelationships among the various causes of MMEs (i.e., the complexity of their relationships).

MMEs can pose serious economic, social, health and environmental issues for all stakeholders, including organisms, companies, workers and local communities. The company experiencing an MME suffers the loss of its biological assets and can even face suspension of its aquaculture licences.[24] One of the major environmental concerns after the occurrence of an MME is the removal and disposal of dead fish. These operations can also expose workers to occupational health and safety (OHS) risks, including injuries, illness/diseases and loss of life.[25,26] Existing research has identified significant policy gaps related to aquaculture OHS surveillance, reporting and regulation in many contexts, making understanding OHS outcomes difficult.[27] MMEs can also significantly affect workers' livelihoods and community resilience through short-term and potentially long-term loss of employment in this sector.[28]

Understanding the factors contributing to MMEs can improve intervention and anticipatory mitigation strategies, protect fish health and welfare, and prevent baseline mortalities and MMEs. Before conducting targeted research to aid in farm management, it is important that we understand the causal processes that contribute to MME risk and delineate the impacts of MMEs. To address this research gap, we developed a comprehensive system model that considers the interactions between various risk factors that lead to Atlantic salmon MMEs and their subsequent consequences. This work involved creating a process system model for the Atlantic salmon aquaculture industry based on established expert-elicitation techniques for model building. The resulting risk model was achieved by combining five subsystems of aquaculture risk. Each subsystem provides a visual representation of how factors interact and allows for identifying strategies to mitigate the risk of MMEs.

2 | RESEARCH METHODOLOGY

This study developed an interactive model that assessed the causes and consequences of Atlantic salmon MMEs. We considered five interactive subsystems of aquaculture production to model risk factors for aquaculture MMEs: environmental risk (biotic and abiotic), fish pathogen and disease risks, nutrition risk, risks from and to aquaculture OHS, and risks from and to workers' livelihood. The first three risk categories are known to affect fish health and welfare and, thus, cause mortality, whereas the latter two risk categories (aquaculture OHS and workers' livelihood) affect workplace safety and the socioeconomic security of workers and their communities due to MMEs. Each risk category was further classified into risk factors that were directly or indirectly linked to mass mortality.

We first worked with expert teams, knowledgeable in each aquaculture subsystem, to understand risk factors within each subsystem. Then, we brought all groups together to model risk across the entire aquaculture production system. A two-day international workshop on Atlantic salmon aquaculture mass die-offs was held to collect data for model building. Participants attended the workshop virtually (the workshop structure is outlined below). In this study, expert teams for each category were formed in various ways. Some experts were identified from a literature search of peer-reviewed articles using the keyword 'aquaculture mass mortality'. These individuals then identified experts who were asked to nominate researchers who have published peer-reviewed articles on Atlantic salmon MMEs and related risk factors. This snowball-sampling approach to identifying experts has been used in the literature (e.g., see reference 29). Experts also included researchers working on aquaculture at the host institution (Memorial University of Newfounland, Canada). The goal was to develop a diversified team, working on different aspects of MMEs as comprehensively as possible. The workshop participants were senior and junior researchers, departmental leaders, and university professors from American, Canadian, Brazilian, German, Norwegian and South African institutions. While many participants were from Canadian institutions, many had experience researching aquaculture across countries. Importantly, every subsystem team had researchers with expertise across country contexts. For example, while many team leads within each subsystem were based at Canadian institutions, they had research experience in Canada, Norway, Chile and the UK, among other locations. This geographical breadth of research experience was a pre-requisite for selecting team leads and a consideration for the make-up within teams. Most experts were interested in contributing further and became co-authors in this work. All experts have extensive research and development experience studying the causes and impacts of Atlantic salmon MMEs and publishing their research in peer-reviewed journals.

The research methodology for this study consisted of three phases. In the first stage, each team of researchers produced reports on risk factors within their subsystems. Three groups studied environmental stressors (biological and abiotic), Atlantic salmon pathogens and disease, and risks related to feeding/nutrition that could lead to MMEs. Two other teams looked at the contextual risk factors that make MMEs more consequential for OHS and communities and increase their vulnerability.

In the second phase, a modified multi-criteria decision-making technique, called Interpretive Structural Modeling (ISM), was applied to develop mutual relationships among risk factors.[30,31] This exercise was conducted on Day 1 of the workshop. In the third phase, a modified Delphi technique was applied to modify graphical networks developed from the ISM. This exercise was conducted on Day 2 of the workshop, and subsequent follow-ups with each team were conducted. The research methodology for this study is shown in Figure 1,

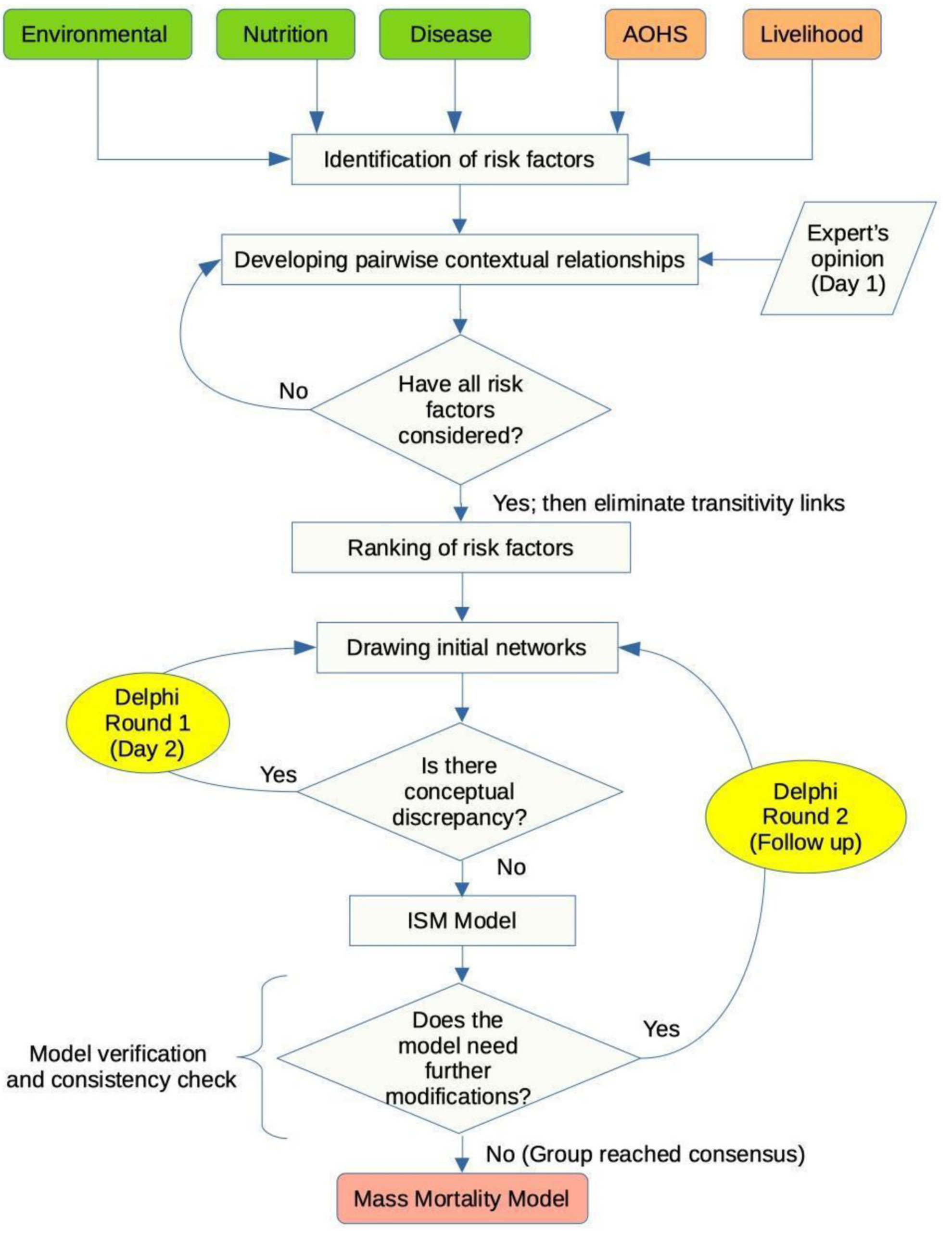

FIGURE 1 The methodological framework for mass mortality risk assessment used in this study. Green risk factors indicate the causes of MMEs, and orange risk factors show the consequences of MMEs. ISM stands for Interpretive Structural Modeling approach. This methodology was applied to the five subsystems individually. MME stands for mass mortality event.

and details are provided in the Supporting Information (see *Phases Involved in the ISM Technique*). On Day 2 of the workshop, experts identified more causes or risks leading to MMEs. In addition to these, they also identified risk mitigation approaches/strategies. Experts were also asked to identify whether an association existed between each pair of risk factors. Their responses were 'yes' if a correlation existed and 'no' if no relationship between the two risk factors could be identified. For example, experts responded 'yes' when asked if the 'aggregation of fishes in sea cages' (i.e., crowding) affects 'low oxygen levels in water (hypoxia)'. This way, experts identified pairwise correlations for each risk factor. Using this information on each pairwise correlation between risk factors, we developed causal structures and put them into directional causal chains. This approach has been extensively used in other fields of study.[32,33]

Further details and the ISM steps utilized are provided in the Supporting Information. We also addressed different kinds of potential biases in collecting experts' data. For example, we addressed overconfidence bias by having group deliberations; experts were encouraged to challenge each other. We also protected against individual voices dominating input by having each individual submit their input without oversight by other experts.[34]

3 | RESULTS AND DISCUSSION

The Appendix shows the list of risk categories and corresponding risk factors analysed in this study. The causal networks suggest that some risk factors directly contribute to MMEs, while others will only result in large-scale mortality if other risk factors are present. Examples of some direct risk factors are very high water temperature (>21-22°C), HABs, cage damage, low water oxygen levels (hypoxia, <60%–70% air saturation), freezing temperatures (winter kill/chill) and possibly winter syndrome (fatty liver disease), viral and bacterial pathogens (e.g., infectious salmon anaemia [ISA] virus, *Vibrio anguillarum*), sea lice, amoebic gill disease and the effect that climate change may have on these factors. Other risk factors influence direct risk factors, and/or indirectly contribute to MMEs. Examples of indirect risk factors, that influence MMEs through mediating variables or that cumulatively combine with other risk factors, are weather and climate, extreme and harsh ocean storms, jellyfish causing gill damage, jellyfish-associated reductions in cage water flow, increased runoff and nutrients, ocean acidification, weather events, low ocean salinity (salinity less than 20 PSU), and the aggregation of fishes (crowding) in sea-cages. There are also risk factors that are more distally related to MMEs and influence direct and indirect risk factors. These include seasonal exposure to environmental risk factors, high ocean salinity (salinity more than 20 PSU), and low protein to high lipid diets. It is acknowledged that not all risk factors occur in every salmon-producing area. For example, 'super chill' is a real challenge in Atlantic Canada, but this problem is insignificant in the UK, Norway, and Chile. Hence, the causes of MMEs are generalized here, and country- or region-specific risks should be identified based on the area of analysis. The causal models also suggest mitigation pathways and the common risk factors across models. For example, feeding regime, sea lice treatment, net cleaning, and use of vaccination are common mitigation pathways across causal networks. The results also identified management actions across models that can contribute to or mitigate risk. For example, a management decision to increase stocking densities can be a catalyst for an MME, and a decision to upgrade cage-site infrastructure (nets, moorings, etc.) can mitigate MMEs. It is worth mentioning that not all the risk factors must be present for an MME to occur, and not all consequences co-occur. Further details are discussed in the sections below.

An aquaculture risk model developed through this study is available at the link.[1] Results are presented and discussed in the order of environmental stressors, disease, salmon nutrition, aquaculture OHS and workers' livelihoods.

3.1 | Environmental stressors (abiotic and biotic) model

We identified and compiled potential abiotic and biotic environmental factors that could lead to MMEs, connected these factors to assess risk, and identified management decisions that could prevent or worsen MMEs at Atlantic salmon farms. There are many environmental challenges to open-pen salmon aquaculture, and while the industry's capacity to monitor (and anticipate) such changes is increasing, companies often have limited ability to control them or mitigate their potential effects. Given restrictions on the length of this review, the text focuses on the impacts of temperature and hypoxia on salmon mortalities, and their interaction with other risk factors. However, there are several other factors that can directly or indirectly result in MMEs (as detailed in Figure 2). For example, HABs are also a major (direct) challenge to salmon aquaculture. They can lead to major MMEs, as they can kill fish via various toxins, damaging their gills and causing hypoxic conditions.[35–37] In addition, several emerging anthropogenic pressures are affecting the natural, biological, chemical, and physical drivers of HABs (including climate change-related changes in salinity, temperature and ocean acidification). Thus, MMEs due to HABS may increase in the future.

3.1.1 | Temperature

Warm temperatures

One of the greatest challenges to Atlantic salmon culture in sea cages is high water temperatures, given that climate change is increasing average ocean temperatures and the frequency and severity of heat waves.[38–41] For example, there have been recent reports of high summer temperatures negatively affecting the production of sea-caged salmon in Tasmania,[42] and 2.9 million salmon died in Newfoundland (Canada) in the summer of 2019.[43] However, it is very unlikely that temperatures of <21–22°C alone lead to salmon MMEs,[21] and such events will only be seen when combined

[1]https://public.flourish.studio/visualisation/17695194/

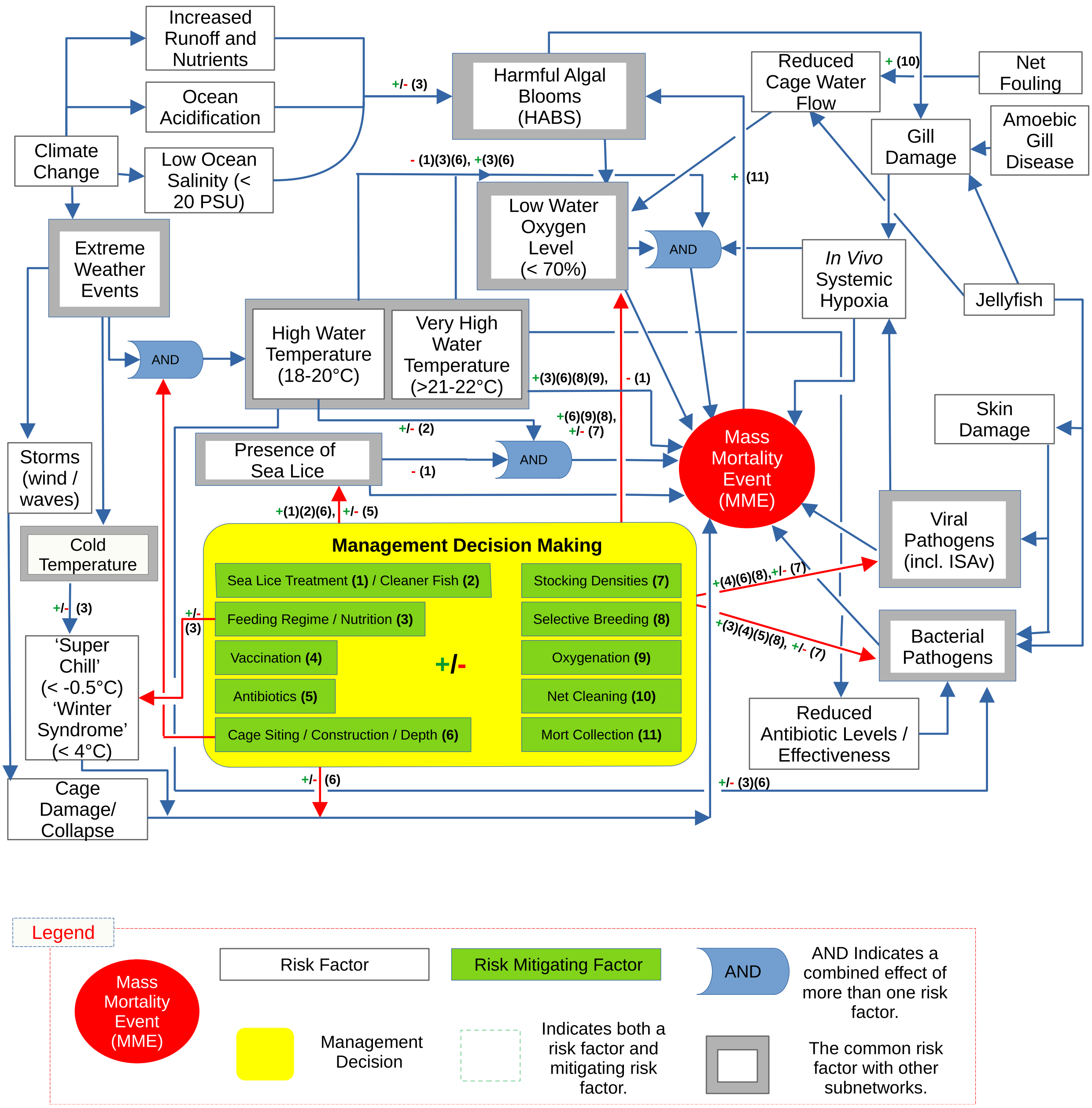

FIGURE 2 The environmental model. The environmental (abiotic) and biological factors that can directly cause and/or contribute to MMEs at Atlantic salmon cage-sites (if other interacting factors are present), and how industry decisions and management protocols can mitigate/reduce (+ effect) or increase (– effect) mortalities. In this figure, mitigation is shown as a (+) sign, while in subsequent figures, it is indicated as a green arrow. In some instances, impacts due to industry decisions and management are marked as red arrows, and the effect of the action taken is indicated. Where it was not possible to draw arrows from management actions so as to not further complicate the figure, numbers in '()' alone correspond to the various strategies/actions taken. Blue-directed lines indicate the connections between risk factors. The yellow box indicates management strategies that can/may reduce (+) and/or increase (–) cage-site losses. The complexity of this figure precludes some effects/interactions from being shown. For example, cold temperatures are known to suppress the immune function of fish, and this increases their susceptibility to certain bacterial diseases. MME, mass mortality event.

with other stressors. For example, salmon can tolerate high temperatures (short-term up to ~26°C; long-term up to ~22°C) even when combined with moderate hypoxia (≥60%–70% air saturation),[21,44,45] but more severe hypoxia (e.g., that associated with HABs and other factors; see below) or in combination with high temperatures, can lead to large-scale mortalities. Sea lice infestation can increase the susceptibility of salmon to mortalities at high temperatures.[46] For example, the combination of a severe lice infestation, chemical delousing and higher water temperature (~18–19°C for several weeks) was credited with the loss of fish in the Newfoundland heat wave of 2019.[43] In addition, high temperatures may increase the abundance and/or virulence of certain pathogens[47] and reduce post-treatment levels of antibiotics,[48] and thus, their effectiveness against bacterial pathogens.

The industry has limited capacity to influence cage site water temperatures, and even if salmon are provided with deeper nets (and thus access to potentially cooler waters), recent data indicates that the salmon will not necessarily avail of these cooler waters.[49] To avoid/reduce the incidence of mortalities at high temperatures, cage-site managers can select sites that are less likely to encounter this environmental challenge and ensure their nets have been cleaned (increasing water flow through the cage) or provide their cages with supplemental oxygen. Further, they could develop specific diets for high temperatures (as done in Tasmania; Optiline HT, Skretting) or select fish/broodstock that are more tolerant of high temperatures. Work on genetic markers of high-temperature tolerance in Atlantic salmon has begun on the east coast of Canada (e.g., references 44,45). Nonetheless, it is clear that environmental risk factors rarely lead to MMEs in isolation and should be understood in a system setting. High temperatures, particularly, enhance MME risk when combined with other factors. Even management decisions that are intended to address other stressors can add to MME risk during high-temperature events. For example, delousing treatments (which raise metabolic demands) can lead to MMEs during high temperatures and can even lead to large-scale mortalities at temperatures considered optimal without these treatments.[50,51] The impacts of chemical delousing are usually restricted to crowding: mechanical delousing involves flushing the salmon with water jets and/or brushing, or using negative pressure and turbulence combined with flushing; and thermal delousing involves submerging the fish in a chamber with 28–34°C water for 20–30 s. These latter two delousing methods also entail crowding, pumping, and straining the fish, and this may lead to stress (and increased metabolic demands), a risk of hypoxia and mechanical injuries (see reference 52 for references).

Cold temperatures

The severity and frequency of winter storms are also expected to increase due to climate change,[53–55] as are polar air outbreaks (southerly transport of extremely cold air[56,57]); however, it remains unclear whether either will become a greater or lesser concern.[58] Nonetheless, 'cold shock' events caused large-scale losses of salmon at sea cages in Atlantic Canada in 2014, 2015, 2019, and 2020.[59] It is possible that the fish died when water temperatures dropped below the freezing point of their blood/tissues (~−0.7°C to −0.8°C[60]), which caused ice crystals to form. However, this is not the only potential cause of winter mortality in Atlantic salmon. In 2020, farmers in Iceland reported that cool sea temperatures caused salmon to move to the bottom of the sea cages, and that wounds caused by rubbing against the netting eventually led to the fish's death.[61] However, recent studies[62,63] have pointed to another cause. This research suggests that, like sea bream,[64] Atlantic salmon can develop 'winter syndrome'—a condition associated with fatty liver disease and opportunistic infections that cause head and dermal ulcers. 'Super chill' can be lessened (but not completely prevented) by ensuring that fish stay in the deeper regions of the cage, and it has been suggested that functional diets can be developed to minimize the incidence of 'winter syndrome' and its associated aetiology.[62]

3.1.2 | Hypoxia

Another serious environmental challenge to Atlantic salmon aquaculture is severe hypoxia (<60%–70% air saturation, depending on temperature). It can be caused by the upwelling of oxygen-poor water from deeper regions,[65] HABs[66] and net fouling (incl. jellyfish swarms which reduce water flow through the cages). Further, it can be exacerbated if the cage has a high stocking density or the fish are crowding within particular regions of the cage (e.g., see reference 67), and directly or indirectly (i.e., by contributing to the severity of HABs) made worse by the accumulation of large numbers of mortalities in cages (i.e., by contributing to the severity of HABs). However, if other factors are at play, fish may succumb to hypoxia at higher oxygen levels. For example, in the disease model (explained in the next section), the infectious salmon anaemia virus (ISAv) reduces the number of red cells in the fish's blood (i.e., causes anaemia). This leads to reduced blood oxygen-carrying capacity. In addition, certain algae,[66] jellyfish tentacles (nematocysts) (see references 68 and 69) and amoebic gill disease[70] can damage the gills and limit the ability of the salmon to take oxygen up from the seawater. Both of these effects result in 'systemic hypoxia' and limit the fish's capacity to deal with high temperatures, moderate environmental hypoxia, and/or other stressors present in the cage-site environment. Management practices that can prevent hypoxia in salmon sea cages include regular net cleaning and the collection of mortalities, siting farms in areas not prone to upwelling or HAB events and with good water currents/flushing, moving sites if HABs have been detected/identified, and aeration or oxygenation of the water within the cages through compressed air or oxygen. Supplemental air or oxygen can be added via various technologies during hypoxia and/or warm surface water temperatures.

Finally, significant interactions between biotic and abiotic environmental impacts and various factors may amplify the potential for MMEs at Atlantic salmon cage sites. For example, tentacles/nematocytes often break off when jellyfish impinge against the cage's netting, which can damage the salmon's skin (i.e., provide a route for bacterial infection). Certain jellyfish species are also vectors for the bacterium *Tenacibaculum*, which leads to gill lesions and skin ulcerations, which can magnify the mortalities associated with jellyfish blooms.[71]

3.2 | Infectious diseases and pathogens model

As in any intensive animal food-producing sector, the Atlantic salmon industry has experienced disease outbreaks that affect fish welfare and challenge the industry's sustainability and profitability. Parasites, pathogenic bacteria, and viruses are natural components of ecological systems and drivers of population dynamics that have the capacity to reshape ecosystems, alter services, biomass production and succession, and overall ecosystem stability. Under normal circumstances, diseases are an episodic component of marine ecosystems where hosts and pathogens co-exist in homeostasis.[72] However, severe disease

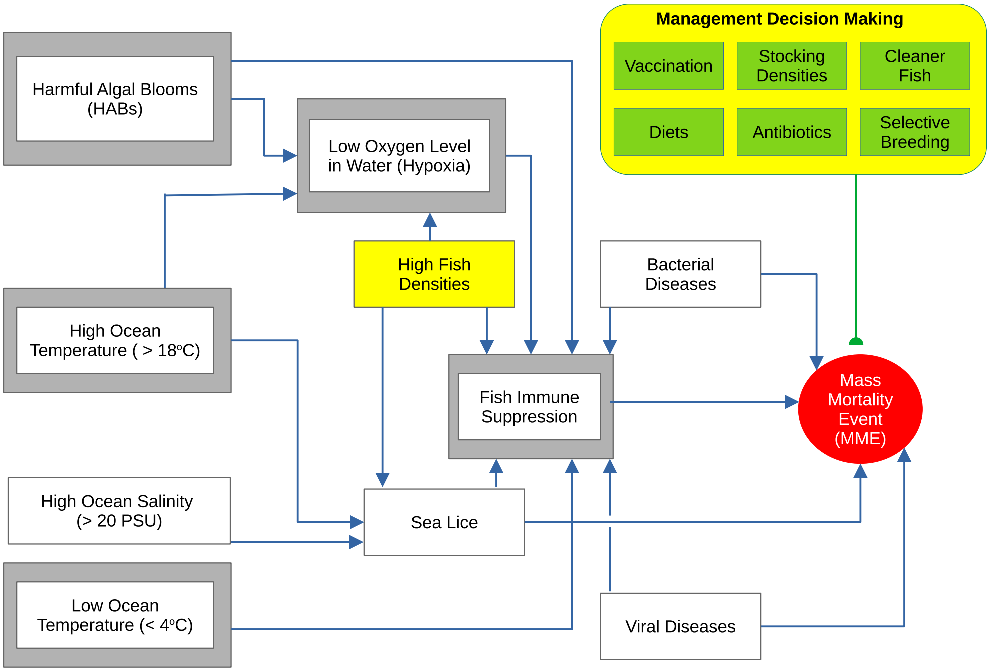

FIGURE 3 The disease model. The legend for Figure 2 also applies to this figure. The green line towards MME indicates the influence of management and mitigating risk factors on MMEs. MME, mass mortality event.

outbreaks can result from issues with the host (e.g., stress and immune suppression), pathogens (e.g., the introduction of a new pathogen, pathogen resistance to antibiotics and vaccines), or environmental conditions (e.g., pollutants, low temperatures that immune suppress the host).[73] For instance, Figure 3 shows that high water temperatures increase sea lice (e.g., *Lepeophtheirus salmonis*) development and the presence of the infective stage,[74–77] increase bacterial transmission[78] and viral burst,[79] but surprisingly do not negatively affect the salmon's immune response.[80] Cold temperatures can also favour the growth of marine psychotrophic bacterial pathogens and viruses (e.g., *Moritella viscosa*, ISAv)[81–84] and/or suppress the fish's (host's) immune system.[62,85,86] Finally, the disease model in Figure 3 shows that water salinity, high temperatures and fish stocking densities contribute to increased sea lice abundance[46,86] and disease transmission,[87] exacerbating the impacts of sea lice.

Figure 3 also shows several intervention points where disease management tools and strategies can be applied to mitigate the risk of MMEs at Atlantic salmon sites. These include adjusting/optimizing stocking densities; the use of cleaner fish to control sea lice infestations; using vaccines to mitigate the effects of infectious diseases; selective breeding or the use of genetically modified fish resistant to infectious diseases; and, as a last resort, the utilization of antimicrobials and chemotherapeutants. For instance, infestations of ectoparasitic sea lice are one of the most severe threats to cultured salmonids in the Northern[88] and Southern hemispheres.[89] Sea lice feed on salmonid tissues, leading to skin erosion, osmoregulatory failure, immunosuppression, and increased disease susceptibility, and require expensive control regimes to prevent mortalities.[90] Over the years, the Atlantic salmon industry has used several methods to combat sea lice infestations.[91] Chemotherapeutic treatment was the dominant sea lice control method for decades until the emergence of resistance in sea lice[92] and increasing negative public opinion about the impacts of anti-lice drugs on the ecological equilibrium, particularly among crustacean populations. In addition, as we noted in the previous section, such interventions can also contribute to MMEs under certain conditions. Mechanical abrasion and thermal treatment are used as physical delousing methods, but adversely affect salmon health and welfare.[50]

The Atlantic salmon industry has adopted Integrated Pest Management (IPM) strategies, in which multiple non-medicinal methods are used (e.g., net barriers/skirts, ultrasound, lice traps and feeding through snorkels).[93] Further, lice control using cleaner fish has been very successful in North Atlantic salmon farms.[94] Cleaner fish are considered an eco-friendly (green) alternative to other methods of sea lice control and a solution to lice infestation from both economic and ecological points of view. However, it is acknowledged that there are potential animal welfare issues with the use of cleaner fish. This concern is more prominent, especially in cases where wild species are being utilized for this purpose. Given these animal welfare issues, there may be a need to move to alternative green control measures for pest management. The mutually beneficial cleaner fish-salmonid association reduces the parasite burden on salmonids while providing a food source for the cleaner fish. In salmonid aquaculture, different wrasse species (e.g., the ballen wrasse [*Labrus bergylta*] and goldsinny wrasse [*Ctenolabrus rupestris*] and lumpfish [*Cyclopterus lumpus*]) are currently being used.[95–97] Wrasses consume more parasites than lumpfish, but they reduce their activity at cool temperatures and eventually enter a hypometabolic winter dormant state (torpor) at water temperatures below 5°C.[98] Lumpfish can effectively delouse at, or even below, 5°C,[97,99] but they do not perform well at temperatures above 18°C.[97,99,100] Nonetheless, the lumpfish has proven to be very effective in removing sea lice from Atlantic salmon[100] and has been domesticated and industrialized in the North Atlantic region.[101–103] Cleaner fish use has become a prevalent practice in the last 10 years, eliminating the utilization of chemotherapeutants and reducing fish stress/immune suppression.

Vaccines are a critical health component in all intensive animal food-producing sectors, and their use has significant economic implications for these industries. However, here again, viewing management interventions holistically and as a part of Atlantic salmon aquaculture can reveal when interventions may be less effective than anticipated or even have negative consequences. Despite the success of fish immunization in the finfish aquaculture sector, microbial and viral infectious disease outbreaks are still having major impacts on this industry. Issues like the lack of vaccine efficacy in the host species or against local pathogens, the emergence of new pathogen variants, co-infections and environmental conditions that prevent vaccine efficacy due to immunosuppression[104,105] can lead to MMEs. Verification of the efficacy of commercial vaccines against local pathogens is critical to deciding which vaccine formulation should be used at a specific site or within a particular region. Several recent disease outbreaks can be linked to climate change, including heat waves during the summer and cold temperature events during winter,[63,106] perhaps associated with unknown or novel host-pathogen interactions. Isolation and characterization of potential new pathogens from farmed fish is a practice that is not widely conducted, but can provide critical information for strains that should be incorporated into customized autogenous vaccines.

Selective breeding for traits such as faster growth, flesh colour and resistance to infectious diseases is a common practice for farm animals, including finfish.[107] For instance, salmonids resistant to pests and pathogenic bacteria and viruses have been selected for, and used in, the industry.[108–110] However, in many cases, the array of genes and molecular mechanisms that determine resistance are not known. The Atlantic salmon has only recently been domesticated. Although broodstock selection has been successful in some instances, climate change might/will require that other attributes be selected, such as increased thermal tolerance and disease resistance. Gene editing (i.e., CRISPR/Cas9)[111] is another potential tool to prevent MMEs. However, this technology must be technically viable, effective at scale, and socially and regulatorily accepted to become a global industrial option.

A recent study showed that the Atlantic salmon industry had the least antimicrobial use across the farmed fish species.[112] Comparatively low antimicrobial application rates in some countries, like Canada,[112] could reflect improved husbandry and management conditions, including high vaccination coverage and specific pathogen-free broodstocks. Ideally, antimicrobials should be restricted to use in hatcheries and high-value animals, like breeders. They should be avoided in open net pens to limit the development of antimicrobial resistance and/or the probability of MMEs. Also, as technologies/tools for vaccines and selective breeding improve, antibiotic use is expected to be further reduced. For instance, several countries have experienced dramatic reductions in antimicrobial use rates since the introduction of vaccination and improved management and husbandry programs.[113,114] Future strategies should aim to strengthen aquaculture production and prevent MMEs without pharmaceutical interventions by the utilization of technologies such as bacteriophage therapy, pre and probiotics, the development of state-of-the-art vaccines (e.g., mRNA, live attenuated and live recombinant vaccines) and fish genome editing technologies.

3.3 | Salmon nutrition model

The relationship between Atlantic salmon diet and nutrition, and MMEs, includes several indirect factors (Figure 4), and this suggests that salmon aquaculture depends on carefully managing feed composition and feeding regimes. In the context of MMEs, the main risk factors regarding salmon nutrition (as shown in Figure 4) are low protein/high lipid diets, high lipid (cholesterol or total fat) levels in the salmon's liver, starvation and increased feed consumption at high temperatures. Studies investigating a sudden increase in mortality in seemingly healthy salmon at 5°C have reported that changes in the dietary protein: lipid ratio may cause/increase mortality. Moribund Atlantic salmon from an MME had significantly higher lipid content in the liver and altered liver fatty acid composition.[115] Diets low in protein and high in total fat can lead to fat accumulation in the liver, ultimately leading to MMEs, particularly when other factors stress fish. For example, while salmon grow optimally on a diet containing 55% protein and 24% lipid, today's salmon feeds typically contain ~35%–45% protein and ~25%–30% lipid.[116] While the salmon's requirement for lipid is generally not this high, these latter diets allow lipid to be used as the primary energy source while dietary protein can be primarily used for tissue growth; a term called protein-sparing.[116] This is also an efficient and economical strategy in feed formulation, since protein is typically the most expensive ingredient. Previous studies indicate that diets with higher protein and lower lipid levels may be beneficial in preventing mortality related to thermal stress in salmon.[115] In addition, high-lipid diets can lead to lipid accumulation in the viscera, particularly in the liver and heart,[117,118] and this has specifically been associated with feeding diets high in plant lipids.[117,119] One of the reasons for this may be that plant oils do not contain phospholipids, such as phosphatidylcholine. Choline has been shown to reduce lipid malabsorption syndrome, which leads to excessive lipid accumulation.[120,121] Adding phospholipids, particularly phosphatidylcholine or dietary choline, may help prevent MMEs related to temperature stress because of lower organ lipid accumulation. Betaine, which has roles in cellular function, is a naturally occurring choline derivative that may also be added to the diet and is also a well-known feed attractant to fish.[122] This latter characteristic would encourage feeding.

Drastic temperature changes are stressful for fish, and cessation of feeding often indicates that a mortality event can occur if environmental conditions do not improve. However, the literature lacks agreement on whether starvation or feeding prior to these events helps to alleviate mortality. Starvation in healthy salmon has been shown to reduce mortality.[115] However, this may depend on the duration of feed deprivation. Stressful environmental conditions, such as an increase in temperature or extremely high temperatures, induce the release of corticotropin-releasing factor (CRF) and cortisol, inhibiting feeding in fish.[123] In a study that held fish at high temperatures of 22.9°C, Atlantic salmon cohorts experienced a temperature-induced cessation of voluntary feed intake for 2 months.[42] The study demonstrated a significant negative linear relationship between feed intake and temperature, and a complete cessation of feeding in all fish as temperatures rose above 21.5°C. In another study, an incremental temperature increase (i.e., 1°C per week) resulted in a ~10% increase in the feed conversion ratio.[21] The decrease in feed consumption was likely related to a direct effect of temperature on appetite. Feeding continuity (encouraging feeding when cessation of feeding would typically occur) and consistently low cortisol levels may help prevent mass mortality. It is possible that when salmon stop feeding due to stress from high temperature and hypoxia, the release of hormones like CRF and cortisol prevents feeding, putting fish at risk for mortality. Encouraging feeding may help alleviate stress and subsequent mortality, without increasing the risk of HABs.

Many risk factors shown in Figure 4 can be mitigated using functional diets that can help to enhance the innate immune system's response to stressors, including temperature and hypoxia. For example, several studies have demonstrated that functional feed additives, such as pre and probiotics, can activate the innate immune system of aquatic animals by enhancing the growth of commensal microbiota.[124] Antioxidants may also have a role in preventing mortality during stressful events. Feeds with higher antioxidant levels (e.g., astaxanthin or vitamin E) that are fed prior to a temperature event may enhance survival. Modulating the dietary fatty acid composition may also positively affect salmon health when they are threatened with thermal stress. Finally, moderate inclusion of arachidonic acid (20:4ω6) and vitamin E in Atlantic salmon feeds has been shown to improve some indicators of non-specific immunity, such as respiratory burst,[125] and may help them deal with temperature stress.

Overall, MMEs can be mitigated or reduced in severity by modifying nutrients and using functional diets for Atlantic salmon. This may include feeding diets with a higher-than-normal protein/lipid ratio and including higher-than-normal dietary phospholipid amounts, particularly of phosphatidylcholine, which will help reduce lipid accumulation in the viscera, especially the liver. During the summer/early fall months when some MMEs are likely to occur, this may include improving/increasing feed consumption during high-temperature events by modulating cortisol through dietary means; for example, dietary inclusion of higher-than-normal arachidonic acid levels, higher astaxanthin and vitamin E for antioxidant capacity and improved immune response. A large body of evidence has accumulated, showing that nutrition strongly influences fish immunity. For example, the dietary replacement of marine ingredients (i.e., fish meal and fish oil) by terrestrial alternatives (e.g., vegetable oils) has been reported to cause

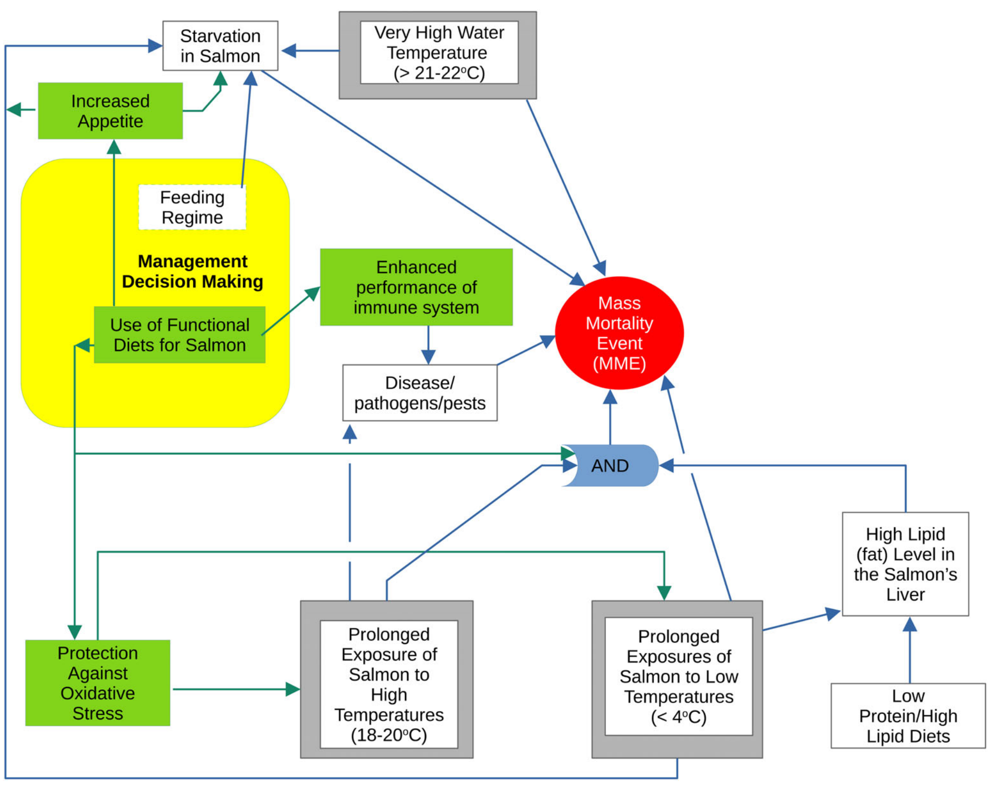

FIGURE 4 Salmon nutrition model. Green lines (with arrows) indicate risk mitigation effects and blue lines indicate the connections between risk factors. The legend for Figure 2 also applies to this figure.

changes in features of the transcriptome related to inflammation, and the antiviral and antibacterial immune responses of Atlantic salmon.[126–128] Some of these effects could be leveraged by tailoring novel feeds to prevent and mitigate diseases in aquaculture. Microbial cell components (e.g., cytosine–phosphate–guanine oligodeoxynucleotide motifs, peptidoglycans) have also been shown to exert interesting immunostimulatory effects on Atlantic salmon as feed additives.[129,130] Sustainably formulated health-promoting feeds are key components of integrated disease management strategies in aquaculture and help to reduce the use of chemotherapeutants and antibiotics. As such, they could become a powerful tool to reduce the risk of MMEs.

3.4 | Aquaculture OHS model

Figure 5 shows that marine Atlantic salmon aquaculture is associated with potential exposure to diverse physical, chemical, biological, ergonomic, and psychosocial hazards aside from safety risks.[26,27,131–134] It is also associated with an elevated risk of injury, illness, and death relative to other industrial sectors, based on national averages in countries where these comparisons are available (see reference 135). Large MMEs are likely to contribute to even higher risk levels due to the nature and pressures associated with dead fish removal operations. Findings from an expert risk assessment synthesis of key existing sources on MMEs and OHS across five candidate countries indicate that MMEs fit a definition of 'significant accidents'.[136] That is, MMEs require rapid mobilization of workers, vessels and other supports. To varying degrees, they can also require staff working under pressure to investigate the extent and cause of the die-off and to remove, transport, and dispose of dead fish. MMEs are also often associated with regulatory and organizational pressures to change farm design, emergency planning, and other practices to reduce future MME risks that may have implications for OHS.

The MME and OHS risk analysis in Figure 5 highlights key hazards and potential pathways between MME-prevention planning, monitoring and response, and OHS risks. MMEs will affect work on vessels (including while transporting workers, feed, equipment, supplies, and dead and live fish). MME response also often encompasses underwater work around, under, and inside net pens, including gathering dead fish in various stages of decay and net cleaning and repair. MMEs can affect the types and levels of exposure to documented hazards, especially regarding diving, working on cages and around cages, seagoing workboats and wharves, and the onshore rendering of dead fish.

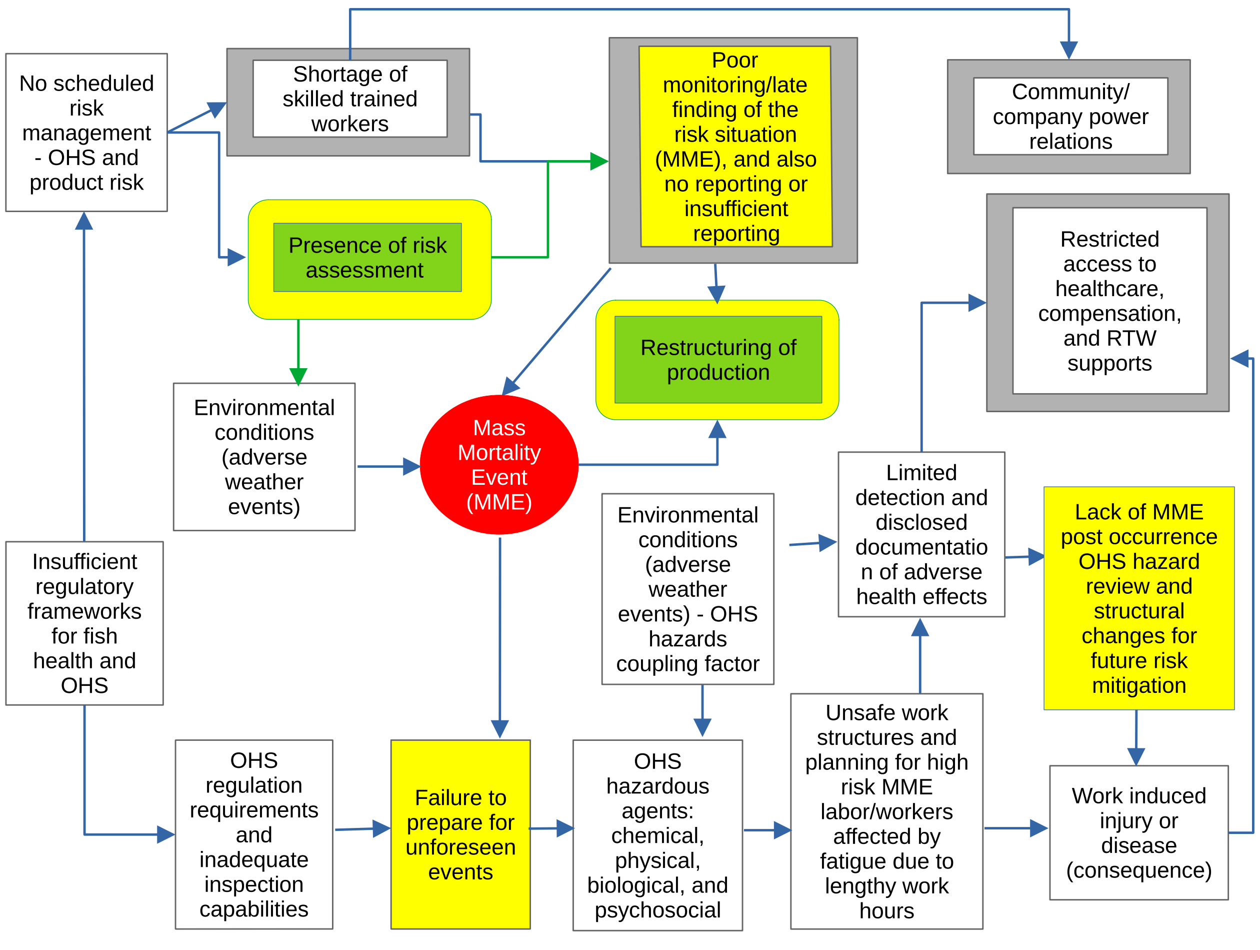

FIGURE 5 Aquaculture occupational health and safety (OHS) model. The legend for Figure 2 also applies to this figure. RTW stands for Return To Work.

Much of this work happens outdoors and is subject to weather-related hazards.

The relationship between MME and OHS risk depends on the cause, scale, duration, timing, and location of the MME, including its relation to adverse weather events. For example, larger MMEs and more extensive and prolonged mortality removal in exposed locations and seasons associated with bad weather are likely associated with higher risk. This means there are links between personnel training and skill levels, monitoring, contingency planning, emergency preparedness, and OHS at the company level.[137–139] The presence and strength of health and safety regulations and inspection systems (including requirements to quickly notify government and health and safety departments at the onset of MMEs; company risk assessments, emergency preparedness, and contingency planning; labour force training and skill levels; and technology and work task design related to key tasks such as mort removal and transport) are all pre-event factors that will indirectly influence the relationship between MMEs and aquaculture OHS risks. Once MMEs begin to unfold, the relationship between these and injury, illness and fatality risk would also be determined by the cause and timing of the event with HABs (causal agent) and MMEs associated with periods of chemotherapeutic/antibiotic treatment, which are potentially associated with enhanced chemical and biological health risks to workers. Where divers primarily remove dead fish, MMEs can increase the already significant diving-related hazards associated with marine net pen aquaculture, including the risk of net entanglement, decompression sickness, and other adverse health events. The removal and transportation of large volumes of dead and decomposing fish may enhance the risk of chemical exposure and related illness among transport workers, including exposure to hydrogen sulfide (H_2S) and water transport-related incidents such as capsizing, slips, and falls. Risks to divers and transport workers are likely greater if MME remediation work requires recruiting inexperienced workers, contracting equipment not designed for aquaculture operations, and where such work takes place in the context of time and other pressures for rapid removal. These situations can increase the risk associated with inexperience and inadequate training, resulting in risk-taking and fatigue-related injuries. Potential longer-term post-event impacts on health and socio-economic implications for injured workers would be mediated by the adequacy of access to appropriate medical care and workers' compensation benefits for injured workers, access to return to work options and programming, as well as any potential OHS impacts of production reorganization triggered by the MME, such as changes in work design and farm locations.

Key intervention entry points for management to act upon and mitigate OHS risks associated with MMEs include: (1) taking OHS risk into account when doing broader risk assessments and contingency planning for MMEs; (2) including OHS agencies and OHS-risk-related details (such as staffing and work task changes associated with mort removal) in requirements for early reporting of emerging MMEs on the part of companies; (3) including OHS-related risks and incidents in MME investigation guidelines and reports to allow for improved surveillance, the mitigation of hazards and comparisons of risk across different events and regional and national contexts; and, (4) implementing a post-MME OHS hazard review.

3.5 | Workers' livelihood model

Based on the workers' livelihood analysis shown in Figure 6, MMEs will have multiple impacts on workers and the communities in which they live. Both immediate short-term and potentially long-term effects will be associated with these events. In the short-term, there will likely be a loss of employment opportunities for workers involved in direct production and fish processing due to the loss of fish that would have been processed, but also potential long-term loss of employment if the MME results in the company losing their licence, as happened in the Newfoundland and Labrador (Canada) case.[43] Employment loss will significantly affect household income, which may not be covered through social assistance and other employment support mechanisms. Over the longer term, an MME may result in people seeking employment opportunities in other sectors of the economy that are considered more secure and not subject to disruptions of this kind. It may also lead to people seeking employment outside of the communities that are adjacent to aquaculture projects, which would, in turn, exacerbate the trend of outmigration with potentially serious impacts on community sustainability. Migrant workers may fill this gap, such as through temporary migrant worker programs in Canada, with short-term employment opportunities.[140] As identified in the aquaculture OHS section, these jobs range from collecting and disposing of dead fish to repairing and cleaning nets. However, the migrant workforce may face different impacts due to gender, race, citizenship status and age.[141] Our model identifies critical intervention points for local governments and management, which can help to reduce the effects of an MME on the livelihood of workers. For example, a weak social security system (such as inadequate employment insurance) can contribute to the loss of local employment and income of the people associated with aquaculture. Such economic hardship may lead employees to lose their health benefits and health facilities for their immediate family members. Therefore, the national, federal, and provincial regulatory systems can play a vital role in minimizing the impact of MMEs on people's livelihoods. Figure 6 suggests that if the government can provide alternate employment and economic safeguards to aquaculture workers and their families, the social implications of MMEs can be minimized.

Additional longer-term impacts relate to an industry's commitment to a production region and an industry's social licence to operate (SLO).[142] MMEs, especially when they happen more frequently, may result in a company deciding to either limit its exposure to a specific production site by reducing investments or, more dramatically, by withdrawing from the site/region altogether. MMEs, again, when they happen on a regular basis, may raise questions about whether the site or region is suitable for intensive, industrial forms of aquaculture production.[143] Sites affected by regular mass die-offs due to environmental, disease, and operational reasons may be considered too risky as production sites. In a changing ocean environment and with parasites

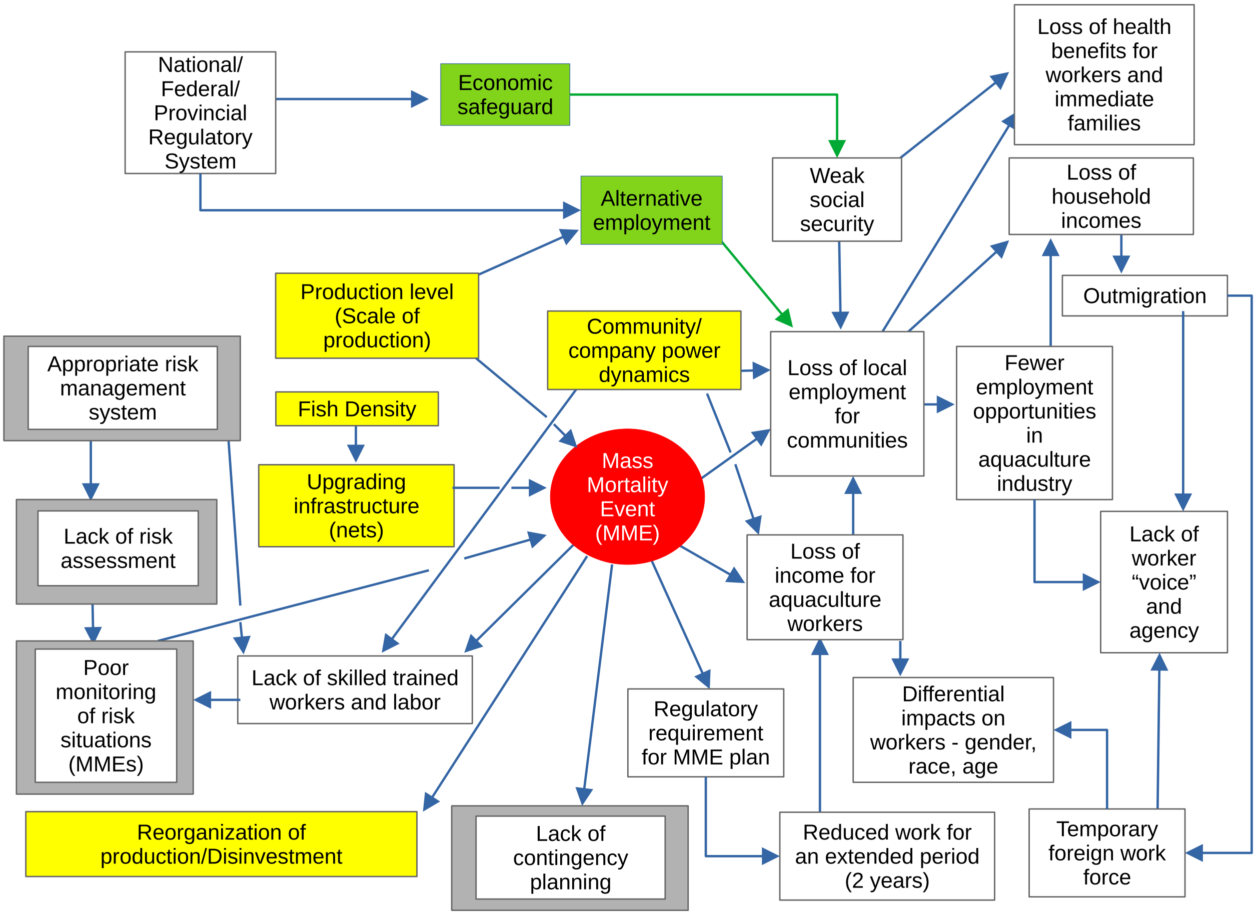

FIGURE 6 Workers' livelihood model for aquaculture. The legend for Figure 2 also applies to this figure.

increasingly resistant to standard treatments, we can expect that some previously productive sites may no longer be suitable for intensive aquaculture production, with potentially serious implications for communities that rely on this industry.[144]

Regarding crucial intervention points for management, Figure 6 shows pre-event and post-event intervening points. Pre-event intervening points for leadership are critical to reducing the occurrence of MMEs. These actions include upgrading infrastructure, production levels, health monitoring and treatment protocols, actively participating in research, and a robust and appropriate risk management system. As discussed in the aquaculture OHS section, a lack of risk assessment and poor monitoring can lead to more and larger MMEs. Community and company dynamics are categorized as pre-event and post-event. The community and company dynamics also play a crucial role in causing MMEs and can help minimize the economic impacts of MMEs on aquaculture workers and the local community. Our findings reveal that MMEs can force production to be reorganized and lead to the development of regulatory requirements to better deal with post-event situations.

3.6 | Implications of this study and future work

This study provides interactive models that help to understand the causes and effects of MMEs in Atlantic salmon sea-cage aquaculture. The networks developed in this study are called qualitative Bayesian networks (BNs), which help to systematically map our current understanding of the structural dependencies among aquaculture risk factors without specifying numerical values. These qualitative BN models aid in visualizing causal reasoning by indicating which risk factors are directly influencing others[145] towards causing MMEs, as well as the direction of their influence. The directional links in each network provide insights into the model's sensitivity to risk factor relationships and dynamics between them.[146]

This work finds significant value in science policy related to aquaculture research. In mapping the causal systems that contribute to MMEs, as well as their impacts, this work identifies critical mechanistic pathways and interactions that should be prioritized in further research. In particular, it can help develop new hypotheses for research into interventions to forestall and mitigate MMEs. Broadly, by mapping the current understanding of the causes and effects of MMEs, this work also provides a baseline understanding that can be updated as new research is done and our understanding of aquaculture risk improves. For example, a next step of this study could be to transform the qualitative BN models presented into quantitative BN models. Given observed evidence, the quantitative BN model will allow probabilistic inference, enabling the calculation of probabilities (likelihood) for MMEs' occurrences. Such an approach could facilitate decision-making under uncertainty by providing a framework[147] to compute the optimal values of each parameter for the aquaculture industry. Quantitative BNs can also help in predictive modelling and forecasting by estimating the probabilities or chances of future MME occurrences, and hence can help the industry to take proactive actions to avoid MMEs or reduce losses due to MMEs.

The model developed in this study can also aid in developing contingency planning to mitigate MMEs. Industry stakeholders can benefit significantly from this research as they seek to implement effective risk management strategies within their aquaculture operations. By utilizing the qualitative BN models of this study, aquaculture companies can consider the system of variables that affect the most influential factors driving salmon mortality, especially interactions that enhance or mitigate these risk factors, and enable them to tailor risk mitigation measures to address specific stressors or vulnerabilities. This targeted approach empowers industry players to make informed decisions regarding site selection, stocking densities, feeding regimes and environmental monitoring protocols, ultimately minimizing the likelihood of MMEs and enhancing the overall resilience of their operations.

In parallel, government policymakers have a crucial role to play in leveraging the insights provided by our research to establish robust regulatory frameworks and guidelines for the aquaculture industry. Equipped with an understanding of the interplay between different risk factors, policymakers can develop regulations that promote sustainable and responsible aquaculture practices while safeguarding environmental integrity, public health and worker safety. Furthermore, the findings from this study can inform the design of monitoring and compliance programs, enabling regulators to prioritize inspections and enforcement actions based on the key risk factors identified in the study. This proactive approach ensures that industry practices align with established standards and guidelines, fostering a culture of accountability and continuous improvement within the aquaculture sector.

It is essential to emphasize the importance of stakeholder collaboration and ongoing monitoring and evaluation in mitigating the risks associated with salmon MMEs. By fostering partnerships amongst aquaculture companies, research institutions, government agencies and non-governmental organizations, stakeholders can collectively develop and implement innovative solutions to address the identified risk factors. Additionally, a commitment to continuous monitoring and evaluation allows industry stakeholders and policymakers to assess the effectiveness of risk mitigation measures and adapt management practices in response to changing environmental conditions and emerging threats. Through these collaborative efforts and dedication to evidence-based decision-making, stakeholders can work together to enhance the resilience and sustainability of the aquaculture sector, ultimately reducing the incidence of salmon MMEs and safeguarding the long-term viability of this vital industry.

4 | CONCLUSION

The demand for Atlantic salmon products has grown enormously in recent years due to their high market value. Atlantic salmon aquaculture has emerged as a promising way to meet such demand and provide additional high-quality protein to the increasing human population. However, MMEs are an important risk to the sustainability of the aquaculture of this species when fish are grown in open net pens/at cage sites. Several environmental, nutritional and disease/pathogen challenges can affect the health and welfare of salmon in complex and non-linear ways, given the difficulty in mitigating these challenges and because intense farming can lead to stressful conditions that exacerbate these factors. This study also identifies and analyses risk factors causing MMEs and post-MME impacts on aquaculture workers and communities. This study has proposed a robust and sustainable Atlantic salmon aquaculture system where MMEs are minimized, and risks to aquaculture production systems are predictable.

The study identifies that, when required, various fish health management strategies such as rigorous vaccination programs, responsible antibiotic and other therapeutic treatments, and integrated pest management strategies, can help prevent MMEs. However, warm and cold temperatures at/or beyond the salmon's tolerances, decreased water or systemic (internal) oxygen levels, increased HABs, sea lice infestations, and jellyfish blooms leave fish more susceptible to physiological stress and secondary (opportunistic) infections.[21] Further, many of these challenges are being exacerbated by climate change.[23] This study identifies that the cumulative effect of all these risks results in significant production losses. However, being a qualitative BN study, the loss's magnitude is impossible to report. For such activity, a quantitative BN model is recommended. Crucially, the complexity of causes leading to MMEs, coupled with the increasing uncertainty and variability from climate change, mean that some interventions intending to reduce mortality may exacerbate MME risk, and such risk is unlikely to be eliminated entirely.

In conclusion, this research underscores the importance of understanding and addressing the complex interplay of risk factors contributing to MMEs in Atlantic salmon aquaculture. Using qualitative BN models, we have elucidated vital risk categories and their relationships, providing valuable insights for industry stakeholders and government policymakers. Moving forward, we must translate these findings into actionable strategies and policies aimed at mitigating risks, promoting sustainability, and safeguarding the health and welfare of salmon populations. Through collaborative efforts and ongoing monitoring and evaluation, we can work towards a future where aquaculture operations thrive in harmony with the environment, ensuring the continued viability and sustainability of the aquaculture industry for generations to come.

AUTHOR CONTRIBUTIONS

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no data sets were generated or analysed during the current study.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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APPENDIX A

Risk category	Risk factor
Environmental stressors (abiotic and biotic) model	Amoebic gill disease
	Bacterial pathogens (bacteria, viruses, sea lice, amoebic gill disease)
	Cage damage/collapse
	Climate change
	Cold temperature
	Extreme weather events
	Gill damage
	High water temperature (18 – 20°C)
	In vivo systemic hypoxia
	Increased runoff and nutrients
	Jellyfish
	Low ocean salinity (< 20 PSU)
	Low water oxygen level (< 70% air saturation)
	Net fouling
	Ocean acidification
	Reduced antibiotic levels/effectiveness
	Reduced cage water flow
	Skin damage
	Storms (wind/waves)
	'Super Chill' (< −0.5°C) 'Winter Syndrome' (< 4°C)?
	Very high water temperature (> 21 – 22°C)
	Viral pathogens (incl. ISAv)
Infectious diseases and pathogens model	Bacterial diseases (pathogens)
	Fish immune suppression
	Harmful algal blooms (HABs)
	High fish densities
	High ocean salinity (> 20 PSU)
	High ocean temperature (> 18° C)
	Low ocean temperature (< 4°C)
	Low oxygen level in water (hypoxia)
	Sea lice
	Viral diseases
Salmon nutrition model	Diseases/pathogens/pests
	Feeding regime
	High lipid (fat) level in the salmon's liver
	Low protein/high lipid diets
	Starvation in salmon
Aquaculture occupational health and safety (OHS) model	Community/company power relations
	Environmental conditions (adverse weather events)
	Environmental conditions (adverse weather events) - OHS hazards coupling factor
	Failure to prepare for unforeseen events
	Insufficient regulatory frameworks for fish health and OHS
	Limited detection and disclosed documentation of adverse health effects
	No scheduled risk management - OHS and product risk

Risk category	Risk factor
	OHS hazardous agents: chemical, physical, biological, and psychosocial
	OHS regulation requirements and inadequate inspection capabilities
	Poor monitoring/late finding of the risk situation (MME), and also no reporting or insufficient reporting
	Restricted access to healthcare, compensation, and RTW supports
	Unsafe work structures and planning for high - risk MME labor/workers affected by fatigue due to lengthy work hours
	Work - induced injury or disease (consequence)
Workers' livelihood model	Appropriate risk management system
	Differential impacts on workers - gender, race, age
	Fewer employment opportunities in aquaculture industry
	Lack of contingency planning
	Lack of risk assessment
	Lack of skilled trained workers and labor
	Lack of worker "voice" and agency
	Loss of health benefits for workers and immediate families
	Loss of household incomes
	Loss of income for aquaculture workers
	Loss of local employment for communities
	national/federal/provincial regulatory system
	outmigration
	Poor monitoring of risk situations (MMEs)
	Reduced work for an extended period (2 years)
	Regulatory requirement for MME plan
	Shortage of skilled trained workers
	Temporary foreign workforce
	Weak social security
Risk factors shared between two or more risk categories	Appropriate risk management system
	Bacterial pathogens
	Cold temperatures (< 4°C)/low ocean temperature (< 4°C)
	Community/company power relations
	Extreme weather events
	Fish immune suppression
	Harmful algal blooms (HABs)
	High water/ocean temperature (18 – 20°C)
	Lack of contingency planning
	Lack of risk assessment
	Low water oxygen level (hypoxia; < 70%)
	Poor monitoring of risk situations
	Poor monitoring/late finding of the risk situation (MME), and also no reporting or insufficient reporting
	Presence of sea lice
	Prolonged exposure of salmon to high temperatures (18 – 20°C)
	Prolonged exposure of salmon to low temperatures (< 4°C)
	Restricted access to according health care, compensation, and RTW supports
	Shortage of skilled trained workers
	Very high water temperatures (> 21 – 22°C)
	Viral pathogens (incl. ISAv)

(Continues)

Risk category	Risk factor
Management decision - making and mitigating risk factors	Alternative employment
	Antibiotics
	Cage siting/construction/depth
	Cleaner fish
	Community/company power dynamics
	Community/company power relations
	Diets
	Economic safeguard
	Enhanced performance of immune system
	Feeding regime/nutrition
	(High) fish densities
	Increased appetite
	Lack of MME post - occurrence OHS hazard review and structural changes for future risk mitigation
	Mort collection
	Net cleaning
	Oxygenation/aeration
	Poor monitoring/late finding of the risk situation (MME), and also no reporting or insufficient reporting
	Presence of risk assessment
	Production level (scale of production)
	Protection against oxidative stress
	Reorganization of production/disinvestment
	Restructuring of production
	Sea lice treatment (incl. cleaner fish)
	Selective breeding
	Stocking densities
	Stocking density
	Upgrading infrastructure (nets)
	Use of functional diets for salmon
	Vaccination