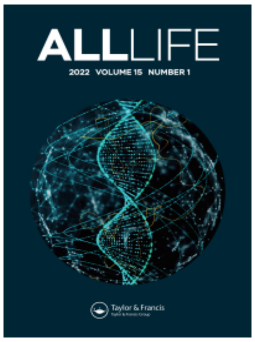

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REVIEW

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Salmon mass mortality events and occupational health and safety in Chilean aquaculture

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ABSTRACT

Mass mortality events (MMEs) threaten the health of fish and are also a potential threat to the health and safety of workers. This paper presents findings from a desktop risk assessment exercise focused on potential aquaculture occupational health and safety (AOHS) hazards and risks associated with MMEs in Chile. The study reviews academic and grey literature, government regulations and MME reports and statistics to assess the scale and distribution of MMEs; identifies associated documented and potential health and safety hazards; and documents and assesses policy responses to MMEs in the Chilean context through the lens of health and safety. The paper documents the size and regional distribution of salmon MME occurrences in Chile from 2016 to 2022. It discusses AOHS hazards associated with MMEs such as exposure to hydrogen sulfide, drowning and diving-related illnesses and potential issues around accessing hospitals and hyperbaric chambers for workers in remote aquaculture regions, as well as exposure to antibiotics and antibiotic residues. Recent Chilean regulatory requirements around reporting and management of MMEs that have the potential to help reduce identified MME-related risks for workers are described and addressed.

Key policy highlights

- Risk of mass mortality events (MMEs) in marine aquaculture is increasing as the industry expands and climate change increases fluctuations in marine conditions. Policies need to be developed to counteract these risks.
- MMEs-related worker accidents and environmental degradation point to the urgent need to develop environmental and occupational health and safety (OHS) guidelines that prevent MMEs and protect workers and the environment.
- The Chilean OHS guidelines related to aquaculture MMEs may be adapted and used in other countries.
- Surveillance programs on harmful algal blooms and antibiotic resistance (AMR) markers may be a preventive measure towards MMEs and exposure to AMR markers.

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Chilean salmon aquaculture; occupational health and safety risk assessment; diving-related hazards; hydrogen-sulfide exposure; antimicrobial resistance

Introduction

Mass mortality events (MMEs) are those where a large number of individuals of a species die in a short period of time (Fey et al. 2015). In recent years, many MMEs ranging in size from thousands to millions of fish have been reported in marine finfish aquaculture globally. MMEs are a significant threat to animal health and industry profits; they can also lead to regulatory and infrastructural changes. From the point of view of a One Health approach, these events are a concern, since they interdependently affect the health of the fish, the environment, public and worker health (Cavalli et al. 2015; Stentiford et al. 2020).

Marine aquaculture is a high risk sector globally including in Chile where the number of fatalities and injuries is high, with one worker injured and/or killed per month during 2021 (Evans 2022). Occupational hazard awareness and knowledge about injury and fatality rates are low in the aquaculture industry globally. Such knowledge gaps are hindering the development of comprehensive risk assessments, surveillance protocols and safety management (Cavalli et al. 2019a). Research on the relationship between MMEs and risk of injury/illness of marine aquaculture workers is just beginning. Data linking work-related injuries, illnesses and fatalities to MMEs are

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not available for Chile or other countries, but a risk assessment exercise related to this study identified multiple potential pathways linking injury risk to MMEs (Neis et al. 2023).

The marine finfish aquaculture industry in Chile has expanded rapidly in recent years and Chile is now one of the most profitable and technologically advanced countries with regards to aquaculture finfish production (FAO 2020a; Cavalli et al. 2021). Aquaculture production in the country is based mainly on salmon, trout and smelt (70% diadromous fish) and mollusc farming (30%) (Cavalli et al. 2021). In 2020, the Food and Agriculture Organization (FAO) ranked Chile as the largest aquaculture-producing country in Latin America and the Caribbean, contributing 1.09% of global aquaculture production (FAO 2020b). In 2022, it was the second largest salmon producer in the world and supplied Atlantic salmon to the United States of America and Brazil, and farmed coho to Japan (FAO 2022).

Given the scale of its salmon aquaculture industry, Chile is clearly at risk of MMEs but this risk and its potential consequences for worker health and safety have not been explored in depth. This paper documents the number and size of salmon MME occurrences in Chile from 2016 to 2022, including their annual and regional distribution. It discusses occupational health and safety (OHS) hazards associated with MMEs identified in Chile, such as exposure to hydrogen sulfide, drowning and diving-related illnesses, and to antimicrobial resistant bacteria. Mapping distances and constraints on transportation between some areas associated with MMEs and hospitals and hyperbaric chambers indicates access to health services could exacerbate risk for injured workers.

Methods

This paper is linked to a larger risk assessment exercise for MMEs in salmon farming examining factors contributing to the risk of MMEs and of negative outcomes including to health and safety. For the health and safety part of the exercise, an international team of aquaculture occupational health and safety (AOHS) researchers generated profiles of five countries where each researcher was responsible for preparing a report for one country (Canada, Chile, Ireland, Scotland, Norway), findings from which were synthesized into an overarching report for the risk assessment exercise and provided the basis for a related publication (Neis et al. 2023). This paper presents findings based on an elaborated study on MMEs and AOHS focused on Chile, from 2016 to 2022. For the Chilean profile, we conducted a targeted review of academic and grey literature and industry, government and media reports related to MMEs in Chile, including any policies and regulations related to AOHS. Sources include peer-reviewed articles, government reports and media reports written in either English or Spanish. Search terms used for the review included: mass-mortality, mass-mortality events, mass-die-off, antibiotic use, antimicrobial resistance, AMR, Chile, salmon, occupational health and safety, worker injury. We used Google, Google Scholar and web databases as search engines and reviewed published reports from the organizations in Chile focused on aquaculture or OHS: SERNAPESCA (*Servicio Nacional de Pesca y Acuicultura*) and SUSESO (*Superintendencia de Seguridad Social*).

SERNAPESCA is the Chilean National Fisheries Service created in 1978 whose main mission is to contribute to the sustainability of the fisheries and aquaculture sectors by protecting hydrobiologic resources and their environment. This agency is responsible for the sanitary health of fish farms and assumes inspection and monitoring duties in the industry. SUSESO is an independent state organization in charge of supervising compliance with social security regulations and guaranteeing respect for the rights of people, especially workers, pensioners and their families. Reports from SERNAPESCA and SUSESO document potential hazards and identify related aquaculture activities likely to be associated with higher occupational and health related risk in the context of responding to MMEs.

After the original risk assessment exercise, we accessed additional data for Chile by contacting SERNAPESCA by e-mail to obtain data on numbers, size and locations of MMEs provided to SERNAPESCA salmon farm operators. SERNAPESCA provided the requested information on December 2022, under the transparency register No. AH010T0002451, ORD. Number: DN – 05562/2022 (Table 1) (Chile 2022a). Chile's transparency law recognizes access to public information, SERNAPESCA (portaltransparencia.cl). We also received additional policy-related information on MME management. We used these data to map the distribution, size and timing of events across regions

Table 1. Summary data of mass mortality events data between November 2016 to June 2022, according to Sernapesca.

Region	Year	Number of events	Cumulative mortality of the year (tons)	Total events in the region	Total cumulative mortalities of the region (tons)
Aysen	2016	18	2,783.54	259	41,971.68
	2017	69	6,403.89		
	2018	46	5,291.34		
	2019	71	14,915.173		
	2020	19	4,177.47		
	2021	24	4,361.3		
	2022	12	4,038.96		
Los Lagos	2016	6	463.04	232	31,282.181
	2017	56	6,160.16		
	2018	41	5,556.46		
	2019	49	3,958.55		
	2020	20	3,793.19		
	2021	25	6,636.097		
	2022	35	4,714.684		
Magallanes	2016	1	44.7206	22	3,325.62
	2017	4	366.75		
	2018	5	1,054.892		
	2019	3	92.94473		
	2020	9	1,766.3167		
Other	2020	2	142.48	8	481.768
	2021	2	41.6		
	2022	4	297.688		

Source: Sernapesca, request information by email to Sernapesca on November 10th, 2022. Under transparency register No. AH010T0002451, ORD. No.: DN – 05562/2022. Request access to information based on transparency law from Chile, Sernapesca (portaltransparencia.cl) (Chile 2022a).

and in relation to key health-related infrastructure such as hospitals and hyperbaric chambers.

Results

Mass mortality events in Chile

The largest documented MME in Chile happened in Los Lagos region in February 2016, prior to the implementation of requirements for MME-reporting in Chile. Based on media and other reports, during that MME, 40,000 tonnes of caged, farmed salmon died; in comparison, cumulative mortalities from 521 MMEs between November 2016 and June 2022 totalled 77,061.249 tonnes for all of Chile (Figure 1). The February 2016 MME was related to the phenomenon 'El Niño' which caused a strong drought, reduced freshwater discharges and increased water temperatures and stratification (Armijo et al. 2020). These events led to the development of a red tide, a harmful algal bloom (HAB) that happened in two pulses (Armijo et al. 2020). The first pulse happened in February 2016; locals called it the brown tide. It was triggered by a harmful algae bloom dominated by the flowering of the algae *Pseudochattonella* sp. and affected forty-five salmon farms (16% of the total active farms) from seven Salmonidae concessions. Fourteen companies were involved (53% of the total number of companies) and mortalities exceeded 25 million fish (10% of the total fish stocked), equivalent to a biomass of approximately 40,000 tonnes. The main species affected was Atlantic salmon, representing 94% of total mortality and 12% of the living salmon in Chilean waters at the time (Armijo et al. 2020). During the cleanup, 158 vessels with a transport capacity ranging from 40 to 1,800 tonnes participated in the removal of dead fish. The MME exceeded the capacity to manage dead fish including dumping waste in landfills (30% of waste) and reducing waste to fishmeal (57% of waste) (Chile 2016). As a result, SalmonChile, the Chilean salmon industry association, requested

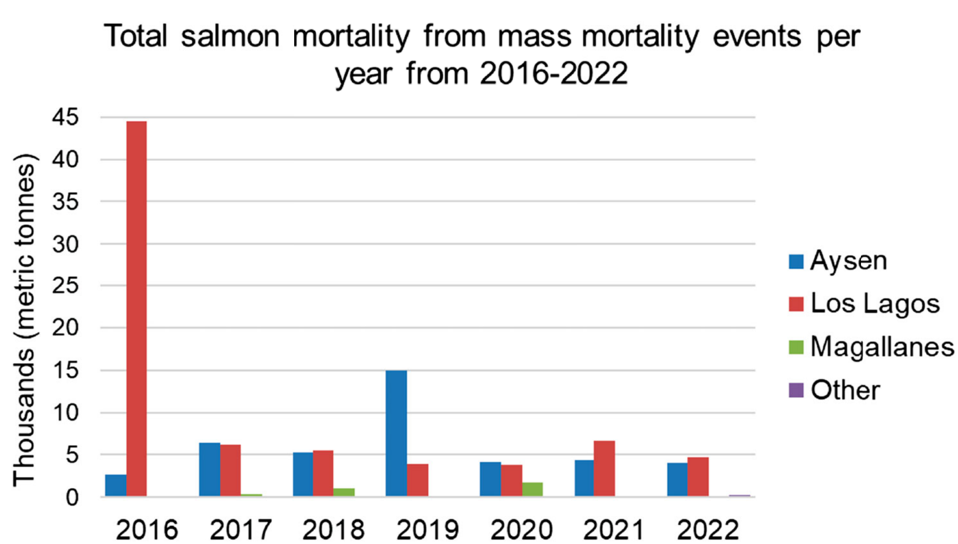


Figure 1. Chilean salmon cumulative mass mortality from February 2016 to June 2022 in tons. Source: Buschman et al. 2016; Armijo et al. 2020; Chile 2022a.

permission to dump 11,600 tonnes of rotten salmon into the ocean stating that they could not cope with the excess waste and that transporting it on land would entail hazardous conditions to people. The request was granted and it is reported that 4,655 tonnes of waste were dumped into the ocean. This dumping took place over a period of 16 days using 7 boats and entailed 11 round-trips to the authorized area (Chile 2016). Waste was dumped 75 nautical miles west of the north coast of Chiloé Island (an island located in the south of Chile, Los Lagos region) over a period of 10 days (Buschman et al. 2016).

Later the same year, a second pulse of red tide led to a massive quantity of stranded shellfish on the coast of Chiloé, initiating a chain of protests from local fish harvesters in the area (Gonzalez 2016; Mascareño et al. 2018). The government requested a thorough environmental investigation to assess any relationship between the dumping of salmon waste into the ocean and the second HAB without finding a relationship (INCAR 2017), although, one research study reported an association between salmon waste and a second HAB (Armijo et al. 2020). A total of 4,500 out of 35,000 aquaculture workers lost their jobs due to the 2016 MME and the aquaculture industry experienced daily losses of $9 million USD. MMEs continue to occur in Chile.

According to SERNAPESCA (Chile 2022a), the 2016 event, which occurred in the Los Lagos region, revealed shortcomings in terms of mortality management, testing the response capacity of companies to this type of contingency, as well as the management and organization capacity of the competent authorities. Once the event was over, SERNAPESCA led a work group, together with different state institutions, in order to coordinate exceptional measures and to establish a system for early detection of MMEs. This system would lead to the execution of immediately available actions to manage mortality events with the purpose of guaranteeing the protection of hydrobiological resources, their environment and the health of people. As a result, SERNAPESCA published on October 28, 2016, Resolution RE No. 8561, which established other deadlines and conditions for the removal and final disposal of specimens in the event of mass mortalities. As authorized by SERNAPESCA's RE 1468/2012, which approves the General Health Program (PSG) for the management of mortality and establishes the first definition of mass mortality in the regulations, '*Any farm that generates or exceeds 15 (fifteen) tons of mortality, during a period of 7 continuous days, must indicate in detail the actions that will be carried out to achieve the total removal of mortality from the center*' (Chile 2022a). Through this provision, as of November 2016, aquaculture centres began to send information associated with mortality events, resulting in 521 MME notifications to SERNAPESCA between November 2016 and June 2022 (Table 1) (Chile 2022a).

SERNAPESCA is in charge of ensuring that fisheries and aquaculture policies are applied. This includes overseeing the cleanup of waste caused by MMEs. The government considers a mass mortality to have taken place if any of the following three conditions occur (Chile 2021a):

- the minimum daily capacity for certified mortality extraction is exceeded (the minimum daily capacity cannot be under 15 tons).
- the minimum daily capacity for certified denaturing is exceeded (the minimum daily capacity of extraction cannot be under 15 tons).
- storage of denatured material reaches 80% of capacity.

The regulation, and its modifications, which establishes and defines what is understood by massive mortality in a salmon farm is called Environmental Regulation in Aquaculture, D.S. N° 320 de 2001, *Reglamento Ambiental para la Acuicultura*, article 4°A, 5°, 5°A, 5°B, 5°C, 6°A, 6°B, 6°C, modified mainly by D.S. N° 151de 201(Chile 2022a). A definition of MMEs is also included in RE n° 1468/2012 and RE n° 8561/2016.

Table 2 summarizes information about MMEs in Chile from 2016 to 2022, and draws on information found in media sources, including the large event reported in February 2016 and described above. SERNAPESCA reported 51 mass mortalities between January and May 2020 (Chile 2021b) that took place in Los Lagos, Aysén and Magallanes regions where more than 50% of events were deemed MMEs, as storage of denatured material surpassed 80% of capacity (Chile, Sernapesca 2020). We did not find detailed information about each event, but only broad information on causes for these mass mortalities (e.g. environmental, sanitary).

Table 1[1] shows data provided by SERNAPESCA (Chile 2022a) with coverage from November 2016 to June 2022. The SERNAPSECA data do not include the

Table 2. Mass mortality events in Chile from 2016 to early 2022, present in media websites and literature.

Date	Company involved	Quantity of dead fish	Location	Cause of mortality	Reference
February 2016	N/A	40,000 tonnes	Chiloé (Los Lagos)	*Pseudochattonella* sp. El niño.	Armijo et al. 2020; Buschman et al. 2016.
February 2017	NA	170,000 smolts of salmon	Magallanes and Los Lagos	During transportation, wellboats took seawater from the Golfo de Penas where several harmful algae were found in the water including the dinoflagellates *Gymnodinium* spp., *Azadinium* spp., and *Karenia mikimotoi* and the diatoms *Skeletonema* spp. and *Pesudo-nitzschia* spp.	Anabalón 2017; Aquiaysen 2017.
November 2018	Australis Mar S.A. (Center Morgan)	15 tonnes	Canal Valdés (province de Última Esperanza, Magallanes)	Low oxygen	Chile 2018.
March 2019	Salmones Camanchaca	123 tonnes	Chiloé, Los Lagos	*Pseudochattonella cf verruculosa*	Chile 2019b.
May 2019	Invermar	N/A	Quellon, Los Lagos	Probably due to environmental causes, which caused a drop in oxygen	Chile 2019c.
March 2020	Aquachile S.A	27,078 fish	Aysén region	Low oxygen	Chile 2020b.
April 2020	Invermar	N/A	Quellon, Los Lagos	Presence of the microalgae *Cochlodinium* sp	Chile 2020c.
	Marine Farm	40 tonnes	Quellon, Los Lagos	Linked to the presence of the toxic microalgae *Cochlodinium* sp.	Salmonexpert 2020.
	Mowi	20,000 units of Atlantic salmon	Chiloé, Los Lagos	Presence of microalgae such as *Chaetoceros cryophilus* and *Cochlodinium* spp and reduced dissolved oxygen content have also been reported in 2020	Chile 2020d.
	Aquachile S.A	40 tonnes (8,000 fish/5 kg each)	Puyuhuapi channel, in the Aysén region		Chile 2020b.
March 2021	Salmones Camanchaca	600 tonnes (162,000 fish, with an average weight of 4 kg, at a likely cost of US $3.5 million)	Chaitén, Los Lagos region,	*Lepidodinium chlorophorum*[16;]	FishFarmingExpert 2021a, 2021b.
	Multiexport Foods	83 tonnes	Quinchao, Chiloé, Los Lagos at two sites in the Rinihue Fjord	*Lepidodinium chlorophorum*[16;]	FishFarmingExpert 2021a, 2021b.

(continued)

Table 2. Continued.

Date	Company involved	Quantity of dead fish	Location	Cause of mortality	Reference
March 27th – April 5th 2021	Ventisqueros, Salmones Camanchaca, Salmones Austral, Cermaq, Mowi, Caleta Bay	1,300 tonnes	Los Lagos	*Heterosigma akashiwo*	Chile 2021c.
April 2021	Cooke Aquaculture, Mowi, Aquachile, Yadran, Multiexport y Granja Marina Tornagaleones.	1,600 tonnes	Aysén	Low oxygen and harmful algae bloom	Chile 2021d.
		5,595 tonnes: (3,076 tons Los Lagos; 2,519 Aysen).	Los Lagos and Aysen	Presence of microalgae such as *H. Akashiwo, Leptocylindrus danicus* and *Leptocylindrus minimus*	Chile 2021e; Chile 2021f.
January 2022	Blumar S.A., Salmones Austral S.A., Camanchaca and Aquachile S.A.	3,550 tonnes	Aysén	*Pseudochattonella verruculosa, Pseudochattonella* spp. and *Rizhosolenia aff. setigera*	Chile 2022b; Chile 2022c.
May 2022	Salmones Multiexport	1,290 tonnes (300,000 fish/4.3 kg each)	Los Lagos	Decrease in dissolved oxygen content	Chile 2022d.

N/A: Not available.

major February 2016 event described above because reporting requirements started after this event (Chile 2022a). These data indicate MMEs were concentrated in the Aysen region which reported 259 MMEs during this period. There were 232 events in the Los Lagos region (Table 1) (Chile 2022a). Reported MMEs since November 2016 have ranged in size from 1 to 1,694 tons with an average size of 148 tons and median size of 77 tons; 49.7% of these MMEs have been concentrated in Aysen region, 44.5% in Los Lagos, with only 5.5% in the other regions. In terms of numbers – MMEs are thus a relatively common occurrence, particularly in Aysen and Los Lagos regions (Figure 2).

MMEs and occupational injury and illness risk and prevention in Chile

Academic and government reports state that MMEs on salmon farms in Chile are mainly caused by HABs or disease outbreaks, and sometimes can be related to exceeding pen storage capacity (Chile 2021b). With regard to Atlantic salmon, a SERNAPESCA report identified that the most commonly reported cause of mortality in 2018 was infectious disease (20%), followed by environmental causes (19.5%). Of the total infectious causes in 2018, 54.5% of the mortalities were caused by *Piscirickettsiosis* (SRS – salmonid rickettsial septicemia), 18.5% by bacterial kidney disease (BKD) and 8.7% by others (Chile 2019a). When high mortality rates from infectious diseases occur, the recommendation is to immediately remove floating dead fish and dead fish from the bottom of cages as a way to control the spread of disease, suggesting that MMEs can result in high pressure events for aquaculture workers and employers.

There are multiple potential AOHS risks associated with responding to MMEs (Table 3) including exposure to hydrogen sulfide (H_2S), diving problems, sanitary emergencies and possible heightened risk of exposures to antimicrobial resistance (AMR) determinants (Neis et al. 2023). Table 3 shows activities and work tasks during MMEs that are potentially dangerous and expose workers to hazards and risks in salmon aquaculture. But the two main risks highlighted in existing sources from Chile include exposure to H_2S and those related to diving. The putative health risks associated with occupational exposures to antibiotics and AMR determinants are of growing concern globally, and are thus contextualized below.

Potential exposures of workers to these MME-related hazards in Chile would occur mainly during cleanup of dead and decomposing fish as Chile's

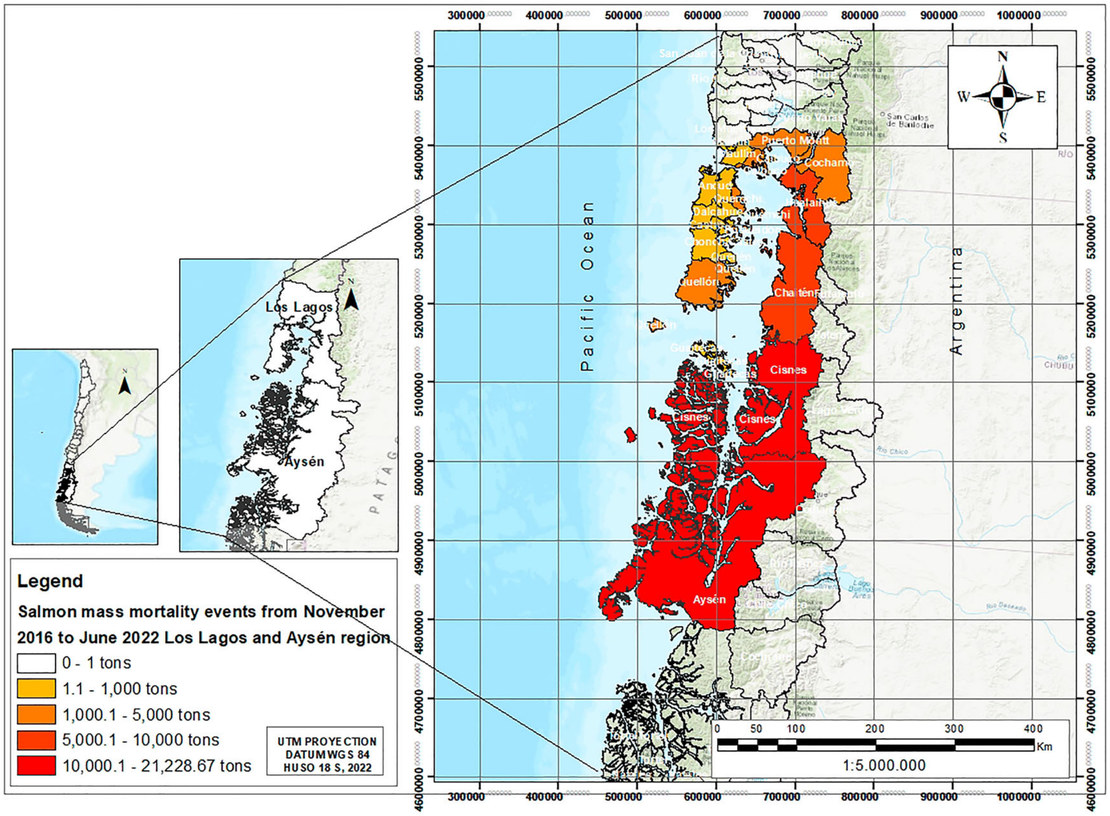


Figure 2. Overall Map of Chilean salmon showing the location of cumulative mass mortality from November 2016 to June 2022 in tons. Source: Chile 2022a.

aquaculture sector remains heavily dependent on divers who perform repetitive diving during MME mort removals (Rodríguez et al. 2015, 2017). Chile's industry also relies to some degree on fishing and other vessels for transporting morts from MME events and vessel crews may have limited training around associated risks. Loading, unloading and transporting large volumes of dead fish encompass the risk of injuries, falls overboard, capsizing and potential exposures to deadly H_2S gas.

The removal, handling, and transport of morts may also expose workers to antimicrobials and their residues, antimicrobial resistant bacteria, and antimicrobial resistance genetic determinants.

Ecological studies have established strong correlational links between antibiotic use in salmon aquaculture and increased AMR in sediment beneath fish farm cages (Buschmann et al. 2012; Hamoutene et al. 2018; Hamoutene and Salvo 2020; Hamoutene et al. 2021). Decreased antibiotic use in food animal production is associated with decreases in AMR rates (Tang et al. 2017; Scott et al. 2018), the inverse implies a risk for higher exposure to these biological and chemical health hazards during MMEs related to disease outbreaks. Working during HABs could also result in exposures to harmful algae but that risk is not explored here. A final risk factor discussed below is the risk of delayed access to appropriate health care for injured/ill marine aquaculture workers in Chile.

Exposure to hydrogen sulfide (H_2S)

H_2S is a dangerous substance heavier than air, flammable, colourless and odourless, and is generated by the oxidation of organic matter by anaerobic bacteria. In the case of aquaculture, H_2S is generated mainly in closed pits and vessel holds where the dead fish are decomposing. According to Chilean Safety Association (ACHS – *Asociación Chilena de Seguridad),* H_2S is a highly toxic gas (ACHS n.d.) that reacts with enzymes present in the bloodstream that inhibit cellular respiration. Exposure to the gas can cause damage to the respiratory tract and nervous system, eye irritation and neutralization of the sense of smell, and can be fatal (Chile 2020a; ACHS n.d.). The Circular 031 (Chile 2020a), a Chilean legal document, has established safety provisions for loading, unloading and removal of waste from fish mass mortalities to protect workers from exposures to H_2S. In 2016, the crew

Table 3. Work tasks and activities during MME and hazard exposure to workers in salmon aquaculture.

	Task/ activity	Hazard/ risk factors	Injury/ illness	Protection	Reference
MME related	Loading (extraction), unloading and removal of fish mort, on vessels, transporting or other places. Working on cages – cleaning or removing dead /live fish. Cleanup of dead and decomposing fish.	Loading, unloading and transporting large volumes of dead fish encompass the risk of potential exposures to deadly hydrogen sulfide (H_2S) gas.	Hazardous to touch or inhale; causes respiratory tract and central nervous system damage, eye irritation, and neutralization of the sense of smell, immediate loss of consciousness and death. H_2S is flammable.	Gas measuring equipment (H_2S); chemical protection suit (in case of emergency); full face mask, with filters for H_2S and carbon monoxide; chemical protection gloves; acid resistant rubber safety boots for chemical protection. Procedure for evacuating victims of poisoning.	Chile 2020a.
	Diving on cages; diving for mort removal (mass and diary mortality).	Physical effort; successive diving.	Entrapment of hands, limbs and body parts; fatigue; drowning; entrapment under ice or fish.		Rodríguez et al. 2015, 2017; Neis et al. 2023.
	Transporting dead fish.	Vessel design including confined spaces in fishing holds; chemical exposure (such as H_2S from decomposing fish) and other exposures; crew experience, training and possibly poor access to PPE.	Poisoning; fires; immediate loss of consciousness and death.	Gas measuring equipment (H_2S); chemical protection suit; full face mask, with filters for H_2S and carbon monoxide; chemical protection gloves; acid resistant rubber safety boots for chemical protection. Training all workers about characteristics, properties and risks of H_2S. Use of PPE; inform about first aid, emergency and salvage plans. Ensure adequate ventilation of the area. No smoking in confined places.	ACHS n.d.; Neis et al. 2023; Kenyon et al. 2008; Chile 2009.
	Equipment cleaning; diving; fish handling; immersed in or come into contact with water, equipment, live fish.	Antibiotic/antibiotic residues exposure.	AMR	Use of PPE. Training. Decrease antibiotic use in aquaculture.	Neis et al. 2023.

(*continued*)

Table 3. Continued.

	Task/ activity	Hazard/ risk factors	Injury/ illness	Protection	Reference
Potential risks	Working long hours to remove dead fish.	Physical effort; working for long hours.	Fatigue; psychological stress.	Take breaks; rotation of workers. Training.	Neis et al. 2023; Chile 2016; Mitchell and Lystad 2019.
	Diving for mort collection; cleaning of counterweights.	Physical effort; successive diving.	Fatigue; decompression disease, low/lack air supply, death, high pressure, neuromuscular disease, dysbaric osteonecrosis.	Follow the diving regulations; appropriate and certified equipment.	Melillanca and Medina 2007; Rodríguez et al. 2015; Nuñez et al. 2019.
	Working/diving on/with contaminated water/fish.	Exposure pathways to cyanobacterial toxins or cells have been identified as incidental contact, consumption, or inhalation of water or aerosols.	Skin itching and sores; swelling of the eyes and face; respiratory symptoms, including shortness of breath.		Neis et al. 2023.
	All activities.	Weak OHS regulation; poor/lack risk assessment management; lack training; work under pressure.	Fatal injuries, diseases and illness; injuries related to aquaculture activities; psychological issues, burn out.	Training; awareness of risks; regulation; risk assessment in industry; emergency and salvage plans.	Neis et al. 2023; Cavalli et al. 2019a.

of a boat, knowing the risk and the dangers of H_2S exposures in this context, abandoned a ship that was in the bay of Calbuco waiting to offload decomposed fish. They reported eye irritation, headaches, nausea and vomiting (Salmonexpert 2016).

Diving safety

Diving is recognized as one of the most physically demanding and risky activities for workers engaging in aquaculture. If the working conditions are not adequate, diving may lead to disabling accidents and even death (Andrade 2009). In 2015, more than 3,500 divers worked in the salmon farming sector in Chile (Rodríguez et al. 2015). Reports show that between May 2013 and May 2019, at least 12 divers died on Chilés salmon aquaculture farms (Nuñez et al. 2019), and in the past 20 years there have been 238 recorded incidents involving injuries, out of which 44 resulted in death (Evans 2022). The activities that divers perform in aquaculture include collecting, removing and transporting dead animals, and cleaning and repairing cage structures. Hazards include the risk of drowning, as well as risk of entanglement and changes in pressure, density and thermo-hygrometric conditions. Divers reported injuries such as entrapment of hands, limbs and body parts, and equipment failures during regular mortality collection activity (Rodríguez et al. 2015) and these hazards could be greater when responding to MMEs due to the volume of diving and time pressures.

Exposure to higher than normal pressures generates an increase in gases dissolved in the tissues, with corresponding physiological effects. In southern Chile these activities are carried out at very low temperatures, which imply a greater physiological load due to thermal effects. According to Nuñez et al. (2019), divers who work long hours at depths greater than 20 meters inside the cages, without proper safety practices (lack of the decompression step characteristic of successive diving), have a high incidence of neuromuscular diseases. Exposure to diving in Chile's diver population is also related to the development of dysbaric osteonecrosis, a form of secondary avascular necrosis caused by accumulation of nitrogen bubbles in the medullary cavity of bone tissue and to permanent auditive damage generated by otic barotrauma (Chile n.d.).

Hookah diving, diving connected to a gas-powered air compressor that delivers air from the surface through a long hose, is a very common practice in aquaculture diving in Chile. For instance, Rodríguez et al. (2015) conducted a study with 193 workers and 85% (n = 165) of them identified hookah diving in their operations and this may pose additional risks to divers, although reports did not indicate hookah diving was performed during the cleanup of salmon mass mortalities.

MMEs require divers to remove and transport potentially large volumes of morts from the water during relatively short periods of time. The likelihood and risks of entanglement and successive diving by divers without commercial certification and appropriate equipment may well be heightened in the context of MMEs, due to the pressure to retrieve dead fish quickly, reliance on divers to do this work, and the large diving labour force required. This can result in diving practices that increase risk (Rodríguez et al. 2017; Osorio et al. n.d.). For instance, successive diving is associated with heightened risks of drowning or decompression sickness.

Existing research on aquaculture-related diving in Chile indicates that hazardous practices are common in the sector even under normal circumstances including successive diving (known as yo-yo diving) to depths that place divers at risk of decompression sickness and other illnesses (Rodríguez et al. 2015). Successive diving consists of a series of uninterrupted dives in periods or intervals of time of less than 12 h. Daily work tasks typically require divers to service an average of eight to ten cages, at depth limits of 30 meters (Rodríguez et al. 2017). Based on diving regulations for professional divers in Chile (Chile 2014), it is determined that for successive dives at a depth of 25 meters, the maximum diving time is 30 min (Rodríguez et al. 2017). Service to each cage without decompression consists of a 7-minute dive followed by a 10-minute break on the surface. Following these regulations, the risk for decompression illness increases on the third cage when the diving time is 6 min (instead of 7) to complete work on the third cage. According to these calculations, successive diving (or yo-yo diving) would allow work for only two cages or three if diving time is reduced to 6 min in the last cage (Rodríguez et al. 2017). However, common practice is to service eight to ten cages during a work day. Dive and decompression time and limits are calculated based on the safe diving tables of the Directmar Diving Regulation (Chile 2014). The accepted total diving time per work day is 50 min including the time for breaks on the surface, however SUSESO's study showed that out of 131 divers participating in the study, 19 (14.5%) dove more than 50 min per day (Rodríguez et al. 2017).

Diving and other activities involving contact with water and fish can also entail a risk of exposure to residual chemicals arising from treatments that are carried out in the cages (Rodríguez et al. 2015) and from exposures to other residual agents such as antimicrobial resistant bacteria to which we now turn.

Sanitary emergencies and exposure to antibiotics and antimicrobial resistance genetic determinants

Major MMEs in Chilean salmon aquaculture have been associated with the development of an important body of research focused on the interconnected animal, environmental, and human health (One Health) implications associated with antibiotic use in salmon aquaculture production. Heightened biosecurity measures and reduced antibiotic use incidentally protect aquaculture workers from biochemical hazards associated with exposures to antibiotics, their residues, and AMR genetic determinants, including when responding to MMEs. However, existing research narratives around antibiotics, AMR and MMEs rarely focus on worker perspectives and there is room for strengthened policy, antibiotic and AMR surveillance programs, and antimicrobial stewardship to address this OHS gap.

With the exception of 2011 and 2012, infectious salmon anemia (ISA), was the viral agent linked to MMEs in Chilean salmon aquaculture annually between 2007 and 2018 (Chile 2019a). The sanitary crisis resulting from ISA outbreaks between 2007 and 2009 led to enhanced efforts to prevent primary infections or lice infestations that increase the vulnerability of salmon to secondary viral infections (Godoy et al. 2013). New biosecurity practices reflect those already in place in Norway, the U.K., and Canada, such as synchronized salmon production cycles, fallowing periods, the use of disease monitoring programs to determine farming densities, and expanded vaccination programs (Miranda et al. 2018; Bachmann-Vargas et al. 2021). These policy changes, together with strengthened antimicrobial stewardship through the implementation of the National Action Plan Against Antimicrobial Resistance in Chile have decreased the industry's reliance on antibiotics (Millanao et al. 2018; Luthman et al. 2019; Bachmann-Vargas et al. 2021).

Nonetheless, despite the intentions of the Chilean Salmon Antibiotic Reduction Program to halve antibiotic use by 2025 in partnership with the Chilean Salmon Marketing Council (White 2019), Chilean aquaculture reported the use of roughly 460 tons of antibiotics in 2021, a notable increase from 2020 (Spolarich 2022). Treatment against *Piscirickettsia salmonis*, a bacterial pathogen and the causal agent of SRS, is now a major driver of levels of antibiotic use that exceed standardized figures reported by the other leading salmon production countries and, in Chile, are concentrated within a smaller geographic area (Buschmann et al. 2006; Shah et al. 2014; Miranda et al. 2018). Furthermore, the high, yet underreported, use of florfenicol and oxytetracycline as the preferred antibiotic treatments against SRS (Chile 2019a) exerts selective pressure for AMR across the three intersecting One Health realms (Millanao B et al. 2011; Cabello et al. 2013; Millanao et al. 2018).

Antibiotics applied in aquaculture settle into the sediment, sediment-water interface, and/or local biota via unconsumed food or fish feces, with distribution and persistence in the aquatic environment varying with antibiotic chemical characteristics, water flow and temperature, and sediment composition (Kim and Carlson 2007). The detection of antibiotics in muscle tissue from wild salmonids in Chile points to a seemingly ubiquitous presence of these pollutants in aquatic environments (Carrizo et al. 2021, 2022).

Documented health risks associated with occupational exposures to these factors in the context of salmon aquaculture are largely limited to systems mapping (Brunton et al. 2019) and human health risk assessments have not proceeded beyond the hazard identification stage. These kinds of data gaps hinder risk assessments and constrain succinct characterization of the occupational health risks associated with exposures to antibiotics, antibiotic residues, and AMR genetic determinants in aquaculture settings. However, chronic, low dose exposures to antibiotic residues through food consumption, including fish, and environmental exposure pathways have been linked to negative health outcomes in humans (Limbu et al. 2018). Researchers in Chile have furthermore illustrated the potential human health risks associated with putative exposures to antibiotics, their derivatives, and AMR genetic determinants within salmon aquaculture environments (Figure 3) (Buschmann et al. 2012; Aedo et al. 2014; Tomova et al. 2015; Muziasari et al. 2016; Higuera-Llantén et al. 2018; Tomova et al. 2018; Chiesa et al. 2019; Domínguez et al. 2019; Ramírez et al. 2022; Salgado-Caxito et al. 2022; Thomassen

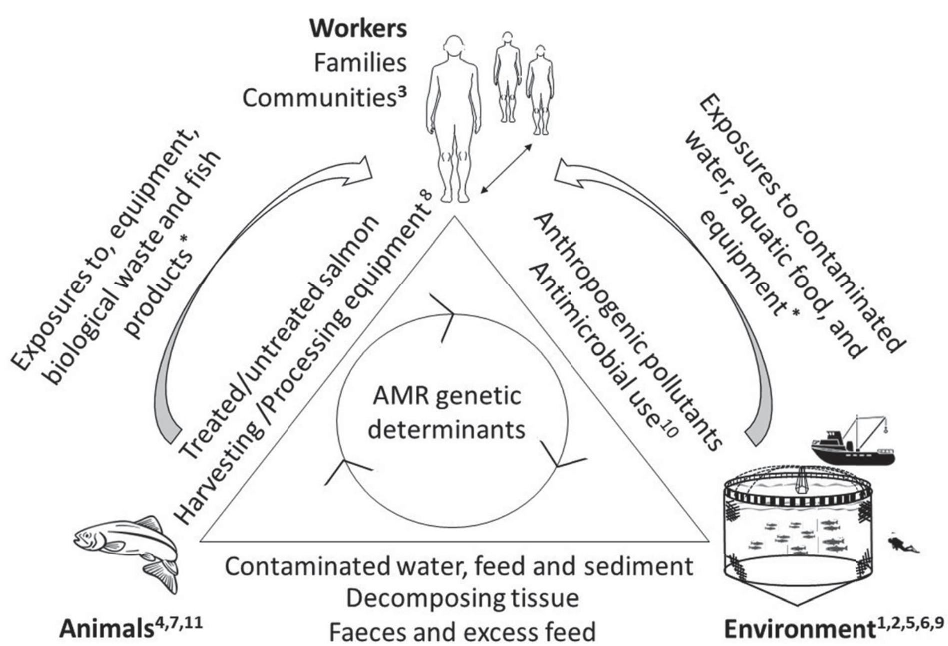
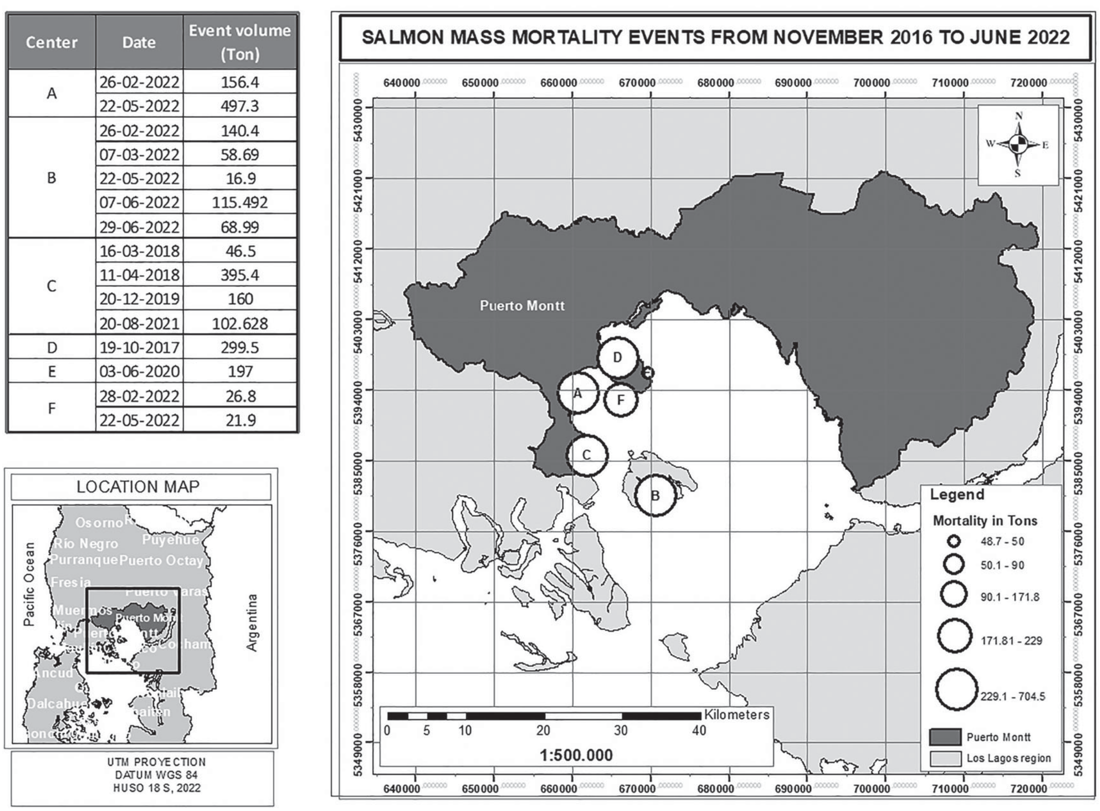


Figure 3. Literature map of peer-reviewed studies that present empirical evidence of antibiotics, their metabolites, and AMR genetic determinants within open systems salmon aquaculture environments. Source: [3](Tomova et al. 2015); [4,7,11](Higuera-Llantén et al. 2018; Chiesa et al. 2019; Salgado-Caxito et al. 2022); [1,2,5,6,9](Buschmann et al. 2012; Aedo et al. 2014; Tomova et al. 2018; Domínguez et al. 2019; Ramírez et al. 2022); [8](Thomassen et al. 2022); [10](Muziasari et al. 2016); WHO 2022. ∗An absence of cross-sectional studies hinders risk analyses to evaluate human health risks directly associated with AMR genetic determinants in aquaculture environments, represented by large external arrows, particularly during intensive and high-contact operations required during MMEs.

et al. 2022; WHO 2022). In Figure 3, possible occupational exposure pathways are presented within a One Health framework (WHO 2022) to highlight the selective pressure exerted by antibiotics on the natural aquatic resistome and the subsequent risk of horizontal gene transfer of mobile genetic elements throughout the aquaculture environment, cultured salmon, and/or aquaculture worker microbiome interface. In short, Chilean aquaculture practices have been linked to the detection of antibiotic residues, and bacteria harbouring AMR genetic determinants to the same antibiotics have been detected in sediment (Buschmann et al. 2012; Shah et al. 2014; Millanao et al. 2018), bacteria isolates from human patients in aquaculture regions (Tomova et al. 2015), and the gut of Atlantic salmon harvested from Chilean fish farms (Higuera-Llantén et al. 2018). A 2022 court ruling requiring the public release of company-level data on antibiotic use in Chilean salmon aquaculture (Spolarich 2022) will facilitate more accurate analyses to better understand the broader human, environmental, and animal health risks associated with exposures. Chilean salmon aquaculture can promote industry leadership with such publicized reporting of antibiotic use and routine integration of studies that can guide innovative solutions to address potential occupational exposure pathways to antibiotics and AMR within aquaculture and terrestrial food animals.

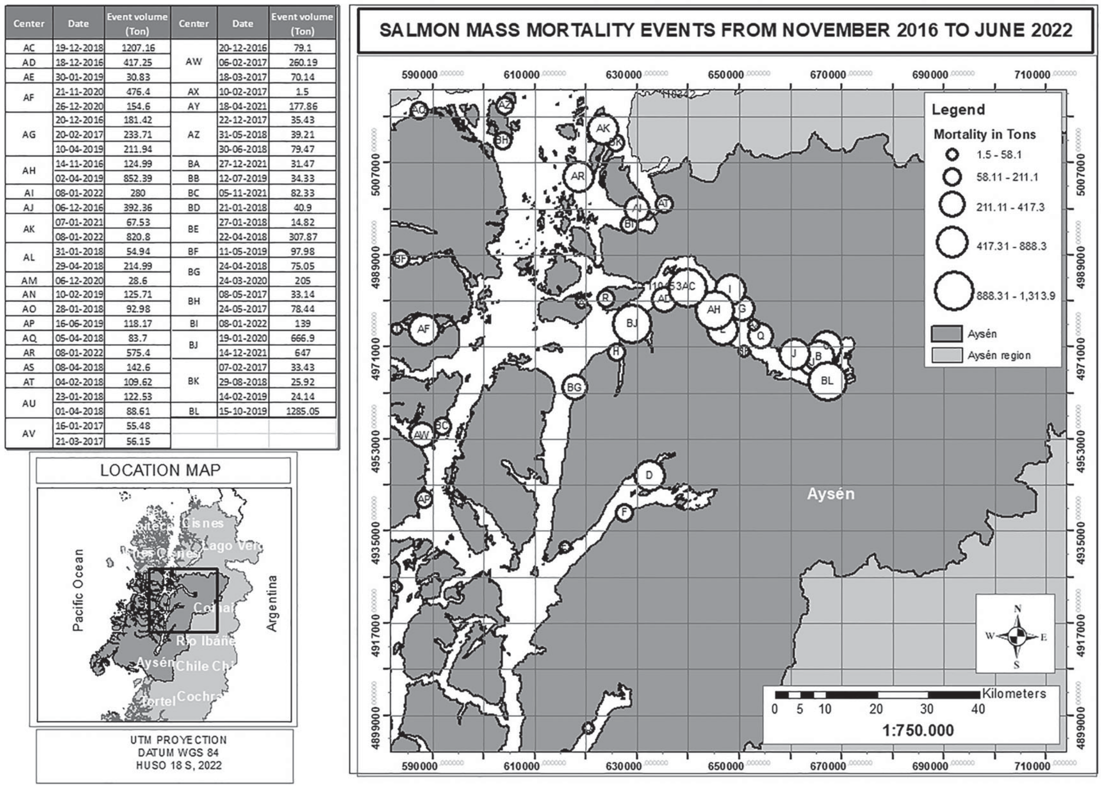
Timely access to appropriate health care

Timely and safe access to appropriate health care is an important factor in limiting the negative health impacts of injuries and illnesses. This may be particularly important in the context of MMEs where more intensive and potentially risky activities concentrated in particular areas and periods could result in multiple incidents. Rural and remote workers can face problems accessing health services due to long distances to health services and potential transportation difficulties (Watterson et al. 2020). Salmon aquaculture in Chile occurs in the remote southern regions of the country (Los Lagos and Aysén) (Porzio and Arancibia 2007), where a limited emergency network hinders quick and effective responses to aquaculture accidents in remote regions (Melillanca and Medina 2007). MMEs have occurred in Puerto Montt, a region of Los Lagos located closer to city hubs (Figure 4) and in the remote community of Aysén (Figure 5).



Center	Date	Event volume (Ton)
A	26-02-2022	156.4
	22-05-2022	497.3
B	26-02-2022	140.4
	07-03-2022	58.69
	22-05-2022	16.9
	07-06-2022	115.492
	29-06-2022	68.99
C	16-03-2018	46.5
	11-04-2018	395.4
	20-12-2019	160
	20-08-2021	102.628
D	19-10-2017	299.5
E	03-06-2020	197
F	28-02-2022	26.8
	22-05-2022	21.9

Figure 4. Salmon mass mortality events in the administrative division of Puerto Montt. The circles' size represents mortality accumulated from November 2016 to June 2022 in each concession. Source: Data from Servicio Nacional de Pesca y Acuicultura (SERNAPESCA) (Chile 2022a).



Center	Date	Event volume (Ton)	Center	Date	Event volume (Ton)
AC	19-12-2018	1207.16	AW	20-12-2016	79.1
AD	18-12-2016	417.25		06-02-2017	260.19
AE	30-01-2019	30.83		18-03-2017	70.14
AF	21-11-2020	476.4	AX	10-02-2017	1.5
	26-12-2020	154.6	AY	18-04-2021	177.86
AG	20-12-2016	181.42	AZ	22-12-2017	35.43
	20-02-2017	233.71		31-05-2018	39.21
	10-04-2019	211.94		30-06-2018	79.47
AH	14-11-2016	124.99	BA	27-12-2021	31.47
	02-04-2019	852.39	BB	12-07-2019	34.33
AI	08-01-2022	280	BC	05-11-2021	82.33
AJ	06-12-2016	392.36	BD	21-01-2018	40.9
AK	07-01-2021	67.53	BE	27-01-2018	14.82
	08-01-2022	820.8		22-04-2018	307.87
AL	31-01-2018	54.94	BF	11-05-2019	97.98
	29-04-2018	214.99	BG	24-04-2018	75.05
AM	06-12-2020	28.6		24-03-2020	205
AN	10-02-2019	125.71	BH	08-05-2017	33.14
AO	28-01-2018	92.98		24-05-2017	78.44
AP	16-06-2019	118.17	BI	08-01-2022	139
AQ	05-04-2018	83.7	BJ	19-01-2020	666.9
AR	08-01-2022	575.4		14-12-2021	647
AS	08-04-2018	142.6	BK	07-02-2017	33.43
AT	04-02-2018	109.62		29-08-2018	25.92
AU	23-01-2018	122.53		14-02-2019	24.14
	01-04-2018	88.61	BL	15-10-2019	1285.05
AV	16-01-2017	55.48			
	21-03-2017	56.15			

Figure 5. Salmon mass mortality events in the administrative division of Aysén. The circles' size represents mortality accumulated from November 2016 to June 2022 in each concession. Source: Data from Servicio Nacional de Pesca y Acuicultura (SERNAPESCA) (Chile 2022a).

These aquaculture hubs are located 40 kms or more from the nearest hospital or hyperbaric chamber (Figures 6 and 7, Los Lagos and Aysén regions respectively), jeopardizing the health outcomes of injured aquaculture workers requiring urgent medical care or the use of a hyperbaric chamber. Aquaculture centres in this southern region are also exposed to harsh weather conditions (e.g. storms) that may trigger port closures and restrictions on navigation, thus creating further obstacles to obtaining prompt medical care. If a diver suffers a decompression injury, it is essential that they can quickly access a hyperbaric chamber. Hyperbaric chambers need to be well-maintained and require trained staff. Reports showed hyperbaric chambers in Quellón, Ancud and Puerto Montt had operational problems in 2010 (Arengo et al. 2010; Riedemann et al. 2021). Furthermore, according to Riedemann et al. (2021) interviewed workers reported a hyperbaric chamber installed in Quellón did not have trained personnel to use it and that the presence of a hyperbaric chamber is only mandatory when diving operations exceed 40 meters in depth. Chile has developed OHS guidelines related to MMEs that speak to some but not all of the potential hazards outlined above.

Regulation of mass mortality events and occupational health

Currently, there is no registry in Chile or elsewhere globally to our knowledge on workers' health and safety incidents, injuries/illnesses or fatalities that distinguishes between MME-related incidents and regular aquaculture production (Neis et al. 2023). Chile's 2016 MME did, however, create much controversy regarding the dumping of salmon waste into the ocean and changing environmental conditions and led to efforts to update the country's environmental and OHS guidelines. As a response, Chile issued Circular 0-31/020 (Chile 2020a) – which includes safety measures in the case of mass fish mortalities – in which worker health threats and steps for preventing injury/illness are identified. Circular 0–31 (Box 1 and 2) establishes the safety measures that must be adopted in cases of mass fish mortality including in removal, loading, transportation, and

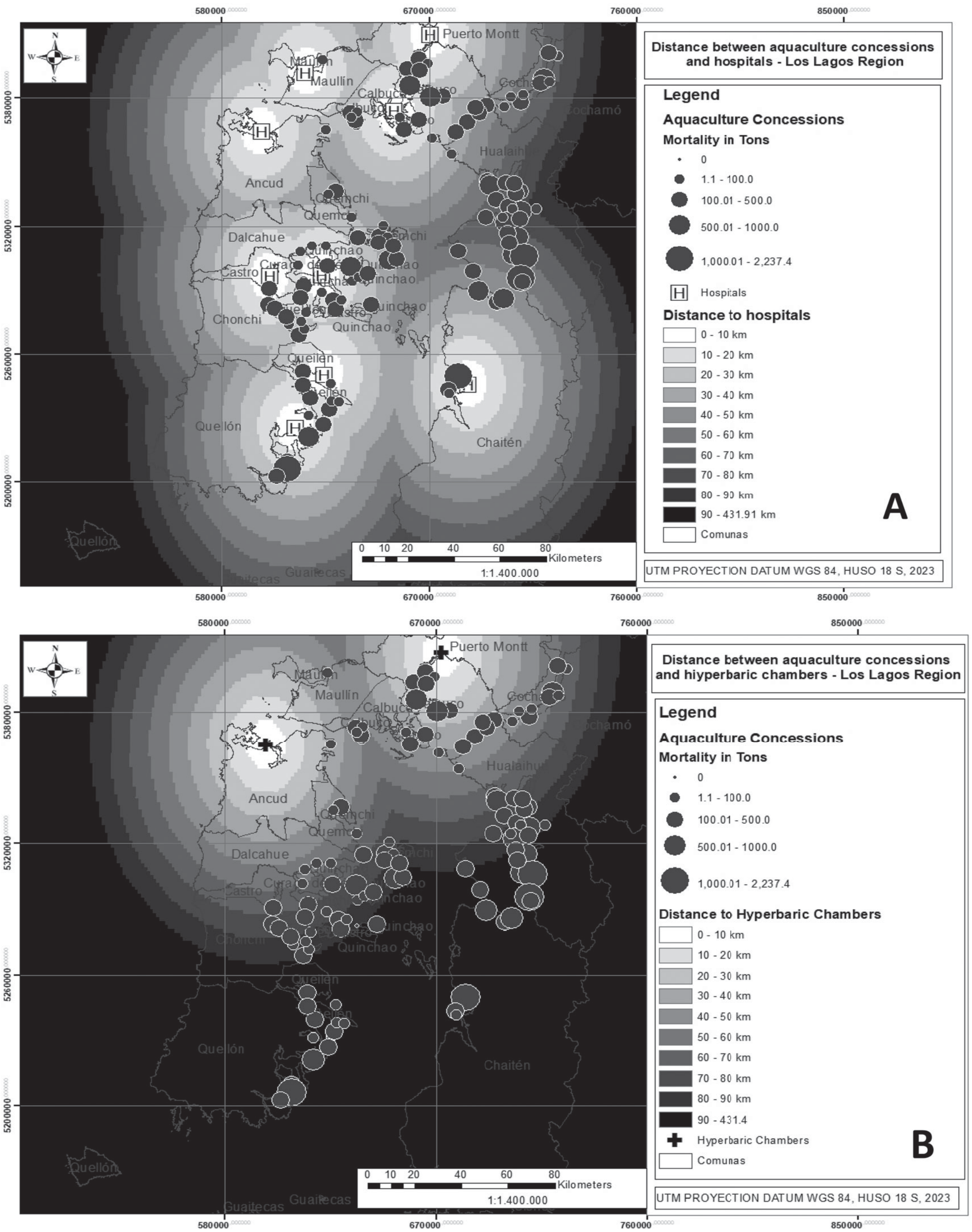


Figure 6. Nearest distance between the aquaculture centers and hospitals (A) and hyperbaric chambers (B) in the region of Los Lagos. Source: developed by authors.

unloading tasks and is under the jurisdiction of the Chilean Maritime Authority. The worker safety provisions in Circular 0–31 focus mainly on the risk of exposure to H_2S and to diving-related hazards. Due to the potential exposures of workers, protocols for action in the case of mass fish mortalities were adopted by the Chilean Ministry of Health when they developed a regulation on health and safety conditions at the workplace (Chile 2000). The D.S. N ° 594, of September, 1999 (Chile 2000), establishes the basic health and environmental conditions that every workplace must comply with, as well as the permitted limits of environmental exposure for chemical agents and physical agents, and the limits of biological

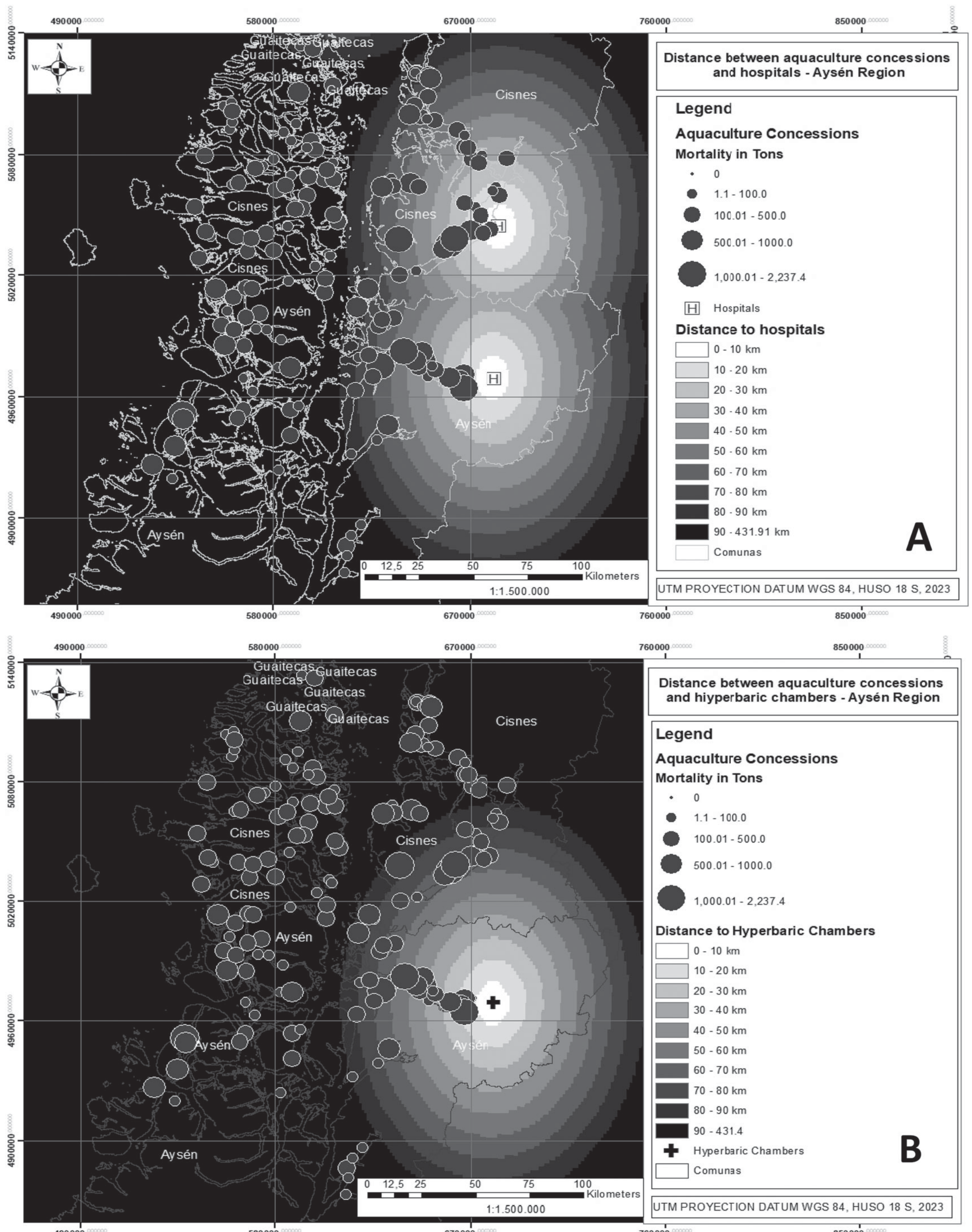


Figure 7. Nearest distance between the aquaculture centers and hospitals (A) and hyperbaric chambers (B) in the region of Aysén. Source: developed by authors.

tolerance for workers exposed to occupational risk (Chile 2000).

Circular 0–31 provides guidance on the mandatory personal protective equipment (PPE) that workers must use in the activities of loading (extracting), unloading and removing dead fish (Chile 2020a). Required PPE includes gas measurement equipment for H_2S, chemical protective clothing, masks with filters for H_2S and carbon monoxide (CO), chemical protection gloves, and safety boots with acid-resistant rubber for chemical protection.

The Government of Chile includes a workflow diagram for detection and action when MMEs occur in the *Regulations Manual for Massive Mortality Events*

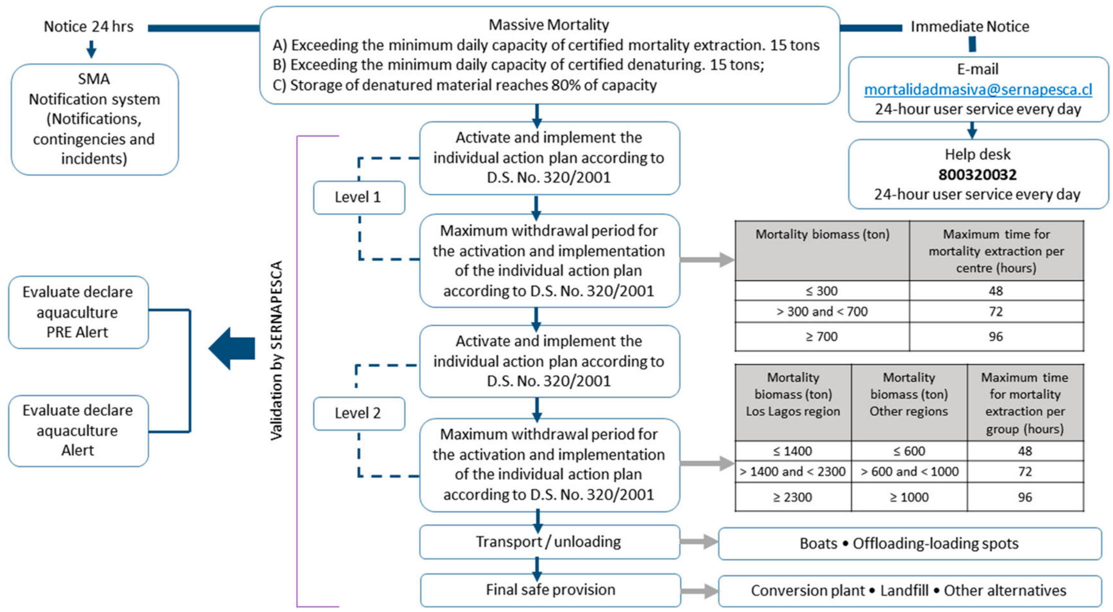


Figure 8. Workflow diagram of measures in the face of mass mortality events. Source: Chile 2021a.

Circular 0-31/020

- Obtain a health certificate from SERNAPESCA for removal of waste.
- Provide detailed documentation about the fleet that will be in charge of removal including storage and bins. All vessels in the fleet should have a Satellite Positioning Device turned on at all times.
- Provide a daily account of the removal of dead fish (Annex A in Circular): number of fish, weight of fish, date and time of mass mortality, mortality causes, mass mortality per day, total biomass of dead fish transported as silage, total biomass of dead fish transported as whole, total biomass transported, date and time of extraction, fleet that conducted removal, and final destination of waste.
- Assign a Supervisor who takes charge of the whole operation.
- The supervisor must measure gases (H_2S) during extraction and loading of mass mortality and record each measurement.
- Have a a risk prevention professional certified by the Regional Health Ministry who will be in charge of: keeping all staff trained about risks and hazards involved in mass mortalities, including exposure to carbon moxide, hydrogen sulfide (H_2S), handling of dead fish, health consequences, evacuation procedures in case of intoxication, handling of equipment aimed to provide oxygen and gas measurement, training the supervisor in charge of mass mortality removal.
- Have a Safe Work Procedure validated by the risk prevention professional in charge that considers: all stages of loading, unloading and extraction of mortality and situation where H_2S may exceed 8.8 p.p.m. concentrations.
- The Safe Work Procedure will contain: tasks regarding loading and extraction of mortality from the farm to the fleet taking into account the tanker truck, extraction of mortality as silage or as whole, unloading of mortality from the fleet to the port or dock, emergency plan covering reach, description of situation, responsibilities, tasks to follow, communication, personal protective equipment (PPE), blueprints of the ship and aquaculture center, communication.

Box 1. Circular 0–31 establishes the safety measures that must be adopted in cases of mass fish mortality. Source: Chile 2020a.

(Chile 2021a) (Figure 8). The workflow diagram consists of a notification system and actions to control and/or eliminate mortality and activate emergency plans for the transportation, unloading and final disposal of dead animals with the aim of ensuring the protection of hydrobiological resources, their environment, and people's health. The plan includes a detailed compilation of rules and regulations that must be followed in the face of an MME.

Human health protective strategies in Chilean salmon aquaculture, including as part of response to MMEs, would benefit from robust and standardized hazard assessments and from surveillance programs for AMR genetic determinants. Improved multi-agency sharing of compatible environmental and human health metrics would provide baseline data to better predict health risks associated with occupational exposures to environmental hazards.

Circular 0-31/020 - For diving activities

- Must be authorized by the Local Maritime Authority and comply with the safety measures outlined in the Diving Regulations for Professional Divers DS No. 752/1982. (These regulations establish the limits of submersion and depth, for successive dives and without decompression. Other standards for professional divers are established by the General Directorate of the Maritime Territory and Merchant Marine (Directemar)).
- The dive must be supervised continuously (by a diving supervisor) and should be carried out by an intermediate shellfish diver ("*buzo mariscador*" a licensed diver dedicated to the extraction, exploitation and commercialization of hydrobiological resources and diving work in aquaculture, they are trained in using semi-autonomous equipment), or commercial diver if the diving task exceeds 20 meters deep.
- All farms must have current diver license, an Inspection certificate for the equipment used, approved by the Local Maritime Authority, and a Contingency Plan for Diving Emergencies (even if tasks are performed by a subcontractor).
- The "diving team" must be formed and supervised by the company responsible for the farm or by the respective subcontractor that performs the task."
- Shellfish Diver Candidates need to complete a theoretical and practice exam evaluating a range of concept/activities from physics applied to diving to rescue processes and first aid.

Box 2. Circular 0–31 establishes the safety measures that must be adopted for diving activities. Source: Chile 2020a.

In Chile, health and safety is regulated by Article 184 of Labor Code D.F.L. N ° 2, 1967 and Law N° 16.744 (Supreme Decree No. 40) (Oñate 2014). The regulations include the duty to inform (company), and the right to know (worker), about work-related risks to health. The employer is obliged to take all the necessary measures to effectively protect the life and health of the workers, to inform them of possible risks and to maintain adequate hygiene and safety conditions in the workplace, including through the implementation of measures to prevent injuries and illnesses (Article 184 of Labor Code D.F.L. N ° 2, 1967) (Oñate 2014). In the case of MMEs, such measures should include a careful risk assessment of MMEs from the point of view of frequency and causes right through to AOHS hazards and treatment (Sajiid et al. 2022).

Conclusion

In Chile and around the world, the marine aquaculture industry is growing rapidly. Climate change events, along with related HABs (Galappaththi et al. 2022) are increasing, as are diseases (León-Muñoz et al. 2018; Aguayo et al. 2019; Soto et al. 2019; Pica-Téllez et al. 2020). These changes will likely contribute to the risk of MMEs in marine aquaculture in the future. The findings of this case study of MMEs in Chile and their potential consequences for AOHS point to the need for future research and monitoring of MMEs including their potential impact on AOHS hazard exposures, risk and ways to mitigate risk. Relative to other countries we have looked at in our broader AOHS risk assessment of MMEs (Neis et al. 2023), Chile appears to be at high risk of MMEs and related injuries and illness. Unlike other countries, it has a set of specific regulations and guidelines for MMEs that encompass some AOHS measures (Cavalli et al. 2019b). However, risks for workers in developing countries such as Chile are often elevated due to socioeconomic, working, environmental and geographical factors that contribute to exposures and to physical and psychological injury risk (Porzio and Arancibia 2007).

These workers generally tend to work more hours per week and are more likely to tolerate hazardous working conditions rather than risk losing their jobs (Giuffrida et al. 2001; Cavalli et al. 2019b). These conditions pose significant problems when implementing AOHS measures. Unfortunately, limited data on AOHS incidents and fatalities are available for Chile, and there is no research that systematically documents AOHS hazards, injuries and fatalities related to marine aquaculture in general that would support separating rates and types of injuries associated with MMEs compared to normal operations. This is also the case in many other countries, so this is an area in need of future research (Cavalli et al. 2019a; Watterson et al. 2020; Neis et al. 2023).

With regard to the risks of antibiotic/AMR exposure, it is necessary for those involved in the aquaculture supply chain to recognize that: (1) invisible biochemical risks exist; (2) surveillance of these risks will strengthen a collective understanding of the risk of exposure; and (3) until we can confirm that the risk does not exist, a preventive health protection strategy is advisable for those involved in MME cleaning operations, particularly if antibiotics have been applied to the salmon cohort or if MME occurs due to an infectious disease.

During the 2016 MME in Chile, some potential injury events were avoided due to the workers' prior knowledge of hazards, as in the case of the crew that abandoned their boat after recognizing symptoms of H_2S intoxication. The Chilean Security Association now recommends preventive measures against H_2S exposures which include training and workshops on the effects of H_2S for workers (ACHS n.d.). Additionally, workers and supervisors working on salmon farms should receive sufficient information regarding the potential effects of MMEs including on workers' health. This case study of Chile shows that more information and regulation is needed in the AOHS sector and that there needs to be a distinction between daily aquaculture work and aquaculture work during MMEs in terms of injury reports, equipment requirements and working conditions. It also points to potential gaps in medical treatment resources that could be exacerbated in MME contexts if the latter are associated with multiple or severe injuries including related to decompression illnesses.

Note

1. Data obtained from media websites and literature (Table 2) may reflect real time reporting of the MMEs and may differ from the data provided by SERNAPESCA (Table 1) which reports the final reported losses in tons based on company reporting.

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Ethical statement

The research presented in this manuscript did not involve any animal or human participants.

Data sharing statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Authorship contributions

Cavalli LS: conceptualization, writing – original draft, data analysis, review and editing; Tapia-Jopia C: writing – original draft, review and editing, map development; Ochs, C. L.: writing – original draft, review and editing, provided the section on AMR; Lopez Gomez MA: writing – original draft; data analysis, review and editing; Neis B: conceptualization, writing, data analysis, review and editing. All authors approve the version to be published; and agree to be responsible for all aspects of the work.

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