Aquaculture 566 (2023) 739225

Contents lists available at ScienceDirect

Aquaculture

journal homepage: www.elsevier.com/locate/aquaculture

Mass mortality events in marine salmon aquaculture and their influence on occupational health and safety hazards and risk of injury

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A R T I C L E I N F O

Keywords:
Marine salmon aquaculture
Mass mortality events
Occupational health and safety

A B S T R A C T

Introduction: Mass mortality events (MMEs) involve the sudden death of thousands to millions of fish. MMEs are a serious problem in marine finfish aquaculture globally and may become more common with climate change. They can entail significant asset losses; pose compliance threats to environmental and animal health, and occupational health and safety obligations; and may undermine social license to operate. MMEs may be defined as major accidents in that they require rapid mobilization of workers, vessels and other supports and working under pressure to a) investigate the extent and cause of the die-off; b) remove, transport, and dispose of dead finfish; and c) adjust farm design and practices to reduce future risk. As with other such events, MMEs have the potential to cause injury or fatalities to persons, damage to cages and vessels and also substantially reduce the welfare or number of fish. Still, no existing research has explored the potential aquaculture occupational health and safety (AOHS) hazards and risks associated with responding to MMEs.
Materials and methods: An international AOHS research team performed a desktop exercise using information on definitions of MMEs, incident reports, legal and regulatory guidance and documentation and media coverage to generate five country profiles (Canada, Chile, Ireland, Norway, Scotland) of potential AOHS hazards and risks associated with MMEs. Country profile findings were synthesized and incorporated into a multi-disciplinary, expert elicitation risk assessment process to identify causes and consequences of MMEs.
Results: Findings indicate variability in MME definitions, requirements for event reporting and AOHS-related contingency planning across countries. To highlight key hazards and potential pathways between MME-prevention planning, monitoring and response and AOHS risks a preliminary bow-tie risk analysis is conducted. Bow-tie risk analysis is a graphical tool to illustrate an accident scenario, with accident causes on one side of the tie and consequences on the other. These findings are also relevant for AOHS in general.
Conclusions: AOHS concerns need to be fully and effectively integrated into broader risk assessments and surveillance systems to prevent MMEs and reduce their consequences in marine finfish aquaculture.

1. Introduction

Marine salmon aquaculture is a major part of the global aquaculture sector. The combination of intensive farming/harvesting/transport activities on the ocean associated with it makes salmon aquaculture a high risk sector. Mass mortality events (MMEs) ranging from the death of thousands to millions of fish in a short period of time are a challenge in the marine salmon aquaculture sector globally. MMEs can have

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https://doi.org/10.1016/j.aquaculture.2022.739225
Received 6 April 2022; Received in revised form 23 December 2022; Accepted 30 December 2022
Available online 3 January 2023

serious consequences for companies in terms of loss of assets and clean-up costs valued at millions of dollars (Armijo et al., 2020; Mutter, 2020; Oesterud, 2016). They fit Rausand and Haugen, 2020's definition of a major accident in fish farming in that they are acute events that entail reduced welfare or mortality of a large number of fish, major damage to the farm and can result in injuries or fatalities (Holen et al., 2019). Because of associated negative effects on animal health and environmental health concerns, MMEs can lead to investigations and regulatory, technological or other changes designed to mitigate future risk. They can disrupt employment and pose a threat to social license to operate by fueling criticisms of the marine salmon aquaculture industry (Mather and Fanning, 2019). They can also pose threats to aquaculture occupational health and safety (AOHS).

AOHS, our focus here, is under-researched globally despite the scale and rapid growth of the sector (Watterson et al., 2020). The existing AOHS peer-reviewed research is largely limited to aquaculture operations in Scandinavia, the United States, Australia, Brazil, Canada and Chile. Researchers have identified multiple and diverse hazards (Thorvaldsen et al., 2020a, 2020b; Fry et al., 2019; Ngajilo and Jeebhay, 2019; Watterson et al., 2020; Cole et al., 2009; Moreau and Neis, 2009) and high rates of injuries and fatalities in aquaculture relative to other industries (Cavalli et al., 2019; Fry et al., 2019; Holen et al., 2018a, 2018b; Holmen et al., 2018; Kaustell et al., 2019; Mitchell and Lystad, 2019; Myers and Durborow, 2012; Ochs et al., 2021). They have also identified significant policy gaps related to AOHS surveillance, reporting and regulation (Fry et al., 2019; Mitchell and Lystad, 2019; Watterson et al., 2020).

While existing research indicates aquaculture, including salmon net-pen aquaculture, is a relatively high risk sector from the point of view of injury and fatality rates, systematic risk assessments of personnel safety and other types of risk are rare, with methodologies still being developed. Even in Norway where risk assessment of fish farm operations is mandatory, the practice needs to be improved across the industry (Holmen et al., 2018). Overall, risk assessment of major accidents/system failures within aquaculture, such as MMEs, is in its infancy with Norwegian researchers beginning to address these gaps by identifying dimensions of risk, and developing frameworks and methods for major accident risk assessment and an assessment of the operational limits in aquaculture (Holen et al., 2019; Yang et al., 2020a, Yang et al., 2020b).

Responding to MMEs requires rapid mobilization of workers and technological and other supports in order to identify the extent and cause of the event, plan and undertake removal of the dead salmon from the pens, and transport these salmon to places where they can be safely disposed of or rendered into fish meal or some other product. MMEs require communication with authorities and media, working under pressure and also often lead to changes in pen distribution, design and other technological changes to reduce future risk, and to changes in work organization and tasks during and following MMEs. All of these activities and changes have potential effects on AOHS, but no existing research appears to have explored the potential AOHS hazards and risk associated with MMEs.

2. Methods

The authors carried out a collaborative, desktop initiative as part of a larger risk assessment exercise on MMEs in salmon aquaculture, including causes and potential consequences. Co-authors from Norway, Scotland, Chile, Ireland and Canada were tasked in the first round, with developing country profiles for aquaculture OHS and mass MEs using studies of hazards, related job tasks and risk in the sector and a review of reports of mass mortality events (MMEs), as well as any policy documents and publicly available data on the cause, frequency and OHS consequences of these events. Country profiles were assembled using policy documents, media coverage and other publicly available data on the cause, frequency and OHS consequences of documented events in these five countries with major marine salmon aquaculture industries and a history of MMEs. Country profiles (developed in winter 2021), mainly focused on collecting information on MMEs for the period from 2016 to 2019.

Profiles covered the following broad topic areas: definitions/descriptions of MMEs for their respective jurisdictions; information on number and scale of MMEs for their countries including, where available, information on causes, working conditions, numbers of workers, seasons; an overview of work tasks likely affected by these MMEs and any information on related injuries/fatalities; information on work organization and relevant regulatory frameworks that might have influenced regulatory and organizational response and risk mitigation; and, information on whether their country/jurisdiction has any particular regulations around MMEs.

Resulting country profiles were then synthesized into a report on MME-related hazards and risk and used to generate a preliminary risk profile of pathways between MMEs and the risk of occupational injury and illness in the sector. The risk profile was discussed and refined as part of an expert elicitation-based process encompassing both experts in causes of MMEs (climate, disease, nutrition) and consequences for AOHS and for communities. Expert elicitation techniques are a used in assessing environmental risks and impacts in environmental management and evidence-driven multidisciplinary expert elicitation can help address the problem of expert overconfidence associated with these techniques (Singh et al., 2017). This expert-elicitation process involved two multi-disciplinary workshops held in spring 2021 results from which are informing a process of interpretive structural modelling related to MME risks and impacts (Sajid et al., 2017; Sajid et al., 2023).

The remainder of this manuscript brings together findings from the country profiles and from the AOHS literature and risk assessment workshop exercise to provide an overview of findings related to mortality events (MEs) and mass mortality events (MMEs) in the various countries and a synthesis of existing knowledge about hazards, accidents and injuries in marine salmon aquaculture. Findings from the different country profiles and assessments of the impacts of particular MMEs in these countries, combined with insights from existing AOHS research, including details on job tasks and descriptions of MMEs where some details are available, show ways and contexts where MMEs are likely to contribute to multiple kinds of hazard exposures and risk. Drawing on these findings, on methodological and other insights emerging from aquaculture risk assessments of hazards developing into accidents (which would include MMEs) from research underway in Norway (Føre and Thorvaldsen, 2021; Holmen et al., 2021), and on insights from the larger MME expert elicitation process, the manuscript presents a preliminary bow-tie analysis of risk pathways encompassing conditions prior to and subsequent to the MME. While more research and dialogue is needed to identify and address real and potential OHS issues related to MMEs across different contexts the findings point to methods that could be used to relatively rapidly expand knowledge and research in these areas.

2.1. Marine salmon aquaculture

Marine salmon aquaculture production is concentrated in coastal areas in relatively few countries including Norway, Canada, Chile, Scotland, the United States, Australia, the Faroe Islands, Ireland and Iceland. It is one of the most capital-intensive aquaculture sectors and, outside of Norway (Holmen and Thorvaldsen, 2018) and perhaps Australia (Smart et al., 1999), the transnational part of the industry is mainly controlled by a few very large corporations, many of which are headquartered in Norway. These companies often subcontract key services including mort removal to smaller, specialized companies. The activities of these companies are governed by different OHS regulatory regimes in different parts of the world (Watterson et al., 2020).

Norway is the leading Atlantic salmon producer globally with about one half of the total global production (Food and Agriculture Organization, 2020). While Norway's aquaculture sector consists almost exclusively of marine salmon aquaculture, other salmon-producing

Table 1
Mortality event (ME) definitions and required actions across countries.

British Columbia, Canada (regulations vary by province in Canada)	Definition: fish mortalities equivalent to 4000 kg or more, or losses reaching 2% of the current stock inventory within a 24-h period; or fish mortalities equivalent to 10,000 kg or more, or losses reaching 5% of the current stock inventory within a five-day period. Regulations: a) reporting of mortality events to the federal Department of Fisheries and Oceans within 24 h of discovery. b) related license requirements include having a Health Management Plan (HMP) and HMP standard operating procedures for retrieval, recording and disposing of fish carcasses with bio-security protocols, c) In the event of a Mortality Event, licensees need to outline actions to handle the additional biomass on site and identification of vessels that will be used to collect and transport mortalities.
Newfoundland and Labrador, Canada	a) The Newfoundland and Labrador government's licensing aquaculture policies and procedures manual introduced in fall 2019 indicates companies must report "abnormal mortality events" within 24 h (as of November 2019) and provide a copy of Standard Operating Procedures for dealing with these events for review and approval by the department and approved by other relevant departments. The manual does not seem to include a definition of "abnormal mortality events." [2] (pg. 62) b) In addition, all applicants for an aquaculture license must submit a Fish Health Management Plan (including a Biosecurity Plan and a Fish Disposal Plan) when they submit their license application$_2$ (pg. 15). c) Prior to October 2020, all licensees were required to implement mitigation measures approved by the Department of Fisheries and Land Resources to prevent mortality events that include installation of minimum 20 m nets, aeration devices and optimal farmed fish stocking density.
Chile	Aquaculture mortality events are defined in relation to capacity for extraction, storage and certified rendering of morts. Government considers a mass die-off to have happened if any of the following occurs: a) the minimum daily capacity for certified mortality extraction is exceeded (the minimum daily capacity cannot be under 15 tons) b) the minimum daily capacity for certified denaturing is exceeded (the minimum daily capacity of extraction cannot be under 15 tons) c) storage of denatured material reaches 80% of capacity[3]
Ireland	"Increased mortality" is defined as "that which is unexplained and above the level of what is considered normal to the site under the prevailing conditions,' i.e., a) mortalities exceeding 1% for fish >750 g in weight b) 1.5% for fish <750 g in weight (FHUMI. 2016. "The Farmed Salmonid Health Handbook."[4]
Scotland	Has no precise definition of what constitutes a mortality event or 'mass die-off' but the Fish Health Inspectorate must be notified of events exceeding the following thresholds: a) 1.5% weekly mortality or 6% 5-week rolling mortality for sites with average weight under 750 g b) 1.0% weekly mortality or 4% 5-week rolling mortality for sites with average weight above 750 g There is no requirement to report mortality events to the Health and Safety Executive.
Norway	Has no formal definition of mass mortalities. Fish farmers are required to report increased mortality at or above the following levels: a) Fish below 0.5 kg: >0.5 per thousand b) Fish above 0.5 kg: >0.25 per thousand c) Mortality should be calculated per fish cage or per (smolt) tub per day[5].

1. (Government of Canada, F. and O.C, 2015 https://www.pac.dfo-mpo.gc.ca/aquaculture/licence-permis/docs/licence-cond-permis-mar/licence-cond-permis-mar-eng.pdf p. 3)
2. (pg. 62) licensing-pdf-aquaculture-policy-procedures-manual.pdf (gov.nl.ca).
3. SERNAPESCA (2021). Manual de normativa de mortalidades massivas. Retrieved January 25, 2022. http://www.sernapesca.cl/sites/default/files/manual_normativa_mortalidades_masivas_28-01-2021_v2.pdf
4. Retrieved February 15, 2021, https://www.fishhealth.ie/fhu/health-surveillance/aquaplan-fish-health-management-ireland/farmed-salmonid-handbook) pg. 17.
5. https://www.mattilsynet.no/fisk_og_akvakultur/fiskevelferd/varslingsplikt_ved_sykdom_og_daarlig_velferd.25660 (in Norwegian)

countries also have shellfish and other types of aquaculture production within the same region or jurisdiction. Marine salmon production comprises 50% of Australian aquaculture production by value and is concentrated in Tasmania(Smart et al., 1999); in Canada, it comprises 65% of value and is concentrated in the coastal provinces of British Columbia (BC), New Brunswick (NB), Newfoundland and Labrador (NL) and Nova Scotia (NS) where shellfish aquaculture also takes place (Knott and Neis, 2019). In Chile, salmon accounts for 54% of value from aquaculture production (FAO, 2020). Atlantic salmon production dominates the Scottish aquaculture sector by volume and value. In Scotland, in 2020, marine salmon production totaled 192,129 tons and generated around £931 million in value (Scottish Government, 2022). Ireland produced 45,400 t of aquaculture products in 2017 including blue mussels, Atlantic salmon and Pacific cupped oyster (Food and Agriculture Organization of the United Nations, 2019).

2.2. MMEs in salmon aquaculture

As with MMEs in wildlife populations (Fey et al., 2015) and in agriculture (Munasinghe et al., 2008; Koopmans et al., 2004), marine aquaculture MMEs can, in some cases, result in the death of thousands and even millions of organisms in a short period of time. Both can also have different and sometimes multiple, interacting causes. In the case of aquaculture MMEs these causes can include harmful algae blooms, warm water and related reductions in dissolved oxygen, sea lice treatments, mechanical factors, and fish disease events. Between 2016 and 2019 fish farm companies reported 760 mortality events to the Scottish government with incidents with the highest mortality rates ranging between 20 and 57% of the stock. (Fish Health Inspectorate Scotland, n. d. https://www.gov.scot/policies/fish-health-inspectorate/). In Norway, production loss is mainly caused by fish dying in cages. In 2020, 16.4% of fish in cages died, a loss of 61.6 million fish (https://www.barentswatch.no/en/havbruk/fish-mortality-and-losses-in-production). In 2016 the mass mortality of 126,225 salmon (300 tons) happened over 26 min at a fish farm owned by SalMar[1] due to over exposure to hydrogen peroxide used during delousing. In 2019 (May/June), fish farmers in the Northern part of Norway experienced a toxic algae bloom (*Chrysochromulina leadbeaterii*) resulting in the mortality of 8 million fish across several farms and companies (Mattilsynet, 2021; Holland, 2019; Karlsen et al., 2019; Welch, 2019). *Notification of Incidents That Result in*

[1] https://www.aftenposten.no/norge/i/d45w/massedoed-av-laks-paa-oppdrettsanlegg (in Norwegian).

Poor Fish Welfare for Farmed Fish | The Norwegian Food Safety Authority, n.d.; *Personvern- og Cookie-erklæring, Schibsted Norge*, n.d.).

The Chilean industry experienced a massive MME in 2016 caused by a toxic harmful algae bloom. This affected 14 companies and mortalities exceeded 25 million fish (10% of the total stock). The volume of dead fish was equivalent to a biomass of 40,000 tons (Armijo et al., 2020). Many other mortality events have occurred in Chile since 2016. For instance, between January and May 2020, there were 51 fish MEs in Chile and >50% of these events were deemed a mass mortality using Chile's criteria (see Table 1) because storage of denatured material surpassed 80% of capacity (SERNAPESCA, S. de A, 2020).

In Ireland, there is limited information on mortality events. A major event in 2003 resulting in the death of 345,000 fish on three farms was attributed to companies trawling for prawns that released hydrogen sulphide into the pens (Siggins, 2003). In late October 2021, MOWI was reported to have experienced an MME with preliminary estimates of 80,000 fish deaths in Ireland. Around the same time, MOWI experienced a large MME comprised of 489,000 salmon deaths (just over half the fish at the relevant site) in its operations on the Island of Newfoundland on Canada's east coast (Godfrey, 2021). This followed an earlier, much larger MME for MOWI in the same Newfoundland region in 2019 consisting of 2.6 million salmon (Montgomery, 2019; White, 2019). Recent MMEs have also occurred in the state of Maine, in the United States (Mitchell, 2021; Rogers, 2021).

Low levels of mortality are a routine feature of salmon aquaculture. Regulation and reporting of this routine mortality is generally tied to animal health concerns and related requirements for efficient, ongoing removal and safe disposal of the fish. As indicated in Table 1 below, for the countries studied, the definition of mortality events (MEs) (i.e., events where the scale of mortality exceeds 'normal' situations and is generally associated with specific reporting requirements) varies across jurisdictions, by time and by the size of the fish. Mortality events are generally managed separately from escapes.

In British Columbia, on Canada's west coast, all mortality events that exceed certain levels (see Table 1) must be reported and a description of each of these reported events and their causes since 2011 is available online at Mortality events at British Columbia marine finfish aquaculture sites - Open Government Portal (canada.ca). According to this portal, there were 432 mortality events between 2011 and 2021. Unfortunately, these data do not include information on the size of the mortality events. Media coverage of incidents like the die-off of 250,000 salmon (approximately 1000 tons) at two Grieg farms in British Columbia in 2018 indicate some of these events would qualify as MMEs (White, 2018). The most common primary causes listed on this site include low dissolved oxygen, followed by algae blooms, treatment, handling, water quality, infectious diseases, and other causes. In some cases, multiple causes are listed indicating interactivity.

In Newfoundland and Labrador, on Canada's east coast, the requirement to report "abnormal mortality events" was introduced in 2019 after an MME, but "abnormal" was not defined. In Chile, reporting requirements are defined in relation to their relationship to certified mortality extraction, storage and rendering capacity for morts (dead fish). In Ireland, Scotland and Norway, the requirement to report mortalities is based on the scale of mortalities relative to the number or weight in the cages.

Occupational health risks associated with MMEs have been identified and addressed in terrestrial animal husbandry with a focus on zoonotic agents including the potential for infection of workers on farms, in mort transport, and in rendering, and on other occupational health risks (Arzey et al., 2012; Munasinghe et al., 2008; Koopmans et al., 2004; Convery et al., 2007). Large-scale MMEs in salmon aquaculture can result in serious challenges for companies and workers. Finding sufficient diving and pump capacity to remove the fish, as well as storage capacity on site and capacity for handling and transporting of ensilage can be especially challenging. MMEs can also result in major technological and other changes on salmon farms that come with attendant hazards such as working with and anchoring larger cages, working in deeper water and other changes. There may also be psychosocial hazards. As with other kinds of major accidents, MMEs point to the importance of prior hazard identification and risk assessments; the development and implementation of emergency preparedness plans, contingency planning, and access to key resources including appropriately trained personnel and surplus capacity for the rapid removal, transportation and processing of dead finfish.

2.3. MMEs and aquaculture occupational health and safety

A systematic evaluation of the relationship between MMEs and AOHS would ideally start with an analysis of data on the timing, scale, location and nature of previous MMEs linked to data on near-misses/injuries/illnesses/fatalities associated with those times and places. MME-related incident patterns could then be compared with patterns during non-MME periods on the same farms or on similar farms where MMEs have not occurred. However, a considerable number of comparable undesired events/accidents with and without MMEs would be needed to make a quantitative comparison. Our country profile findings indicate that in most cases, this kind of rigorous comparison would not be feasible based on available data due to lack of clear definitions of MMEs and critical gaps in information on mortality events. Furthermore, as noted by Watterson et al. (2020), data on occupational injuries/illnesses and fatalities are often hard to isolate from compensation claims data for agriculture or fisheries more generally in some countries, and aquaculture workers are not always eligible for workers' compensation. Subcontracting of some activities, such as diving, reliance on informal workers in some contexts, and likely delays between exposures and illness in the case of some diving-related and other activities would further complicate such an analysis. It may be possible to use the approach outlined above in future risk assessments for hazardous events which might result in MMEs in some countries, particularly if the analysis of administrative data is coupled with qualitative interviews with industry personnel who have experienced MMEs.

An alternative approach and one we use here is to identify the tasks, conditions and processes associated with MMEs that are likely to affect the nature and scale of hazard exposures and risk levels based on existing AOHS research, and then to map the risk pathways. Norwegian research suggests that aquaculture work-related accident causality is often complex and associated with a range of contributing factors including the work environment, demanding work, variability in skills and training, safety management that is poorly implemented, and other challenges (Thorvaldsen et al., 2015; Føre and Thorvaldsen, 2021; Holmen et al., 2021). MMEs are primarily system failures, a type of major accident similar to spills and blow-outs in the oil and gas and chemical sectors. Like other major accidents, MMEs are relatively rare and highly variable events and may be associated with enhanced or changed risk profiles associated with them without these resulting, in all cases, in reported injuries/illnesses or fatalities or claims for compensation.

Development of holistic risk management systems for system failures in aquaculture is in its infancy and, unlike in the oil and gas and chemical sectors, the risk profile in aquaculture involves rearing live animals, thus requiring attention to, for instance, animal health and food quality, in addition to environmental, material as well as worker occupational health and safety issues (Holen et al., 2019; Yang et al., 2020b; Holmen et al., 2021). Potential interactions across and within these dimensions need to be taken into account in aquaculture risk assessments as illustrated by research showing that monitoring and penalties for certain kinds of events such as fish escapes and problems with fish health including MMEs, can lead to workers placing more attention on these issues than on protecting their own health and safety (Thorvaldsen et al., 2015; Størkersen, 2012). One way to do this is to carry out systems-based risk assessments in relation to MMEs and aquaculture more generally. With the exception of Norway, there appear to be few such publicly available assessments for the sector that also focus on AOHS and we draw on those in our bowtie risk assessment below (Holmen et al., 2018; Thorvaldsen et al., 2020a, 2020b; Størkersen, 2012).

Marine salmon aquaculture work activities likely to be affected by MMEs include work on vessels transporting workers, feed, equipment, supplies and dead and live fish; installing and removing and possibly moving cages; working around installed cages including as part of diving support as well as on and around feed barges. It also encompasses underwater work around, under and inside of net-pens, including gathering morts in various stages of decay, net cleaning and repair, as well as work on wharves and onshore rendering of dead fish. MMEs can trigger technological changes designed to reduce future risk that may affect risk. Much of this work happens outdoors and is subject to the effects of weather-related exposures.

Although limited, the growing body of research on AOHS indicates aquaculture is associated with occupational diseases due to diverse physical, ergonomic, chemical and biological hazards, as well as high injury and fatality rates (Watterson et al., 2020; Ngajilo and Jeebhay, 2019). These hazards are also prevalent in marine finfish aquaculture, including within the work activities outlined above. Norwegian, Finnish, American, Australian and Canadian researchers have used administrative datasets obtained from occupational incident and injury reporting systems to document injury characteristics most frequently encountered in the aquaculture sector. They have also tracked trends in fatality and injury rates and compared these to other sectors (Fry et al., 2019; Kaustell et al., 2019; Mitchell and Lystad, 2019; Holen et al., 2018a, 2018b; Holmen et al., 2018; Ochs et al., 2021). Their research indicates aquaculture, including marine salmon aquaculture, is associated with a relatively high risk of injury and fatality. In Norway, salmon aquaculture is the second most hazardous industry after fisheries with high occupational injury and fatality rates, although these rates have declined in response to interventions and changes in the industry (Holen et al., 2018a, 2018b; Thorvaldsen et al., 2020a, 2020b). In Australia, Mitchell and Lystad (2019) found that serious injury compensation claims for the period 2012–2016 were most common in the offshore caged aquaculture sector (42.6%) and almost two-thirds of disease claims were from this sector.

Common occupational diseases and injuries in marine salmon aquaculture include musculoskeletal disorders, falls on the same level and lacerations or open wounds of the hands, fingers or thumb. Being hit by moving objects is a common source of injury. Physical hazards include working outdoors in environmentally-variable conditions (Sandsund et al., 2022; Holen et al., 2018a, 2018b; Holmen et al., 2018; Douglas et al., 1995, Thorvaldsen et al., 2020a, 2020b). Mitchell and Lystad (2019) also identified multiple psychosocial hazards in Australian fishing and aquaculture including long work hours, irregular work hours, shift work and occupational stress linked to working away from families. Similar findings regarding long work hours have been described in a recent study from Norway (Thorvaldsen et al., 2020a, 2020b).

Ngajilo and Jeebhay (2019) reviewed the literature on occupational injuries and diseases in aquaculture. They found:

> "[f]or salmon farms (excluding hatcheries), studies have identified safety issues related to diving, falls from cages, sea-going workboats, cranes and hoists … Documented chemical hazards include … pesticides, polychlorinated biphenyl and organochlorines contaminating fish feed … Biological hazards include leptospirosis infection, … allergenic dust from fish feed, needle-stick injuries and associated complications, as well as self-injection of fish vaccine which can result in inflammation and anaphylaxis … Ergonomic hazards from lifting nets can result in musculoskeletal injuries … Moreover, a recent study from Norway highlighted several safety hazards related to operating cranes and capstans, blows from objects, and drowning as important causes of injuries and fatalities in salmon farming …" (pg. 41).

Workers in technical positions requiring specialized training (diving, net pen cleaning) encounter risks of decompression sickness, entanglement, entrapment under ice in some contexts, and other hazards (Myers and Durborow, 2012; Guerrero et al., 2018; Smart et al., 1999). These and other workers including equipment cleaners, divers, fish handlers, and processing workers that may be immersed in or come into contact with water, equipment, live fish, and fish waste contaminated with chemicals and antibiotics. This may, as a result, increase their risk of adverse health effects associated with exposures to the chemicals, antibiotics, and to antimicrobial resistant bacteria (Lulijwa et al., 2020; Love et al., 2020; Brunton et al., 2019; Sapkota et al., 2008).

2.4. Risk factors associated with mass mortality events

The review of AOHS research on marine salmon aquaculture in the previous section shows that many of the tasks affected by MMEs are already associated with increased injury risk. How and under what conditions would MMEs tend to enhance the risk of injury, illness and fatality? MMEs can affect types and levels of exposures to documented hazards in finfish aquaculture especially in diving, work on cages and around cages, on seagoing workboats, in confined spaces, and with cranes and hoists. The ultimate adverse effects will depend on the scale, duration and timing of the MME including in relation to weather events. Their OHS impacts will also be affected by risk assessments, emergency preparedness, and contingency planning, as well as technology and work task design, and other factors.

MMEs can lead to the need to recruit new divers and to more sustained diving activities with changed profiles, as was the case during the MME in Chile in 2016 and in the one in Newfoundland and Labrador in 2019. MMEs can, for instance, change net configuration due to the weight of large numbers of fish, thus changing dive depth. They can affect dive frequency and duration with potential OHS effects. When MME-related demands exceed local or normal diving capacity, this can lead to changes in labour force composition by requiring the recruitment of extra divers from outside the region and sector who may or may not be as well trained, experienced and as well-equipped as regular dive labour forces. The volume of material, pressure for rapid removal and safe disposal of the dead fish can lead to long working hours and fatigue for divers and other workers.

In some contexts, like Norway, most of the fish removal in response to an MME triggered by an algae bloom in 2019, was done using pumps rather than divers, and dead fish were transported in specialized aquaculture vessels. In this context, however, insufficient staffing was still the most prominent OHS concern in that several companies did not have enough workers to assist. In particular, smaller companies needed additional staffing during the crisis since workers were required to work long shifts (Karlsen et al., 2019). Previous studies have shown that fatigue and tiredness due to heavy workloads and lack of personnel can contribute to fish escapes and to threats to personal safety (Føre and Thorvaldsen, 2021; Thorvaldsen et al., 2020a; Thorvaldsen et al., 2020b). It is thus likely that insufficient staffing, long work hours and high levels of stress related to operations such as moving the fish may have a negative impact on worker safety. However, a service vessel operator in a fish farm company in Nordland County, reported that to his knowledge, no occupational accidents happened during the busy period.

In Newfoundland and Labrador during the 2019 MOWI MME and in Chile MME during 2016, dead fish were transported in fishing vessels operated by fishermen, raising questions about potential issues with vessel design including confined spaces in fishing holds, chemical (such as hydrogen sulphide from decomposing fish) and other exposures, as well as issues with experience, training and possibly poor access to PPE (Kenyon, 2008). Timing of fish removal in relation to chemical and antibiotic treatments as well as the degree of fish decay might be different from normal operations affecting potential exposures and risk for divers, shore and transportation personnel as well as for the marine environment. Technologies that indirectly protect workers from exposures to contaminated water, fish, and equipment, may not be readily available to smaller operations.

Of the countries profiled in the study only Chile had issued a health and safety circular related to AOHS hazards associated with MMEs. In that case, the circular focused on diving and potential hydrogen sulfide (H_2S) exposures in the transport of dead fish. Chile issued Circular 0–31/020 – safety measures in the case of mass fish mortalities - in which health threats, and steps for preventing injury/illness are identified. Circular 0–31 establishes the safety measures that must be adopted in cases of mass fish mortality including in removal, loading, transportation, and unloading tasks and is under the jurisdiction of the Maritime Authority. The Circular and some other documents explicitly address two key risks: the risk of exposure to H_2S and diving safety.

High antibiotic use is also reported in Chilean aquaculture (Millanao et al., 2018), largely driven by outbreaks of *Piscirickettsia salmonis* (Miranda et al., 2018; Buschmann et al., 2006). Risk of exposures to antibiotics, antibiotic residues, and AMR genes is exacerbated by the concentration of Chilean aquaculture operations within a small geographical region and their situation relatively close to land (Bachmann-Vargas et al., 2021; Tomova et al., 2015). Research has shown the presence of antimicrobial resistant bacteria (AMR) is higher in regions under selective pressure from antibiotic use in aquaculture than in unexposed regions (Shah et al., 2014; Buschmann et al., 2012). Furthermore, there is evidence of horizontal gene transfer of AMR genes from aquatic to human pathogens in Chilean regions exposed to intense aquaculture operations (Tomova et al., 2015). Removing, transporting and processing fish and fish biomass in the wake of an MME might contribute to enhanced risk of exposures to antibiotic residues that exert selective pressure for AMR and to AMR genetic determinants.[2] Assessments of the risk of exposures to AMR genetic determinants will require local and value-chain specific information due to variation in operations, technologies, AMR bacteria abundance, and environmental and socioeconomic factors (Reverter et al., 2020).

Based on the country profile for Scotland, MMEs have been linked to various operations, all of which raise some general and some specific OHS hazards and related risks. Failed treatments such as chemical applications and in de-licing machines, and poor handling, involve known hazards and risks to workers. Data on specific injuries and illnesses are not available but clearing dead fish and net cleaning are major problems. MMEs could affect the weight and porosity of nets. The lifting of nets out of the water by [3]crane is a difficult task due to the unknown weight of the net and is covered by a variety of generic health and safety laws and regulations. Removal of nets from the sea to enable cleaning may also expose workers to pathogenic bacteria with exposures potentially affected by MMEs. COSHH 2002 Regulations cover some of the occupational health risks and the UK Veterinary Medicines Directorate has a role in dealing with aquaculture workers affected by animal medicines and veterinary products. The HSE does not appear to keep information specifically on MMEs and related worker injuries and illnesses but it may be possible to extract such information at a later date. Field inspectors do have knowledge of some of the risks.

Findings in the Irish profile were similar to those for Scotland in terms of the lack of information on MMEs and related worker injuries and illnesses. The Irish Health and Safety Authority (HSA) provides specific information on biological, chemical and physical hazards, confined space working, equipment and machinery, lifting gear and manual handling in fish farming all of which could be affected by MMEs. Some HSA information dates back to 2014 and although it covers generic fishing hazards applicable to offshore fish farming, little or no information in these generic guides would specifically cover groups like divers, for instance, when dealing with mass die-offs. However, the HSA does have specific guidance on diving at work that encompasses aquaculture and uses UK HSE as a source of information on some diving hazards.

Many MMEs are associated with Harmful Algae Blooms (HABs). In the case of Chile, for example, HABs were implicated as the causal agent for most of the MMEs in Chilean salmon aquaculture between 2016 and 2021. The latter were driven by blooms of *Karenia mikimoti*, *Gymnodinium* spp., *Pesudo-nitzschia, Azadinium* spp., *Skeletonema* spp., *Chaetoceros cryophilus,* and *Cochlodinium* spp. (Chile, nd. Sernapesca - Servicio Nacional de Pesca y Acuicultura (available at: http://www.sernapesca.cl/busqueda?search=mortalidad+masiva, accessed December 2022)[4]).

These HAB events are anticipated to increase in frequency and intensity globally due to climate change as a result of increases in sea water temperature, salinity and nutrient concentration caused by evaporation. Toxins and cells released by HABs are linked to adverse human health outcomes as identified in a number of anecdotal and case reports. There is, however, a paucity of epidemiological studies reporting adverse health outcomes associated with acute, and particularly chronic, exposures (Young et al., 2020).

Occupational exposure pathways to cyanobacterial toxins or cells have been identified as incidental contact, consumption, or inhalation of water or aerosols (Young et al., 2020; Grattan et al., 2016; Backer and McGillicuddy, 2006; Carmichael and Falconer, 1993). Adverse health outcomes associated with these latter exposures include dermatological, ocular and respiratory health effects, as a result of irritation caused by these toxins. Common clinical problems reported include skin itching and sores; swelling of the eyes and face; and respiratory symptoms including shortness of breath (Backer and McGillicuddy, 2006; Young et al., 2020; Hort et al., 2021; Said et al., 2018; Ngajilo and Jeebhay, 2019).

2.5. Bow-tie risk analysis

Bow-tie risk analysis is a graphical tool used to illustrate an accident situation, starting from causal factors and ending potential with consequences. Compared with other models available, the reliability and efficiency of bow-tie analysis is well proved and it is used in broad range of applications in safety and risk analysis (Khakzad et al., 2012; Chevreau et al., 2006; de Dianous and Fiévez, 2006). A preliminary bow-tie risk analysis (Figs. 1 and 2) presents key potential factors associated with enhanced risk of MMEs and related enhanced hazard exposures during and following such events, with an overall focus on potential pathways between MME prevention, planning, monitoring and interventions and AOHS risks. In Fig. 1, AOHS risk is affected by such pre-event factors as the location, season, scale, cause and duration of the MME, as well as by regulatory and social-organizational factors. Weak regulatory frameworks for fish health and OHS, weak monitoring of threats to fish health, lack of MME hazard assessments, weak OHS regulatory requirements and inspection capacity and related shortcomings in training and hazard assessments for MMEs, as well as environmental factors like extreme weather events can contribute to MME risk including for injury/illness

[2] This is discussed in more detail in relation to Chile in Cavalli, L.S., López Gómez, M.A., Ochs, C., Neis, B., Jopia, C.T., 2022. Overview on Salmon Mass Mortality Events and Occupational Health and Safety in Chile Aquaculture. All Life (under review).

[3] Information on MMEs in aquaculture in Scotland and Ireland and AOHS can be found at the following links: HSE (nd) Scottish Aquaculture Industry Forum. Working in the marine environment is a dangerous occupation. https://www.hse.gov.uk/scotland/saif.htm UK Government (1997) Diving at Work Regulations 1997 and the Approved Code of Practice – Commercial Diving Projects Inland/Inshore - L104 https://www.legislation.gov.uk/uksi/1997/2776/contents/made Health and Safety Authority Ireland (2014) Managing Health and Safety in Fishing https://www.hsa.ie/eng/Publications_and_Forms/Publications/Fishing/Managing_Health_and_Safety_in_Fishing.pdf

[4] The particular case of MMEs and aquaculture health and safety is dealt with in more detail in Cavalli, L.S., López Gómez, M.A., Ochs, C., Neis, B., Jopia, C. T., 2022. Overview on Salmon Mass Mortality Events and Occupational Health and Safety in Chile Aquaculture. All Life (under review).

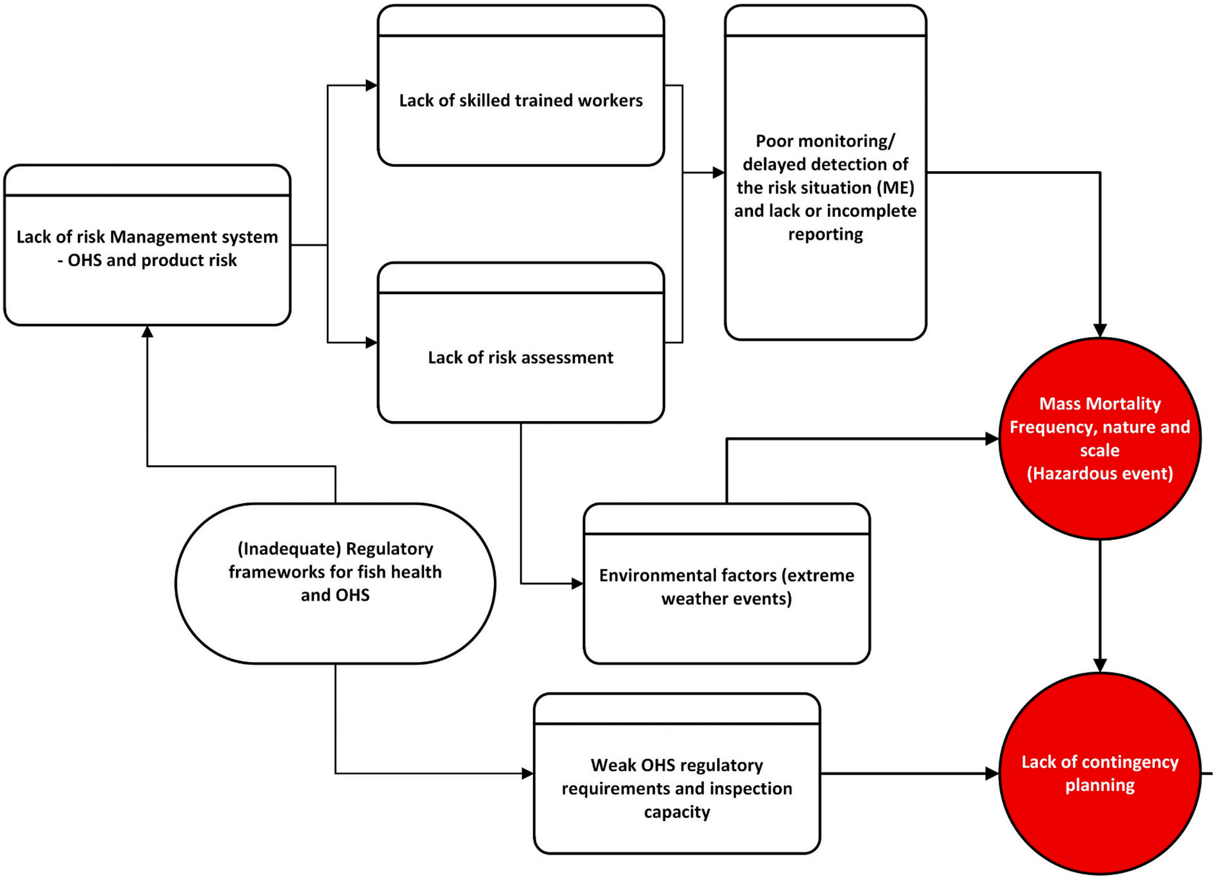

Fig. 1. MME bowtie barrier health and safety risk analysis: Pre-event contributing factors.
Caption: Fig. 1 highlights a number of pre-MME factors that can contribute to enhanced health and safety risk for aquaculture workers. The arrows show how the factors interact with each other to contribute to an MME with enhanced health and safety risk. OHS refers to Occupational Health and Safety. ME refers to Mortality Event.

among workers.

As indicated in Fig. 2, after the onset of the MME, factors that contribute to risk of injury/illness as a consequence of the MME include lack of contingency planning, potential environmental factors like extreme weather events that might happen during the event, and hazardous work design for key MME-related jobs including shortcomings in safe operating procedures, net design (including size and depth and placement relative to other pens) and integrity, as well as technologies, processes, procedures and training for fish removal, transport and disposal. Demand for skilled labour/shipping/pumping technology may exceed available resources, enhancing risk by increasing reliance on less skilled/experienced workers and increasing the risk of long working hours, stress and fatigue. Subcontracting of hazardous jobs such as diving and other forms of fish removal can add to risk and mask exposures and health and safety impacts. Gaps in detection, inspection and reporting of adverse health effects, as well as limited access to appropriate health care, compensation and RTW supports enhance current risk by potentially magnifying the effects of injury and illness. Lack of post-event hazard review and system adjustments contribute to future risk.

The NL Canada MOWI MME in 2019, and the 2016 MME in Chile, would be located at one end of a spectrum of risk with serious gaps and weaknesses across multiple variables including a lack of contingency planning, heavy reliance on divers for mort removal and other underwater work, and very limited access to surplus experienced personnel with the training and equipment required for rapid removal and transport of millions of dead fish. Delayed removal and the scale of the event complicated the task of retrieving, loading, transporting dead fish and fish 'biomass' in both NL and Chile and had the potential to increase the risk of exposures to chemical and therapeutant residues in the water for divers and to H_2S on board fishing and other vessels. At the opposite end of the spectrum, Norway's 2020 MME also exceeded existing removal capacity but not to the same degree, and reliance on specialized technologies (pumps and specialized service vessels and crew plus tighter environmental and OHS surveillance may have reduced risk.

3. Conclusion

Mortality events (ME) are an anticipated and persistent aspect of marine salmon aquaculture that, depending on their cause and scale, require different types of interventions and reporting. It is not uncommon for animal health agencies to require reporting of MEs that exceed 'normal' levels of mortality. These vary across countries and are also often tied to license provisions for companies. Where they exist, ME data might indicate causes but seem to rarely include information on the scale of the events making it difficult to track MMEs except where there has been media coverage and sometimes a public investigation. Based on the country profiles, MMEs of several thousands of fish appear to be relatively common whereas those involving more than a million salmon appear to be relatively rare. Larger MMEs vary in terms of causes, timing, scale and duration, all of which can influence hazard exposure and risk.

Monitoring and mitigating AOHS impacts does not appear to be a priority in management of MMEs and in MME investigations which appear to generally be managed according to generic OHS procedures. The country profiles point to unevenness across major marine salmon aquaculture producing countries in terms of definitions of MMEs, access to data, requirements for reporting, and requirements for risk

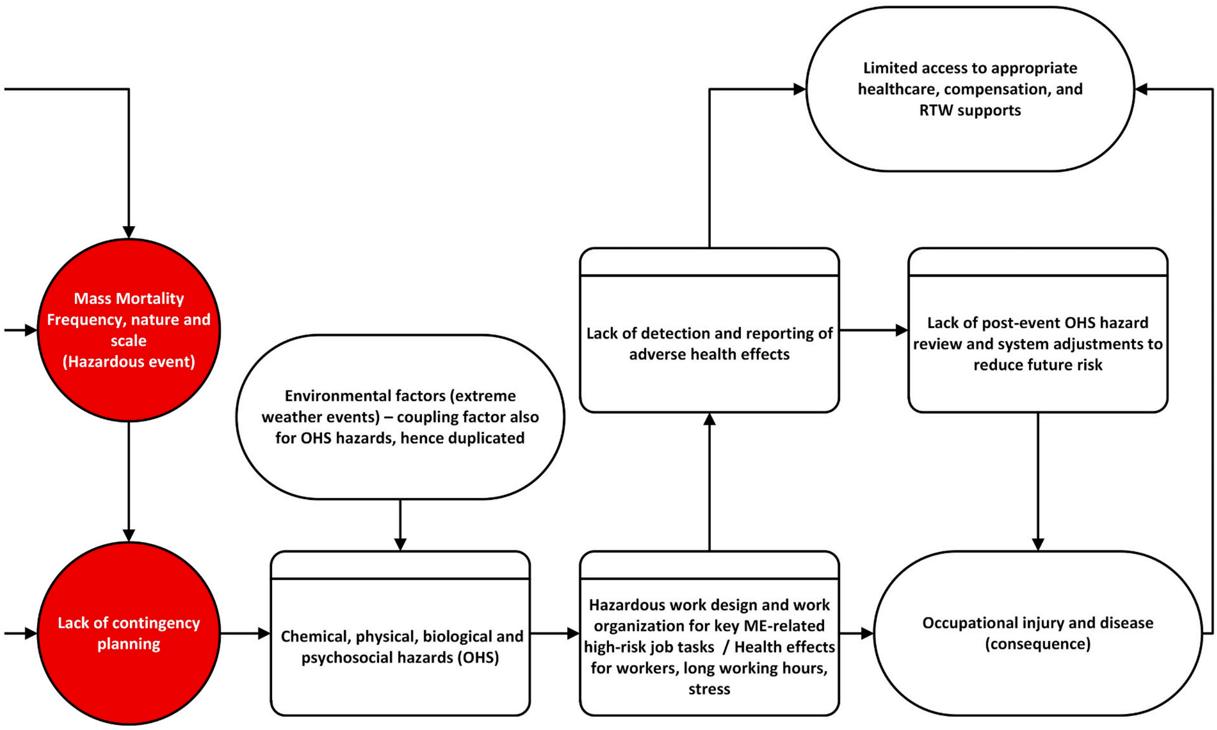

Fig. 2. MME bowtie barrier health and safety risk analysis: Post-event factors mediating risk.
Caption: Fig. 2 highlights post-MME factors that mediate health and safety risk for aquaculture workers. The arrows show how multiple factors interact with each other to influence risk of injury/illness among aquaculture workers. OHS = Occupational Health and Safety and RTW = Return To Work.

assessments and contingency planning, including for impacts on AOHS. They also point to key knowledge gaps that should be addressed in order to better understand when, how, and at what critical junctures such events enhance risk, for what types of workers, as well as ways to eliminate/mitigate risk through preventing MMEs and, when they occur, minimizing AOHS hazard exposures as these events unfold.

MMEs unfold in marine environments where companies have some limited control over environmental conditions and their cause(s) and effects are spread across multiple segments associated with the production system from net design, placement, monitoring of the pens, through to removal, transportation and disposal of waste products. Although more research is needed, many of the work activities affected by MMEs, including diving and other jobs related to retrieval of the dead salmon, loading, transporting and unloading varying volumes of dead salmon and salmon biomass, are also associated with increased risk under normal circumstances. MMEs (particularly large ones) can increase the number of workers exposed in hazardous tasks and potentially the level of exposures to key hazards. There is also some risk of larger-scale system failures that could generate injury/illness/fatality clusters, although none are documented.

A preliminary bow-tie risk analysis highlights key hazards and potential pathways between MME-prevention planning, monitoring and response, and AOHS risks. It indicates that the nature and extent of risk enhancement with an MME will likely vary with the cause and scale of the die-off, industry preparedness and contingency planning, related ready access to sufficient, appropriately trained personnel and technologies well-designed for the safe removal and transport of the dead salmon in a timely fashion, environmental conditions prior to and at the time of the MME, and access to appropriate health care, OHS expertise and compensation. As with fish escapes, fish health and disposal and rendering of morts are regulated and monitored by government, environmental groups and sometimes third party certification agencies in salmon aquaculture because of their environmental and animal health effects. This may not always be the case for OHS, thus contributing to a possible scenario that other concerns will draw attention away from OHS in the context of MMEs. This needs to change. The preliminary bow-tie hazard and risk assessment presented here indicates that AOHS concerns need to be fully and effectively integrated into broader risk assessments on ways to reduce MMEs and their consequences in marine finfish aquaculture.

Moving forward, more detailed knowledge of the timing, scale, cause and unfolding of MMEs and data on compensation claims and OHS incidents/investigations would make it possible to compare near misses and injury/accident/fatality rates during and in the wake of MMEs with those associated with 'normal' working conditions. It would also support integration of insights across countries, likely essential for robust risk assessment and safety management for these kinds of relatively rare major accidents. Where the same company operates across different countries, more detailed analysis of how they deal with MME AOHS in each country may also prove valuable.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This Research Project was partially sponsored by the Ocean Frontier Institute, through an award from the Canada First Research Excellence Fund [grant number: 20181253] and by the Department of Industry, Energy and Technology, Government of Newfoundland and Labrador, Canada [grant number: 20210487]. It was also partially sponsored by The Research Council of Norway, SFI EXPOSED Aquaculture Research Centre [grant number 237790].

Data availability

Data will be made available on request.

References

Armijo, J., Oerder, V., Auger, P.-A., Bravo, A., Molina, E., 2020. The 2016 red tide crisis in southern Chile: possible influence of the mass oceanic dumping of dead salmons. Mar. Pollut. Bull. 150, 110603 https://doi.org/10.1016/j.marpolbul.2019.110603.

Arzey, G.A., Kirkland, P.D., Arzey, K.E., Frost, M., Maywood, P., Conaty, S., Hurt, A.C., Deng, Y-M., Iannello, P., Barr, I., Dwyer, D.E., Ratnamohan, M., McPhie, K., Selleck, P., 2012. Influencza Virus A (H10N7) in chickens and poultry abattoir workers, Australia. Emerging Infectious Diseases 18,5 www.cdc.gov/eid.

Backer, L., McGillicuddy, D., 2006. Harmful algal blooms at the Interface between coastal oceanography and human Health. Oceanog. 19, 94–106. https://doi.org/10.5670/oceanog.2006.72.

Bachmann-Vargas, P., van Koppen, CSA., Lamers, M., 2021. Re-framing salmon aquaculture in the aftermath of the ISAV crisis in Chile. Marine Policy 124, 104358. https://doi.org/10.1016/j.marpol.2020.104358.

Brunton, L., Desbois, A., Garza, M., Wieland, B., Mohan, C., Hasler, B., Tam, C., Le, Phuc Thien, Phuong, N., Thi Van, P., Nguyen-Viet, H., Eltholth, M., Pham, D., Duc, P., Linh, N., Rich, K., Mateus, A., Hoque, A., Ahad, A., Khan, M., Adams, A., Guitian, J., 2019. Identifying hotspots for antibiotic resistance emergence and selection, and elucidating pathways to human exposure: application of a systems thinking approach to Aquaculture systems. Sci. Total Envrion. 687, 1344–1356.

Buschmann, AH, Riquelme, VA, Hernández-González, MC, Varela, D, Jiménez, JE, Henríquez, LA, Vergara, PA, Guíñez, R, Filún, L, 2006. A review of the impacts of salmonid farming on marine coastal ecosystems in the southeast Pacific. ICES. Journal of Marine Science 63 (7), 1338–1345. https://doi.org/10.1016/j.icesjms.2006.04.021.

Buschmann, A.H., Tomova, A., López, A., Maldonado, M.A., Henríquez, L.A., Ivanova, L., Moy, F., Godfrey, H.P., Cabello, F.C., 2012. Salmon aquaculture and antimicrobial resistance in the marine environment. PLoS One 7, e42724. https://doi.org/10.1371/journal.pone.0042724.

Carmichael, Wayne W., Falconer, I.R., 1993. CHAPTER 12 - Diseases related to freshwater blue-green algal toxins, and control measures. In: Falconer, I.R. (Ed.), Algal Toxins in Seafood and Drinking Water. Academic Press, San Diego, pp. 187–209. https://doi.org/10.1016/B978-0-08-091811-2.50017-4.

Cavalli, L., Jeebhay, M., Blanco Marques, F., Mitchell, R., Neis, B., Ngajilo, D., Watterson, A., 2019. Scoping global aquaculture occupational safety and health. J. Agromed. 24 https://doi.org/10.1080/1059924X.2019.1655203.

Chevreau, F.R., Wybo, J.L., Cauchois, D., 2006. Organizing learning processes on risks by using the bow-tie 559 representation. Journal of Hazardous Materials 130 (3), 276–283. https://doi.org/10.1016/j.jhazmat.2005.07.018.

Cole, D.W., Cole, R., Gaydos, S.J., Gray, J., Hyland, G., Jacques, M.L., Powell-Dunford, N., Sawhney, C., Au, W.W., 2009. Aquaculture: environmental, toxicological, and health issues. Int. J. Hyg. Environ. Health 212, 369–377. https://doi.org/10.1016/j.ijheh.2008.08.003.

Convery, I., Mort, M., Bailey, C., Baxter, J., 2007. Role stress in front line workers during the 2001 foot and mouth disease epidemic: The value of therapeutic spaces. Australasian Journal of Disaster and Trauma Studies 2007, No Pagination Specified-No Pagination Specified.

de Dianous, V., Fiévez, C., 2006. ARAMIS project: a more explicit demonstration of risk control through the use of bow–tie diagrams and the evaluation of safety barrier performance. J. Hazard. Mater. 130 (3), 220–233. https://doi.org/10.1016/j.jhazmat.2005.07.010.

Douglas, J.D.M., McSharry, C., Blaikie, L., Morrow, T., et al., 1995. Occupational asthma caused by automated salmon processing. Lancet 346, 737–740. https://doi.org/10.1016/S0140-6736(95)91505-2.

Fey, S.B., Siepielski, A.M., Nusslé, S., Cervantes-Yoshida, K., Hwan, J.L., Huber, E.R., Fey, M.J., Catenazzi, A., Carlson, S.M., 2015. Recent shifts in the occurrence, cause, and magnitude of animal mass mortality events. Proc. Natl. Acad. Sci. 112, 1083–1088. https://doi.org/10.1073/pnas.1414894112.

Food and Agriculture Organization of the United Nations, 2019. FAO Fisheries & Aquaculture - Fishery and Aquaculture Country Profiles - Ireland [WWW Document]. http://www.fao.org/fishery/facp/IRL/en (accessed 2.15.21).

Food and Ariculture Organization, 2020b. The State of World Fisheries and Aquaculture 2020: Sustainability in Action. FAO, Rome, Italy, The State of World Fisheries and Aquaculture (SOFIA). https://doi.org/10.4060/ca9229en.

Føre, H.M., Thorvaldsen, T., 2021. Causal analysis of escape of Atlantic salmon and rainbow trout from Norwegian fish farms during 2010–2018. Aquaculture 532, 736002. https://doi.org/10.1016/j.aquaculture.2020.736002.

Fry, J., Ceryes, C., Voorhees, J., Barnes, N., Love, D., Barnes, M., 2019. Occupational safety and health in U.S. aquaculture: a review. J. Agromed. 24, 1–19. https://doi.org/10.1080/1059924X.2019.1639574.

Godfrey, M., 2021. Mowi Experiences More Salmon Die-Offs in Canada, Ireland [WWW Document]. seafoodsource. https://www.seafoodsource.com/news/aquaculture/mowi-experiences-more-salmon-die-offs-in-canada-ireland.

Government of Canada, F. and O.C, 2015. Environmental Management and Reporting [WWW Document]. https://www.dfo-mpo.gc.ca/aquaculture/environment-environnement-eng.html.

Grattan, L.M., Holobaugh, S., Morris, J.G., 2016. Harmful algal blooms and public Health. Harmful Algae 57, 2–8. https://doi.org/10.1016/j.hal.2016.05.003.

Guerrero, R., Yáñez, S., Ortega, N., 2018. Documento 13: Estudio observacional de buzos dedicados a la acuicultura, año 2017 [WWW Document]. SUSESO: Publicaciones. https://www.suseso.cl/607/w3-article-496928.html (accessed 4.1.21).

Holen, S.M., Utne, I.B., Holmen, I.M., Aasjord, H., 2018a. Occupational safety in aquaculture – part 1: injuries in Norway. Mar. Policy 96, 184–192. https://doi.org/10.1016/j.marpol.2017.08.009.

Holen, S.M., Utne, I.B., Holmen, I.M., Aasjord, H., 2018b. Occupational safety in aquaculture – part 2: fatalities in Norway 1982–2015. Mar. Policy 96, 193–199. https://doi.org/10.1016/j.marpol.2017.08.005.

Holen, S.M., Yang, X., Utne, I.B., Haugen, S., 2019. Major accidents in Norwegian fish farming. Saf. Sci. 120, 32–43. https://doi.org/10.1016/j.ssci.2019.05.036.

Holland, J., 2019. Millions of Norwegian salmon wiped out. World Fish. Aquac. 68, 8–9.

Holmen, I., Thorvaldsen, T., 2018. Occupational Health and Safety in Norwegian Aquaculture: National Profile for a FAO Report on Global Aquaculture OHS.

Holmen, I.M., Utne, I.B., Haugen, S., 2018. Risk assessments in the Norwegian aquaculture industry: status and improved practice. Aquac. Eng. 83, 65–75. https://doi.org/10.1016/j.aquaeng.2018.09.002.

Holmen, I.M., Utne, I.B., Haugen, S., 2021. Identification of safety indicators in aquaculture operations based on fish escape report data. Aquaculture 544, 737143. https://doi.org/10.1016/j.aquaculture.2021.737143.

Hort, V., Abadie, E., Arnich, N., Dechraoui Bottein, M.-Y., Amzil, Z., 2021. Chemodiversity of Brevetoxins and other potentially toxic metabolites produced by Karenia spp. and their metabolic products in marine organisms. Mar. Drugs 19, 656. https://doi.org/10.3390/md19120656.

Karlsen, K.M., Robertsen, R., Hersoug, B., 2019. Mapping the Course of Events and Preparedness for Algal Blooms in Spring-(In Norwegian). [Kartlegging av hendelsesforløp og beredskap under giftalgeangrepet våren 2019 - Astafjorden, Ofotfjorden, Vestfjorden og Tysfjorden] [WWW Document]. Nofima. https://nofima.no/publikasjon/1743795/ (accessed 3.30.22).

Kaustell, K.O., Mattila, T.E.A., Ahvonen, A., Rautiainen, R.H. 2019. Occupational injuries and disease in fish farming in Finland, 1996-2015. International Maritime Health 70: 1 47-54.

Kenyon, C., Jeebhay, M., 2008. Hydrogen sulphide gas poisoning aboard a fishing trawler: a report of four fishermen. Occup. Health South. Afr. 14, 20–23. https://doi.org/10.13140/2.1.1904.1921.

Khakzad, N., Khan, F., Amyotte, P., 2012. Dynamic risk analysis using bow-tie approach. Reliab. Eng. Syst. Saf. 104, 36–44. https://doi.org/10.1016/j.ress.2012.04.003.

Knott, C. and B. Neis, 2019. Aquaculture occupational health and safety: Canada Profile. Report produced as part of the FAO Scoping study on aquaculture OHS. 58 pp. Available at: https://coastalfutures.ca/projects/ohs-country-profile.

Koopmans, M., Wilbrink, B., Conyn, M., Natrop, G., van der Nat, H., Vennema, H., Meijer, A., van Steenbergen, J., Fouchier, R., Osterhaus, A., Bosman, A., 2004. Transmission of H7N7 avian influenza a virus to human beings during a large outbreak in commercial poultry farms in the Netherlands. Lancet 363, 587–593. https://doi.org/10.1016/S0140-6736(04)15589-X.

Love, D.C., Fry, J.P., Cabello, F., Good, C.M., Lunestad, B.T., 2020. Veterinary drug use in United States net pen Salmon aquaculture: implications for drug use policy. Aquaculture 518, 734820. https://doi.org/10.1016/j.aquaculture.2019.734820.

Lulijwa, R., Rupia, E.J., Alfaro, A.C., 2020. Antibiotic use in aquaculture, policies and regulation, health and environmental risks: a review of the top 15 major producers. Rev. Aquac. 12, 640–663. https://doi.org/10.1111/raq.12344.

Mather, C., Fanning, L., 2019. Social licence and aquaculture: towards a research agenda. Mar. Policy 99, 275–282. https://doi.org/10.1016/j.marpol.2018.10.049.

Mattilsynet, 2021. Notification of incidents that result in poor fish welfare for farmed fish. In: The Norwegian Food Safety Authority [WWW Document]. Mattilsynet. https://www.mattilsynet.no/fisk_og_akvakultur/fiskevelferd/varsling_av_hendelser_som_gir_daarlig_fiskevelferd_for_oppdrettsfisk.25660 (accessed 1.5.22).

Millanao, A., Barrientos-Schaffeld, C., Siegel-Tike, C.D., Tomova, A., Ivanova, L., Godfrey, H.P., Dolz, H.J., Buschmann, A.H., Cabello, F.C., 2018. Antimicrobial resistance in Chile and the one Health paradigm: dealing with threats to human and veterinary Health resulting from antimicrobial use in Salmon Aquaculture and the clinic. Rev. Chil. Infectol. 35, 299–308. https://doi.org/10.4067/s0716-10182018000300299.

Miranda, C.D., Godoy, F.A., Lee, M.R., 2018. Current status in the use of antibiotics and the antimicrobial resistance in the Chilean salmon farms. Front. Microbiol. https://doi.org/10.3389/fmicb.2018.01284.

Mitchell, J., 2021. Authorities Investigating Mass Salmon Die-Off At Down East Aquaculture Operation [WWW Document]. Maine Public. https://www.mainepublic.org/business-and-economy/2021-08-27/authorities-investigating-mass-salmon-die-off-at-down-east-aquaculture-operation (accessed 1.5.22).

Mitchell, R.J., Lystad, R.P., 2019. Occupational injury and disease in the Australian aquaculture industry. Mar. Policy 99, 216–222. https://doi.org/10.1016/j.marpol.2018.10.044.

Montgomery, M., 2019. Fish Farming Controversy Over Massive Salmon Die-Off [WWW Document]. Radio Canada International. https://www.rcinet.ca/en/2019/10/10/fish-farming-controversy-over-massive-salmon-die-off/ (accessed 3.30.22).

Moreau, D.T.R., Neis, B., 2009. Occupational health and safety hazards in Atlantic Canadian aquaculture: laying the groundwork for prevention. Mar. Policy 33, 401–411. https://doi.org/10.1016/j.marpol.2008.09.001.

Munasinghe, S., Brown, G., Pereira, A., Keeble, B., Nair, P., Sundkvist, T., 2008. Public health response to an avian influenza a (H5N1) poultry outbreak in Suffolk, United Kingdom, in November 2007. Eurosurveillance 13, 5–6. https://doi.org/10.2807/ese.13.05.08027-en.

Mutter, R., 2020. Chilean salmon farmer reports massive 1 million salmon die-off; cause unknown. In: Intrafish [WWW Document]. Intrafish | Latest Seafood, Aquaculture and Fisheries News. https://www.intrafish.com/aquaculture/chilean-salmon-farmer-reports-massive-1-million-salmon-die-off-cause-unknown/2-1-788419 (accessed 12.29.21).

Myers, M., Durborow, R., 2012. Aquacultural safety and health. In: Health and Environment in Aquaculture. IntechOpen, pp. 385–400.

Ngajilo, D., Jeebhay, M.F., 2019. Occupational injuries and diseases in aquaculture – a review of literature. Aquaculture 507, 40–55. https://doi.org/10.1016/j.aquaculture.2019.03.053.

Ochs, C., Neis, B., Cullen, K., McGuinness, E.J., 2021. Occupational safety and health in marine aquaculture in Atlantic Canada: what can be learned from an analysis of provincial occupational injury compensation claims data? Aquaculture 540, 736680. https://doi.org/10.1016/j.aquaculture.2021.736680.

Oesterud, T.I., 2016. Mass Death of Salmons at Fish Farm. Norway Today. https://norwaytoday.info/finance/mass-death-of-salmon-farms/ (accessed 12.29.21).

Rausand, M., Haugen, S., 2020. Risk assessment: Theory, methods and applications, Second. ed. Wiley, Hoboken, USA.

Reverter, M., Sarter, S., Caruso, D., Avarre, J.-C., Combe, M., Pepey, E., Pouyaud, L., Vega-Heredía, S., de Verdal, H., Gozlan, R.E., 2020. Aquaculture at the crossroads of global warming and antimicrobial resistance. Nat. Commun. 11, 1870. https://doi.org/10.1038/s41467-020-15735-6.

Rogers, S., 2021. Salmon "Die-Off" Incident Raises Concerns About the State's Future in Large-Scale Aquaculture [WWW Document]. newscentermaine.com. https://www.newscentermaine.com/article/tech/science/environment/salmon-die-off-incident-raises-concerns-about-the-states-future-in-large-scale-aquaculture/97-6fd16147-eac3-4e34-9b06-d242b7588d79.

Said, A.H., Kyewalyanga, M.S., Msuya, F.E., Mmochi, A.J., Mwihia, E.W., Skjerve, E., Ngowi, H., Lyche, J.L., 2018. Health Problems Related to Algal Bloom Among Seaweed Farmers in Coastal Areas of Tanzania, pp. 303–312. https://doi.org/10.5897/JPHE2018.1020.

Sajid, Z., Gamperl, K., Caballero-Solares, A., Cembella, A., Neis, B., Mather, C., Parrish, C., Knott, C., Ochs, C.L.G., Couturier, C., McKenzie, C., Murray, H.M., Fleming, I., Holmen, I., Santander, J., Romero, J., Grant, J., Cavalli, L.S., López Gómez, M.A., Fast, M., Wells, M., Rise, M., Jeebhay, M., Filgueira, R., Lehnert, S., Colombo, S., Thorvaldsen, T., Gao, W., Singh, G.G., 2023. Preparation for submission to Reviews in Aquaculture. The structure and consequences of mass mortality events in salmon aquaculture.

Sajid, Z., Khan, F., Zhang, Y., 2017. Integration of interpretive structural modelling with Bayesian network for biodiesel performance analysis. Renew. Energy 107, 194–203. https://doi.org/10.1016/j.renene.2017.01.058.

Sandsund, M., Wiggen, Ø., Holmen, I.M., Thorvaldsen, T., 2022. Work strain and thermophysiological responses in Norwegian fish farming — a field study. Industrial Health 60, 79–85.

Sapkota, A., Sapkota, A.R., Kucharski, M., Burke, J., McKenzie, S., Walker, P., Lawrence, R., 2008. Aquaculture practices and potential human health risks: current knowledge and future priorities. Environ. Int. 34, 1215–1226. https://doi.org/10.1016/j.envint.2008.04.009.

Scottish Government, 2022. The Value of Aquaculture in Scotland [WWW Document]. (accessed 1:04:23 https://www.gov.scot/publications/scottish-fish-farm-production-survey-2021/pages/8/.

SERNAPESCA, 2021. Manual de normativa de mortalidades massivas [WWW Document]. http://www.sernapesca.cl/sites/default/files/manual_normativa_mortalidades_masivas_28-01-2021_v2.pdf (accessed 1.25.22).

SERNAPESCA, S. de A, 2020. Boletín Ambiental: Evaluacion de Los Informes Ambientales de Los Centros de Cultivo Regiones de Los Lagos, Aysen y Magallanes.

Shah, S.Q.A., Cabello, F.C., L'Abée-Lund, T.M., Tomova, A., Godfrey, H.P., Buschmann, A.H., Sørum, H., 2014. Antimicrobial resistance and antimicrobial resistance genes in marine bacteria from salmon aquaculture and non-aquaculture sites. Environ. Microbiol. 16, 1310–1320. https://doi.org/10.1111/1462-2920.12421.

Siggins, L., 2003. "Combined Causes" Behind Fish Kill [WWW Document]. The Irish Times. https://www.irishtimes.com/news/combined-causes-behind-fish-kill-1.367200 (accessed 1.5.22).

Singh, G.G., Sinner, J., Ellis, J., Kandlikar, M., Halpern, B.S., Satterfield, T., Chan, K., 2017. Group elicitations yield more consistent, yet more uncertain experts in understanding risks to ecosystem services in New Zealand bays. PLoS One 12, e0182233. https://doi.org/10.1371/journal.pone.0182233.

Smart, D., Rubidge, S., McCartney, P., Broek, V., 1999. Tasmania's aquaculture industry: a ten-year review of improved diving safety. SPUMS J. 31 https://doi.org/10.26749/rstpp.133.1.77.

Størkersen, K.V., 2012. Fish first: Sharp end decision-making at Norwegian fish farms. In: Safety Science, Papers Selected from 5th Working on Safety International Conference (WOS 2010) 50, pp. 2028–2034. https://doi.org/10.1016/j.ssci.2011.11.004.

Thorvaldsen, T., Holmen, I.M., Moe, H.K., 2015. The escape of fish from Norwegian fish farms: causes, risks and the influence of organisational aspects. Mar. Policy 55, 33–38. https://doi.org/10.1016/j.marpol.2015.01.008.

Thorvaldsen, T., Kongsvik, T., Holmen, I.M., Størkersen, K., Salomonsen, C., Sandsund, M., Bjelland, H.V., 2020a. Occupational health, safety and work environments in Norwegian fish farming - employee perspective. Aquaculture 524, 735238. https://doi.org/10.1016/j.aquaculture.2020.735238.

Thorvaldsen, T., Størkersen, K., Kongsvik, T., Holmen, I.M., 2020b. Safety management in Norwegian Fish Farming: current status, challenges, and further improvements. Saf. Health Work. https://doi.org/10.1016/j.shaw.2020.08.004.

Tomova, A., Ivanova, L., Buschmann, A.H., Rioseco, M.L., Kalsi, R.K., Godfrey, H.P., Cabello, F.C., 2015. Antimicrobial resistance genes in marine bacteria and human uropathogenic E scherichia coli from a region of intensive aquaculture. Environ. Microbiol. Rep. 7, 803–809. https://doi.org/10.1111/1758-2229.12327.

Watterson, A., Jeebhay, M.F., Neis, B., Mitchell, R., Cavalli, L., 2020. The neglected millions: the global state of aquaculture workers' occupational safety, health and well-being. Occup. Environ. Med. 77, 15. https://doi.org/10.1136/oemed-2019-105753.

Welch, L., 2019. Norway loses millions of farmed salmon to algae bloom. In: National Fisherman [WWW Document]. https://www.nationalfisherman.com/national-international/norway-loses-millions-of-farmed-salmon-to-algae-bloom/ (accessed 12.29.21).

White, C., 2018. Algae Bloom Hits Grieg Seafood Farms in British Columbia, Killing 250,000 Salmon [WWW Document]. https://www.seafoodsource.com/news/aquaculture/algae-bloom-hits-grieg-seafood-farms-in-british-columbia-killing-250-000-salmon (accessed 1.5.22).

White, C., 2019. Mowi CEO Apologizes for Salmon Die-Off; Newfoundland Tightens Aquaculture Policies [WWW Document]. https://www.seafoodsource.com/news/aquaculture/mowi-ceo-apologizes-for-salmon-die-off-newfoundland-tightens-aquaculture-policies (accessed 1.5.22).

Yang, X., Ramezani, R., Utne, I.B., Mosleh, A., Lader, P.F., 2020a. Operational limits for aquaculture operations from a risk and safety perspective. Reliab. Eng. Syst. Saf. 204, 107208 https://doi.org/10.1016/j.ress.2020.107208.

Yang, X., Utne, I.B., Holmen, I.M., 2020b. Methodology for hazard identification in aquaculture operations (MHIAO). Saf. Sci. 121, 430–450. https://doi.org/10.1016/j.ssci.2019.09.021.

Young, N., Sharpe, R.A., Barciela, R., Nichols, G., Davidson, K., Berdalet, E., Fleming, L. E., 2020. Marine harmful algal blooms and human health: a systematic scoping review. Harmful Algae 98, 101901. https://doi.org/10.1016/j.hal.2020.101901.