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Spatiotemporal patterns of mortality events in farmed Atlantic salmon in British Columbia, Canada, using publicly available data

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Monitoring mortality is an essential strategy for fish health management. Commercial marine finfish sites in British Columbia, Canada, are required to report mortality events (MEs) to Fisheries and Oceans Canada (DFO), which makes these data publicly available. This study aimed to analyze the spatial and temporal patterns of ME composition and total MEs. Between June 2011 and June 2022, 561 MEs were reported. The annual incidence ranged from 1.36 (95% CI: 0.55–2.81) MEs per 100 active site-months in 2013 to 17.98 (95% CI: 13.26–23.84) MEs per 100 active site-months in 2022, with a broadly increasing trend over the period under consideration. The primary causes of MEs were low levels of dissolved oxygen, fish health treatments, and harmful algal blooms (HABs). Both HABs and low dissolved oxygen followed similar patterns, increasing from 2014, peaking in 2019, and declining thereafter. Treatment-related MEs were first reported in 2017 and saw a sharp increase in subsequent years, becoming the leading cause of MEs by 2020. Nearly all treatment-related MEs were linked to sea lice treatments, highlighting the urgent need for adaptive strategies to mitigate these impacts. Sites on the west coast of Vancouver Island demonstrated a higher risk of reporting MEs compared to Mainland sites, likely due to their higher levels of exposure to fluctuating oceanographic conditions. Long-term climate change and persistent periods of warming events, such as marine heat waves, are warming the oceans, altering water parameters, and likely increasing the occurrence and severity of HABs and low dissolved oxygen-related MEs. Further studies are needed to quantify the effects of ocean warming on salmon aquaculture and the resulting increase in fish mortalities.

Keywords Farmed salmon, Public data, Sea lice treatment, Mortality events, Environmental factors, Climate change

Mortality monitoring and management are essential components to ensure the operational performance in all sectors of animal food production, including aquaculture. A small number of mortalities are generally observed in salmon aquaculture[1,2]. However, sudden and unexpected mortalities, known as mortality events (MEs), are particularly concerning due to the increased management challenges they present and their negative impacts on the environment, economy, and overall sustainability of aquaculture. The intensity and severity of MEs in the production cycle of Atlantic salmon have been increasing in recent years in major salmon-producing countries, including Norway, the UK, and Canada[3,4]. This underlines the necessity of understanding the causes associated with mortality events and their spatial and temporal components to minimize their impact.

Canada is the world's fourth-largest producer of farmed salmon[5,6]. Salmon farming in Canada is practiced along the eastern Atlantic and western Pacific coasts. However, public access to salmon aquaculture data differs between the two coasts as they differ in their regulatory regimes[7]. Fisheries and Oceans Canada (DFO) is the federal agency responsible for regulating salmon aquaculture on the western coast of Canada, particularly in

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British Columbia (BC), where three-quarters of Canada's total salmon production by volume occurred in 2022[8]. Under the conditions of the licences issued by DFO, salmon farming sites are required to provide scheduled reports (such as sea lice counts) and event-based reports (such as MEs) to DFO[9]. These data are made publicly available by DFO through the Open Government Portal of Canada (https://search.open.canada.ca/data/). On the contrary, on the eastern Atlantic coast of Canada, respective provincial government departments regulate the salmon aquaculture industry, and neither scheduled nor event-based data are made publicly accessible[7].

Salmon aquaculture in BC is practiced on the coastlines of Mainland and Vancouver Island. Environmental factors, including water currents, temperature, dissolved oxygen (DO), the incidence of harmful algal blooms (HABs), and freshwater discharge in the ocean, vary at different degrees between the coastlines of Mainland BC and Vancouver Island. The variation in environmental factors is hypothesized to be correlated with differences in the distribution of diseases and parasites between the coasts[10–12]. The ocean waters in BC are affected by the long-term trend of ocean warming as the coastal waters have warmed about 0.7 °C in the past 80 years[13]. In BC, the prolonged period of marine heat waves significantly increased water temperatures by up to 3 °C between 2014 and 2016[13]. These events also alter other water parameters, such as dissolved oxygen, salinity, acidity, and HABs level, impacting the ecosystem of all marine life, including farmed and wild salmon, and leading to mortality events of varying scales[14–16].

Infectious diseases, environmental factors, and mechanical stress have long been the primary causes of mortality in salmon aquaculture in major salmon-producing countries[17–20]. However, in recent years, managing sea lice has become a growing concern for aquaculture industries in countries like Norway, Chile, Scotland, and Canada[21–24]. Fish mortality, particularly those associated with sea lice treatment that involves the handling of fish, has been increasing significantly[22,25]. In BC, Canada, prior to the amendments to the Marine Finfish Aquaculture Licence under the Fisheries Act on July 1, 2024, salmon farmers were required to maintain a sea lice count of no more than an average of 3 motile *Lepeophtheirus salmonis*[9]. This threshold will decrease to 2.8 in 2025 and further to 2.6 by 2026[26]. The reduction in the threshold is likely to result in increased fish mortalities, as more frequent and intensive sea lice treatments may be required to maintain lice counts within the prescribed limits.

Every salmon-producing country has its own definition of mortality events and has established specific thresholds for these events. In BC, mortality reaching up to 1% of the current stock within 24 h or 2.5% within five days is classified as a ME[9]. However, before June 30, 2022, MEs were defined as instances where the biomass/proportion of dead fish surpassed either (a) 4,000 kg or more, or losses totaling 2% of the present stock inventory in a 24-hour period, or (b) 10,000 kg or more, or losses reaching 5% of the present stock inventory in a five-day period[27]. To date, no study has identified the space-time distribution of MEs and associated factors in BC. This study aimed to analyze the spatial and temporal patterns of ME composition and total MEs by providing a descriptive summary of ME incidence patterns in different Aquaculture Management Units (AMUs) in BC from June 2011 to June 2022, using publicly available data. Additionally, we aimed to identify high-risk areas (clusters) of mortality events in both space and time.

Materials and methods

Study area

In BC, the farming coastlines are organized into two primary zones and several sub-zones, determined by ocean and fisheries watersheds. Zone 2 is situated along the coastlines of Vancouver Island, while Zone 3 is located east of Vancouver Island, extending from the Fraser River northward through the inside passage to the North Coast[28]. Each of these major zones is further divided into smaller sub-zones called Fish Health Zones (FHZs). Zone 2 comprises four FHZs (2 – 1 to 2–4), and Zone 3 contains five FHZs (3 – 1 to 3–5) (Fig. 1). These FHZs include multiple Aquaculture Management Units (AMUs). All these sub-zones and AMUs are used for sampling, auditing, and reporting purposes to monitor fish health and disease events in salmon sites across BC[28]. Currently, the publicly available data from DFO is reported at the level of AMUs, with FHZs being less frequently used. Therefore, our results are also presented at the AMU level. Furthermore, since there are no clear boundaries defining the AMUs, we have used circles to represent them in the study area map (Fig. 1). The nomenclature for AMUs has been adopted from Jyoti et al.[29].

Data sources

We utilized the publicly available MEs and the sea lice count dataset from DFO[30,31] to extract the information on mortality events and perform the cluster analysis (explained in statistical analyses section).

a. **Mortality events (MEs) dataset**: In British Columbia, marine finfish aquaculture licence holders are required to notify DFO within 24 h of any "mortality event" as defined in their licence conditions[9]. This urgent initial notification should provide DFO with detailed information about the event's nature and extent. Following this urgent notification, a comprehensive report is due within ten days, which must include the total weight or percentage of dead fish, the number of deceased fish, and the cause of the mortality. If the event continues, updated reports are required every ten days until normal mortality levels are restored[27]. We assessed the publicly available site-level data of MEs reported by salmon sites to DFO between June 2011 and June 2022[31]. The data considered were based on the old definition of MEs before June 30, as described in the last paragraph of the introduction. The published data included information on the site's location, AMUs, type of MEs, species, and the action taken by the facility. However, it lacked information on the number and weight of dead fish. The data beyond June 2022 were not considered for the study because of the implementation of new DFO guidelines for reporting MEs[9]. Of the 565 MEs reported from 21st June 2011 to 30th June 2022, 561 were considered for the study. The remaining four MEs were excluded as they were from fish species other than Atlantic salmon.

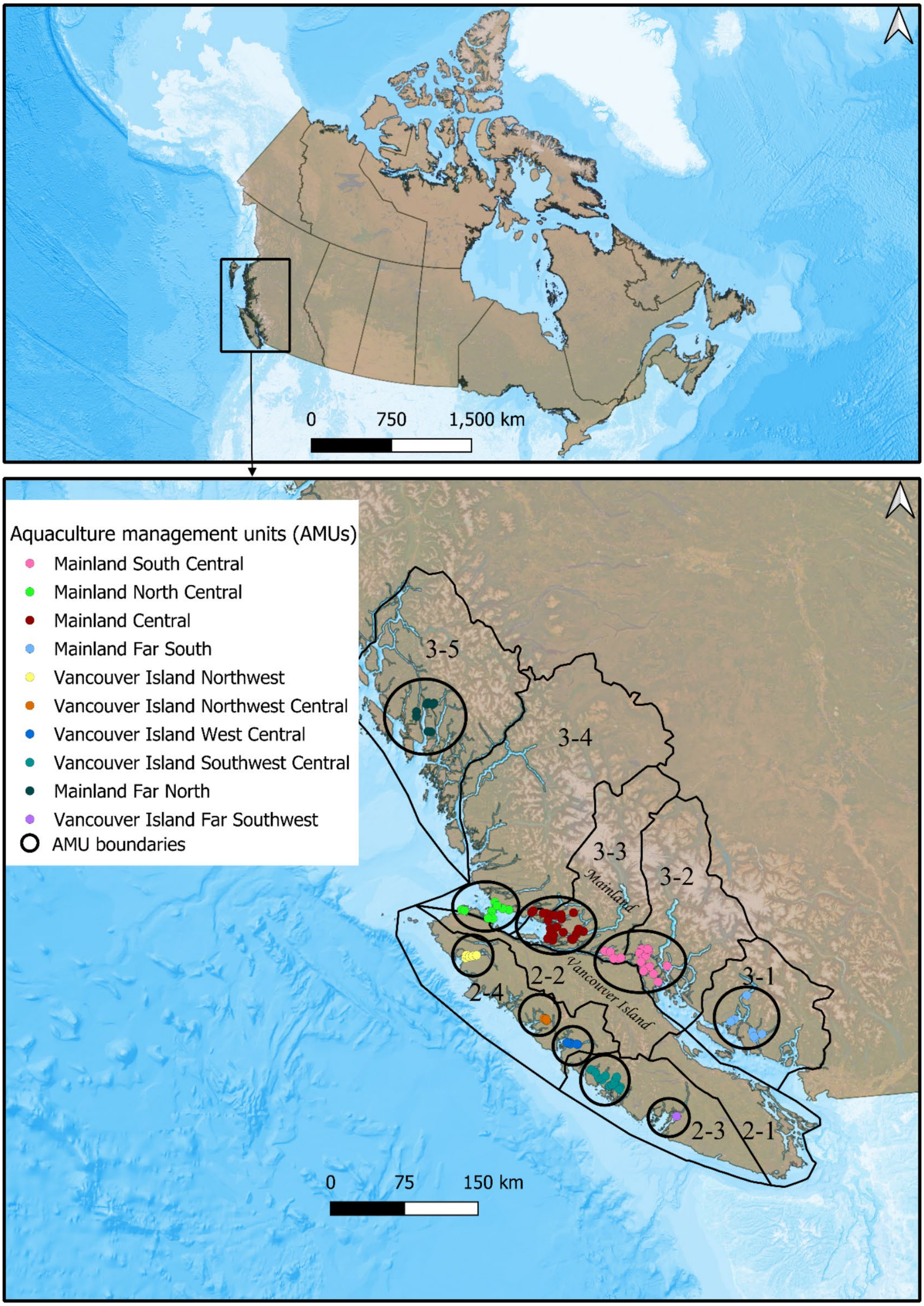

Fig. 1. Map of the study area. The upper panel shows the geographical location of British Columbia (BC) within Canada, while the lower panel provides a detailed view of the study area. Fish Health Zones (FHZs) are delineated by black lines and labeled with numeric identifiers, while sites within an Aquaculture Management Unit (AMU) are represented by the same color, with their boundaries marked by black circles. The map was created using QGIS software version 3.30.1 with data on salmon sites obtained from Fisheries and Oceans Canada (DFO).

b. **Industry sea lice count dataset**: The dataset contains information on the monthly sea lice count of the active sites of marine aquaculture licence holders in BC between 2011 and now. Fish health professionals from the BC salmon companies perform a sampling event to count the sea lice and report the data to DFO. The counting events are performed atleast once a month during the non-migration window (July 1-January 31) and twice a month during the pre-migration (February 1-February 29) and out-migration (March 1-June 30) window[9].

Data management

The original data downloaded from the Canada Open Government Portal was imported to Stata 15.1[32]. The inconsistency in data entry was checked, and the names of licence holders, reporting date, MEs, and fish species were made uniform wherever required. The locations of salmon sites were confirmed by plotting them on the map using QGIS[33].

For each calendar month, control sites were selected as those active sites (sites stocked with fish) that did not report any MEs during that month. The location of all the active sites per month was extracted from the "Industry sea lice count" data. The relevant data for control sites from the industry sea lice count dataset were merged with the MEs dataset (Supplementary Table S1).

Statistical analyses

Descriptive analyses and incidence rate of site-level MEs

The three most common MEs were presented individually, and the remaining MEs were grouped into broad categories based on their similarities. Their frequencies were presented in a table. The annual proportions of reported MEs were summarized graphically. Information on the stocking year was extracted from the sea lice data, and the proportion of MEs for each category was estimated. The cumulative number of active site-months was calculated for each site, calendar year, and AMU. Incidence rates for the total and the most frequent MEs were also calculated (Eq. 1)[29].

$$\text{Incidence rate} = \frac{Number\ of\ new\ mortality\ events}{Number\ of\ active\ site - months} * 100 \tag{1}$$

The 95% confidence interval for the incidence rate was computed in Stata 15.1[32], assuming a Poisson distribution due to the count nature of the data. Plotting was achieved using the "ggplot2" package[34] in RStudio[35].

Trend analysis

To evaluate long-term monotonic trends, a trend analysis was performed for the three most common mortality events (MEs) and the total number of MEs, examining monthly incidence data from June 2011 to June 2022. A non-parametric Mann-Kendall test was employed to detect monotonic trends over time[36,37]. Since the Mann-Kendall test assumes independence between data points, autocorrelation was assessed using the Durbin-Watson test[38] and visually inspected through the autocorrelation function (ACF) plot[39]. For events exhibiting significant autocorrelation, a modified Mann-Kendall test was applied[40]. This modified approach ensures greater accuracy in terms of empirical significance levels compared to the original test under conditions of autocorrelation. To visualize the temporal trends, locally weighted scatterplot smoothing (LOWESS) regression was utilized[41]. This method effectively captures non-linear patterns in the data, providing a clear and intuitive depiction of trends over time. The analysis was performed utilizing "Kendall"[42] and "modifiedmk"[43] packages in Rstudio[35].

Space-time cluster analyses

A cluster analysis for each of the three most frequent and the total MEs was performed using the Bernoulli model available in SaTScan™ software version 10.1.2[44]. Scan statistics determine whether events are randomly distributed across space, time, or both and identify clusters of these events[45]. The method uses a likelihood-ratio test to help pinpoint areas with increased incidences, while relative risks and p-values for the identified clusters are calculated using Monte Carlo simulations[46,47]. The maximum spatial cluster size of 25% of the population at risk was set to obtain moderate-sized clusters[29], and the temporal cluster size was maintained at default (50%) as recommended in the software. In the space-time cluster analysis, calendar months (January to December) were used as a time component to identify the seasonal patterns of the MEs. Euclidean and seaway distances were used to identify the space and time clusters. Seaway distances between the sites were calculated using the "gdistance" package in RStudio[35,48]. The obtained distance matrix from R was reorganized into a neighborhood matrix in such a way that for each site, the neighboring sites are arranged in rows based on the nearest location as described in SaTScan™ user guide[46]. The neighborhood matrix was fed into the non-Euclidean neighbors' window in SaTScan™ software. The clusters identified using the seaway distance were represented manually by creating a polygon and connecting the outermost sites in the graph. The identified clusters were considered statistically significant at p-value <0.05 (calculated via 999 simulated Monte Carlo replications). The detected clusters in SaTScan™ were processed in QGIS[33] The detailed results of clusters identified based on seaway distances are presented in the Results section, while clusters identified using Euclidean distances are provided in Supplementary Material 1. The methods employed for space-time cluster analysis were adapted from the approach developed by Jyoti et al., which was previously applied to investigate the patterns of fish health events in farmed Atlantic salmon in British Columbia[29].

Results

Descriptive statistics

A total of 561 MEs were reported by three companies across nine different salmon aquaculture health management zones in BC between June 2011 and June 2022. During this period, 6,923 active site-months were recorded across the study area, resulting in an overall incidence rate of 8.10 MEs per 100 active site-months (561/6923*100 active site-months). Low dissolved oxygen (low-DO) (28.16%), treatment-attributed mortality (mortalities caused due to the application of treatment of any kind in the aquaculture site) (24.6%), and harmful algal blooms (HABs) (23.7%) were the three leading causes of MEs in farmed Atlantic salmon in British Columbia (Table 1). Mechanical factors like fish handling and transport contributed 9.45% to the total MEs. Infectious and non-infectious diseases, on the other hand, contributed only 3.39% and 2.14%, respectively, to the total MEs. Except for low-DO and HABs, other environmental factors contributed 5.25% to the total MEs (Table 1). The incidence rate of total MEs showed an increasing annual pattern, with the lowest rate of 1.36 MEs per 100 active site-months (95% CI: 0.55–2.81) in 2013 and the highest rate of 17.98 MEs per 100 active site-months (95% CI: 13.26–23.84) in 2022 (Fig. 2). Both HABs and low-DO-related MEs have been consistently encountered since 2011, with the highest incidences observed in 2018 and 2019, respectively. Interestingly, reports of treatment-related MEs were only recorded in 2017, and since then, the incidence rate of these events has shown an upward trend. In 2017, 9.5% of the total MEs were attributed to treatment, with marginal increases in 2018 and 2019, before rising to 33% in 2020 and 54% in 2021. From January to June 2022, 69% of the reported MEs were treatment-associated. Out of the total treatment-related MEs, sea lice treatment alone accounted for approximately 74%, with the other 23.19% coming from the combination of sea lice treatment and other contributing factors (Table 2). Only 2.90% of the treatment-associated mortalities are not related to sea lice. The majority (77.54%) of the treatment-associated mortalities were related to the second year-class fish. Similarly, all other MEs were reported more frequently in the second year-class fish. (Supplementary Figure S2).

The higher incidence rates of total MEs (per 100 active site-months) were recorded in Vancouver Island West Central (16.04, 95% CI: 12.74–19.94), Vancouver Island Northwest Central (15.93, 95% CI: 11.16–22.05), and Vancouver Island Southwest Central (11.42, 95% CI: 9.62–13.47). All these AMUs also show an increasing pattern of MEs over the years, as shown in the left panel of Fig. 3. Incidences of HABs and low-DO-related MEs were reported from all the AMUs at different rates. Similar to the total MEs, higher incidences (per 100 active site-months) of treatment-related MEs were mainly reported in Vancouver Island Northwest Central (5.75, 95% CI: 3.06–9.84), Vancouver Island Southwest Central (4.75, 95% CI: 3.61–6.12), and Vancouver Island West Central (3.96, 95% CI: 2.42–6.12).

Categories	Types of mortality events (MEs)	Frequency	Total (%)
Most frequent mortality events	Low dissolved oxygen (low-DO)	158	429 (76.47)
	Treatment	138	
	Harmful algal blooms(HABs)	133	
Environmental (except low-DO and HABs)	Water quality	20	30 (5.35)
	Jellyfish related	10	
Mechanical	Fish handling	46	53 (9.45)
	Transport	7	
Infectious disease	Amoebic Gill disease	1	19 (3.39)
	Atypical furunculosis	1	
	Furunculosis	3	
	Infectious Hematopoietic Necrosis	1	
	Mouth rot	5	
	Salmonid rickettsial septicemia	6	
	Viral hemorrhagic septicemia	1	
	Winter ulcer	1	
Non-infectious disease	Net pen liver disease	4	12 (2.14)
	Poor gill health	4	
	Proliferative gill disease	1	
	Mixed	3	
Others	Predation	6	18 (3.21)
	Maturation	2	
	Poor performers	4	
	Tides and storm	4	
	Management issue	2	

Table 1. Types of mortality events reported across farmed Atlantic salmon (*Salmo salar*) sites in British Columbia (BC) from June 2011- June 2022.

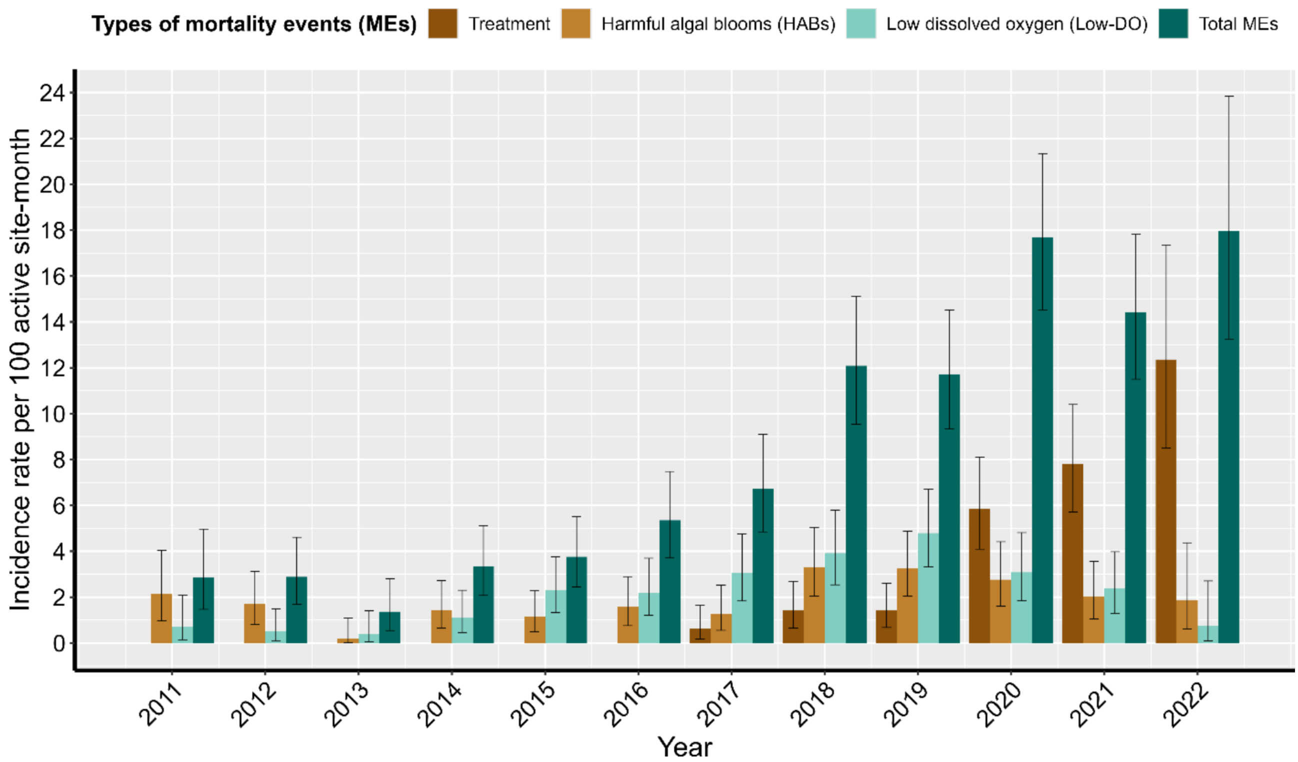

Fig. 2. Incidence rates of mortality events (MEs) related to treatment, harmful algal blooms (HABs), and low dissolved oxygen (low-DO), as well as total MEs, across farmed Atlantic salmon (*Salmo salar*) sites in British Columbia (BC) from June 2011 to June 2022.

Treatment types (+ contributing factors)	Frequency
Mechanical removal (sea lice treatment)	**68**
Mechanical removal treatment	58
Mechanical removal treatment (Poor gill health)	8
Mechanical removal treatment (Toxin exposure)	1
Mechanical removal treatment (Salmonid rickettsial septicemia)	1
Medicinal bath (sea lice treatment)	**55**
Medicinal bath treatment	34
Medicinal bath treatment (Poor gill health)	15
Medicinal bath treatment (Winter Ulcer)	3
Medicinal bath treatment (Winter Ulcer and Poor gill health)	2
Medicinal bath treatment (Poor gill health and Skin ulceration)	1
Non-medicinal bath (sea lice treatment)	**11**
Non-medicinal bath treatment	10
Non-medicinal bath treatment (Mouth rot)	1
Poor gill health	**1**
Others	**3**

Table 2. Mortality events (MEs) related to treatment ($n = 138$), categorized by type, reported by farmed Atlantic salmon (*Salmo salar*) sites in British Columbia (BC) from June 2011- June 2022.

Trend analysis

The trend analysis revealed significant monotonic trends in the monthly incidence of MEs associated with treatment (Kendall's tau = 0.554, p-value < 0.001), highlighting an increasing scope of treatment-related MEs from 2017 to 2022 (Fig. 4). The trendline for MEs related to Low-DO displayed an upward pattern until 2019, followed by a decline. A fluctuating trendline was observed for MEs related to HABs, with alternating periods of increase and decrease. However, the trendline statistics for Low-DO and HAB-related MEs were non-significant.

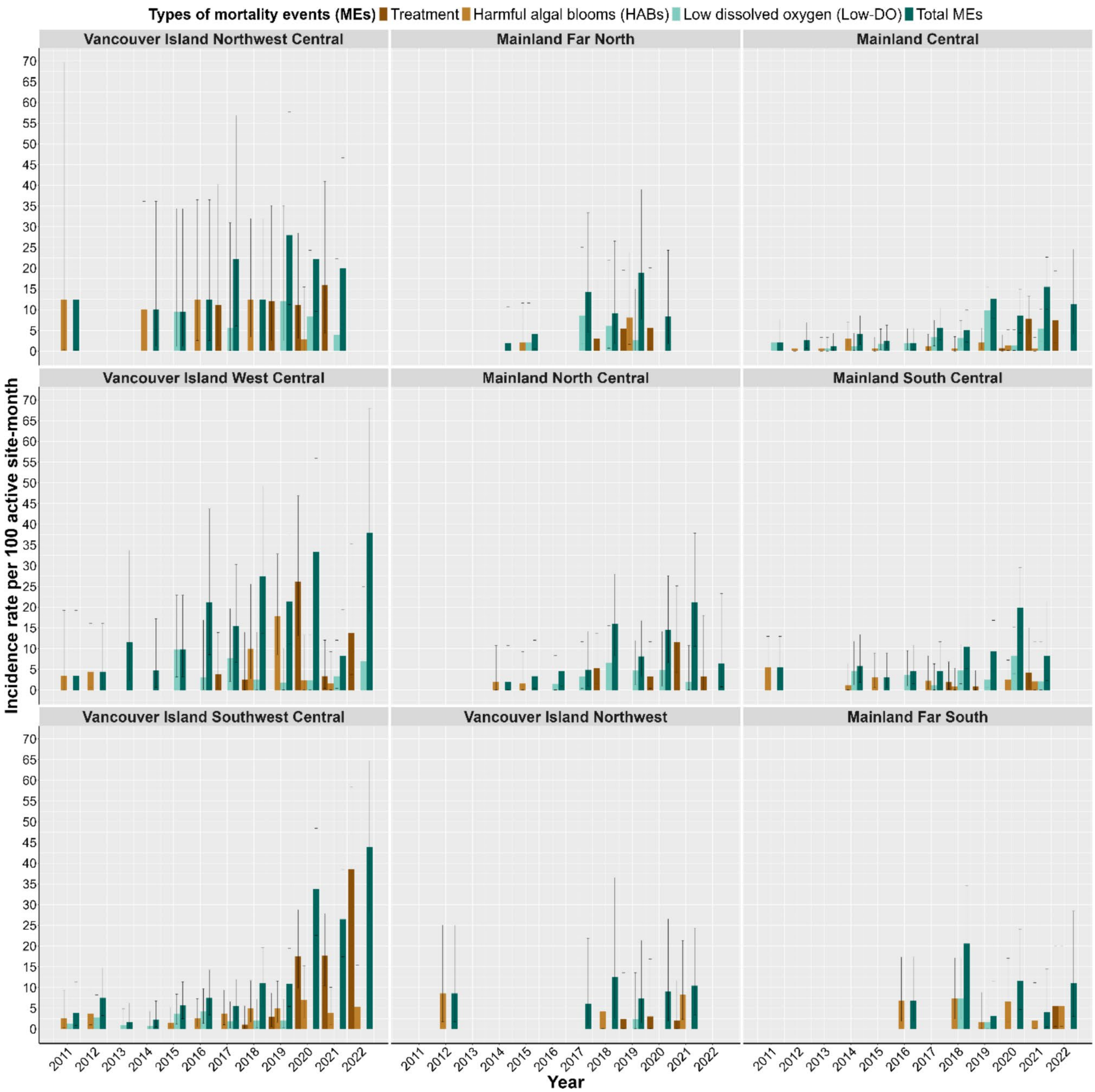

Fig. 3. Yearly incidence rates of mortality events (MEs) related to treatment, harmful algal blooms (HABs), and low dissolved oxygen (low-DO), as well as total MEs across the Aquaculture Management Units (AMUs) reported by farmed Atlantic salmon (*Salmo salar*) sites in British Columbia (BC) from June 2011- June 2022.

For total MEs, a significant and increasing monotonic trend was observed (Kendall's tau = 0.451, p-value < 0.001), indicating a rising incidence rate of overall MEs during the study period. Since treatment accounted for a substantial portion of total MEs, particularly after 2020, we also evaluated the trend of total MEs excluding those associated with treatment. Even after excluding treatment-related MEs, the trend remained statistically significant but was weakly positive (Kendall's tau = 0.277, p-value < 0.001) (Supplementary Figure S1).

Spatial and spatio-temporal cluster analysis

Low dissolved oxygen (low-DO)-related mortality events (MEs)

Two significant spatial clusters of low-DO-related MEs were detected. Both clusters were small and limited to one or two sites (Fig. 5). The clusters were identified around the sites of Mainland South Central (S1-LDO) and Mainland Central (S2-LDO) regions.

Unlike the small space clusters, two large clusters (ST1-LDO and ST2-LDO) were detected with the space-time cluster analysis (Fig. 5; Table 3). The primary cluster (ST1-LDO) was detected in the Mainland Central

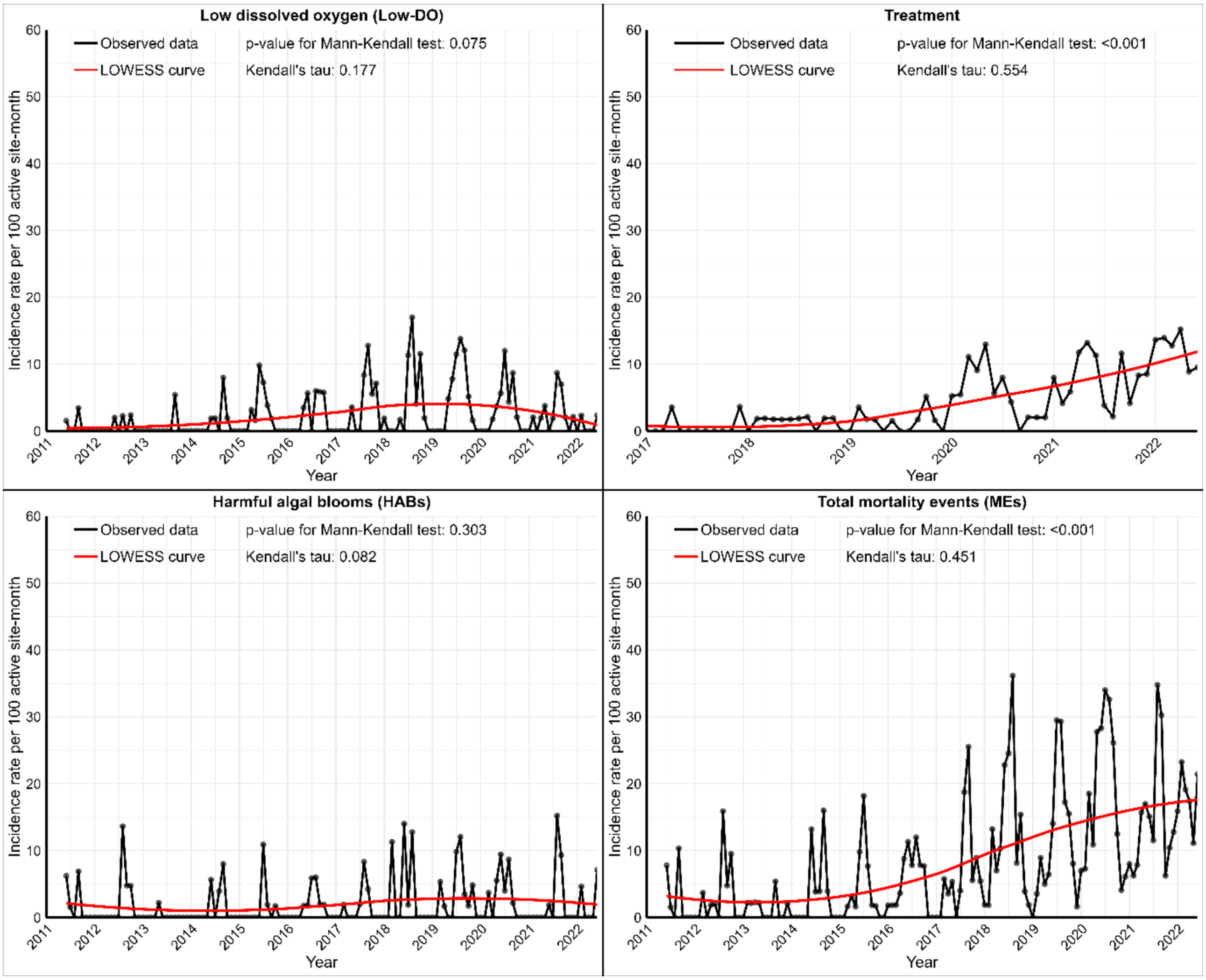

Fig. 4. Monthly trends in the incidence rates of the three most frequent mortality events (MEs) and total MEs. Each panel represents an individual category, with low dissolved oxygen (low-DO)-related MEs, harmful algal blooms (HABs)-related MEs, and total MEs analyzed from June 2011 to June 2022, while treatment-related MEs analyzed from January 2017 to June 2022. Panels are annotated with Kendall's tau values and corresponding p-values from the Mann-Kendall test.

region between July and September, while the secondary cluster (ST2-LDO) was identified in Vancouver Island Northwest Central, Vancouver Island West Central, and Vancouver Island Southwest Central regions between May and July.

Treatment-related mortality events (MEs)

A single space cluster (S-Treatment) was detected in the regions of Vancouver Island Northwest Central, Vancouver Island West Central, and Vancouver Island Southwest Central (Fig. 6).

Likewise, when the temporal component was added to the analysis, the spatial location of the cluster changed slightly from the spatial cluster. The space-time cluster (ST-Treatment) included sites of Vancouver Island West Central and Vancouver Island Southwest Central regions and was detected between the months of January and May (Table 3; Fig. 6).

Harmful Algal blooms (HABs)-related mortality events (MEs)

The spatial cluster analysis revealed one significant cluster of HABs (Fig. 7; Table 3). The identified cluster (S-HABs) encircled all the sites of Vancouver Island Northwest Central, Vancouver Island West Central, and most of the sites of Vancouver Island Southwest Central regions.

The space-time cluster analysis revealed two significant HABs cluster (ST1-HABs and ST2-HABs) (Fig. 7). The primary cluster (ST1-HABs) included sites from Vancouver Island Northwest Central, Vancouver Island West Central, and Vancouver Island Southwest Central regions (similar to the space cluster) and was identified between the months of June and September (Fig. 7; Table 3). The secondary cluster, ST2-HABs, was identified in Mainland South Central and Mainland Far South between the months of June and August.

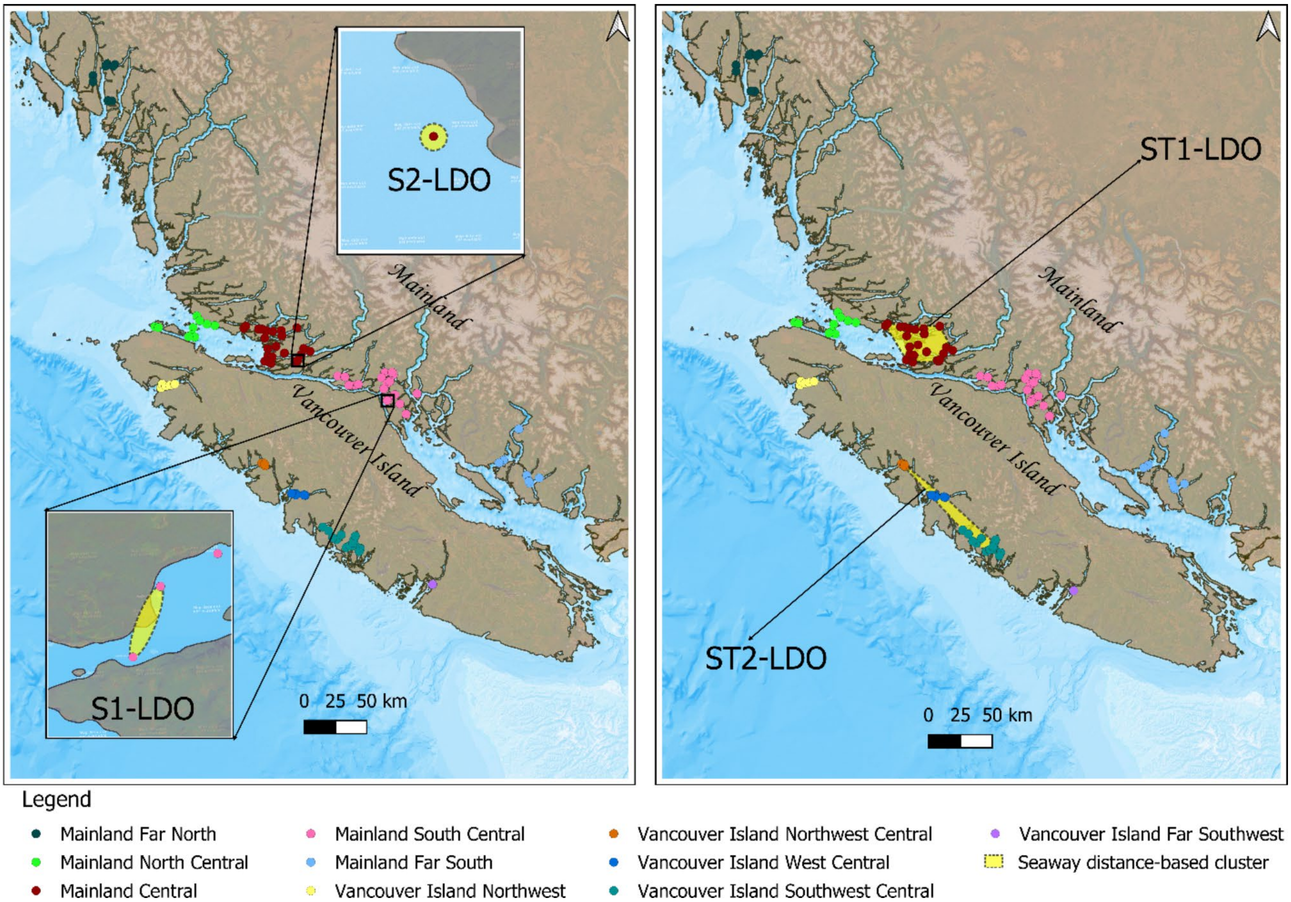

Fig. 5. Space (left) and space-time (right) clusters of mortality events (MEs) related to low dissolved oxygen (low-DO) across farmed Atlantic salmon (*Salmo salar*) sites in British Columbia (BC) from June 2011 to June 2022. In the graph, S1-LDO and S2-LDO represent space clusters, while ST1-LDO and ST2-LDO are space-time cluster. The map was created using QGIS software version 3.30.1 with data on salmon sites obtained from Fisheries and Oceans Canada (DFO).

Types of mortality events (MEs)	Cluster type	Reference Figure number	Cluster ID	Observed number of cases	Expected number of cases	Time frame	Relative risk (RR)	Log likelihood ratio (LLR)	P-value
Low dissolved oxygen (low-DO)-related MEs	Space	5	S1-LDO	16	5		3.45	8.31	0.006
			S2-LDO	6	0.93		6.68	6.55	0.042
	Space-time	5	ST1-LDO	37	10.21	July-September	4.43	24.33	< 0.001
			ST2-LDO	27	10.57	May-July	2.87	10.16	0.03
Treatment-related MEs	Space	6	S-Treatment	81	34.38		4.28	36.2	< 0.001
	Space-time	6	ST-Treatment	58	14.03	January-May	6.41	48.87	< 0.001
Harmful algal blooms (HABs)-related MEs	Space	7	S-HABs	64	33.14		2.8	16.99	< 0.001
	Space-time	7	ST1-HABs	45	10.5	June-September	5.97	37.61	< 0.001
			ST2-HABs	28	7.78	June-August	4.3	17.91	< 0.001
Total MEs	Space	8	S-Total	236	139.77		2.19	43.26	< 0.001
	Space-time	8	ST1-Total	156	71.62	March-August	2.63	49.95	< 0.001
			ST2-Total	76	33.39	June-September	2.48	24.3	< 0.001
			ST3-Total	43	20.73	July-September	2.16	10.7	0.016

Table 3. Description of space and space-time clusters of mortality events (MEs) related to treatment, harmful algal blooms (HABs), and low dissolved oxygen (low-DO), as well as total MEs reported by farmed Atlantic salmon (*Salmo salar*) sites in British Columbia (BC) from June 2011- June 2022.

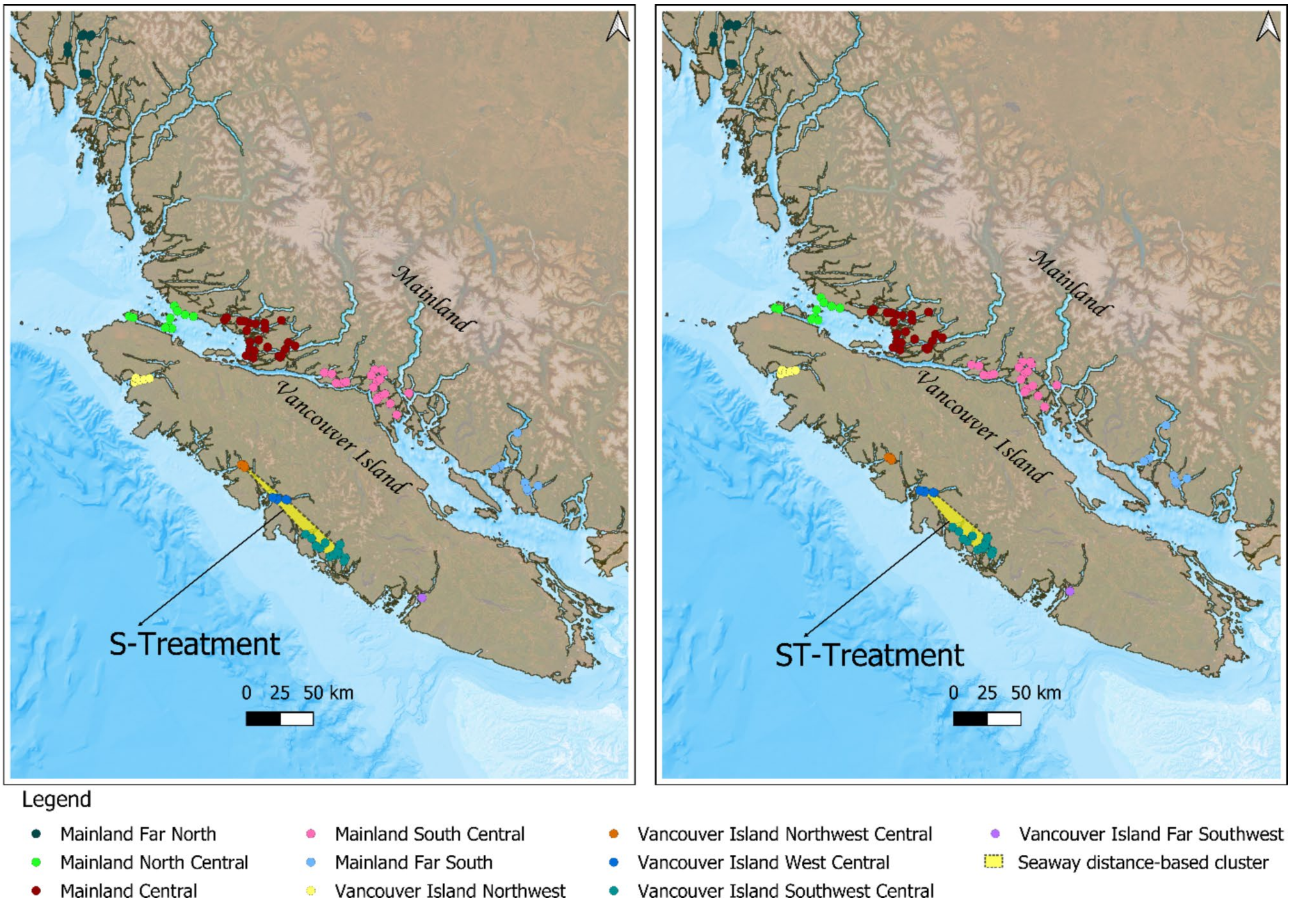

Fig. 6. Space (left) and space-time (right) of mortality events (MEs) related to treatment across farmed Atlantic salmon (*Salmo salar*) sites in British Columbia (BC) from June 2011 to June 2022. In the graph, S-Treatment represents the space cluster, and ST-Treatment represents the space-time cluster. The map was created using QGIS software version 3.30.1 with data on salmon sites obtained from Fisheries and Oceans Canada (DFO).

Total mortality events (MEs)

Spatial cluster analysis revealed a single significant cluster (S-Total) of the total MEs. The cluster was detected in Vancouver Island Northwest Central, Vancouver Island West Central, and Vancouver Island Southwest Central regions (Fig. 8).

The space-time cluster analysis of the total MEs identified three clusters at different times of the year (Fig. 8; Table 3). The primary cluster (ST1-Total) was identified in the Vancouver Island Northwest Central, Vancouver Island West Central, and Vancouver Island Southwest Central from March to August. The secondary cluster (ST2-Total) was detected between June and September and included the majority of sites of Mainland South Central and a few sites of Vancouver Island Northwest Central. The tertiary cluster, ST3-Total, was identified between July and September and was primarily identified in the Mainland North Central region but included some sites from the Mainland Central region.

Discussion

Aquaculture holds considerable promise as a sustainable solution to meet the rising global demand for healthy and nutritious food in the face of a growing human population[49]. However, MEs pose a challenge due to the associated economic burden with negative consequences on the environment, animal welfare, and the overall sustainability of aquaculture. Climate change, water pollution, the evolution of pathogens, and, at times, fish farming practices and disease management strategies have directly or indirectly impacted the global salmon aquaculture sector, contributing to fish mortality[3,50]. The factors associated with MEs might vary across regions and may be influenced by the local environment, managemental practices, and pathogen dynamics. By identifying the root causes of MEs, stakeholders can work to mitigate baseline mortality, enhance fish health and welfare, and implement proactive preventive measures[50].

Dissolved oxygen (DO) concentration in water is a major factor influencing fish wellbeing and development. Therefore, monitoring DO level in the water is crucial since it directly impacts the amount of food that fish consume, their growth, health, welfare, and survival[51,52]. We detected a similarity in the temporal patterns in clusters identified in the Central Mainland and Northwest, West, and Southwest Central regions of Vancouver

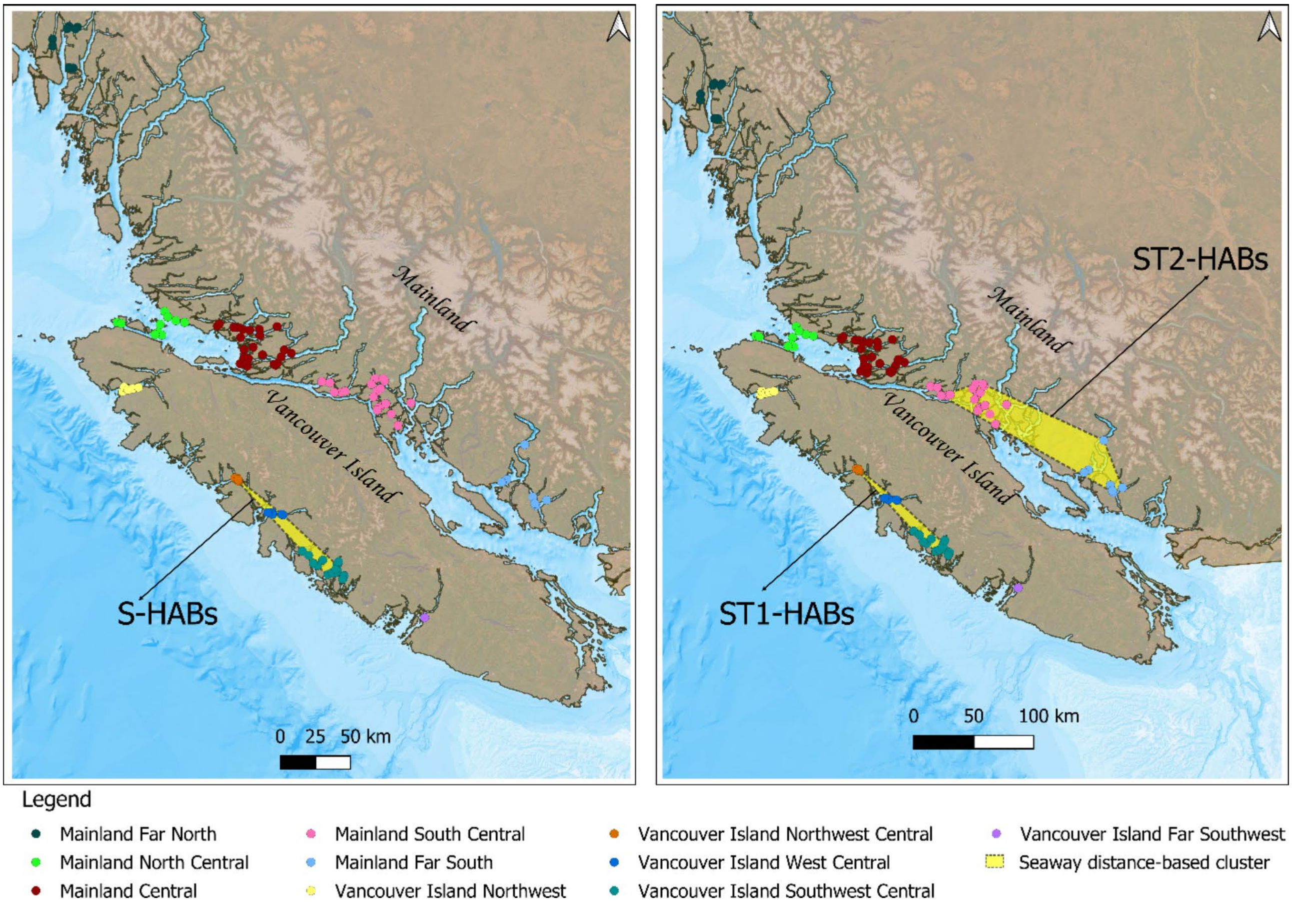

Fig. 7. Space (left) and space-time (right) of mortality events (MEs) related to harmful algal blooms (HABs) across farmed Atlantic salmon (*Salmo salar*) sites in British Columbia (BC) from June 2011 to June 2022. In the graph, S-HABs represents the spatial cluster, while ST1-HABs and ST2-HABs are the space-time clusters. The map was created using QGIS software version 3.30.1 with data on salmon sites obtained from Fisheries and Oceans Canada (DFO).

Island. Both clusters were identified in relatively warmer seasons (from late spring to early fall). Some other studies have identified relatively similar seasonal patterns of low-DO[52,53]. As the water temperature rises in the summer, oxygen solubility in seawater drops[54,55]. Also, when a water body's surface layer warms up, thermal stratification occurs, preventing oxygen-rich surface waters from mixing with deeper layers, leading to low dissolved oxygen levels in those deeper waters[56,57]. Furthermore, periodic water warming during marine heat waves has been shown to decrease the dissolved oxygen concentration in BC[13,58,59]. The Marine heat waves recorded in 2014–2016, 2018, and 2020[13] , with waters in the Salish Sea experiencing warming beyond the initial heatwave years[60], could be one of the factors contributing to low-DO-related mortalities in BC. Some research has shown that the oxygen requirements for Atlantic salmon increase with increasing water temperature due to increased metabolic rates[61,62], making the situation even worse in warmer weather. Furthermore, the concentration of Chlorophyll-a (chl-a) produced by phytoplankton is a significant factor that influences the level of DO in marine water[53,63]. Even though increasing chlorophyll-a raises the concentration of oxygen during the day, it has the opposite effect at night[64]. While the seasonality of phytoplankton varies depending on location, research in BC's coastal regions found that, on average, the west coast of Vancouver Island experiences its highest concentration of chlorophyll at the beginning of July, while the strait of Georgia experiences it around the beginning of May[65]. Also, climate change over a long period has influenced the population dynamics of these phytoplanktons, which could also have influenced the DO concentration in marine waters[66,67]. Hence, chlorophyll-a concentration may also have affected the seasonal pattern of low-DO-related MEs.

The treatment of sea lice alone accounted for around 74% of the treatment-related MEs, with the remaining coming from the combination of sea lice treatment and other contributing factors. BC salmon farmers use four major types of treatment to control sea lice: in-feed treatment, mechanical removal treatment, medicinal bath treatment, and non-medicinal bath treatment. Except for in-feed treatment, all other sea lice treatments involve fish handling and have triggered the threshold of MEs. In British Columbia, treatment-attributed mortality was first reported in 2017. Since then, it has been increasing at an alarming rate, becoming the leading cause of MEs by 2022. Most treatment-related mortalities (77.54%) involved second-year fish (larger fish), and the ME reporting threshold, defined by the weight, may have contributed to the increased reporting of treatment-related

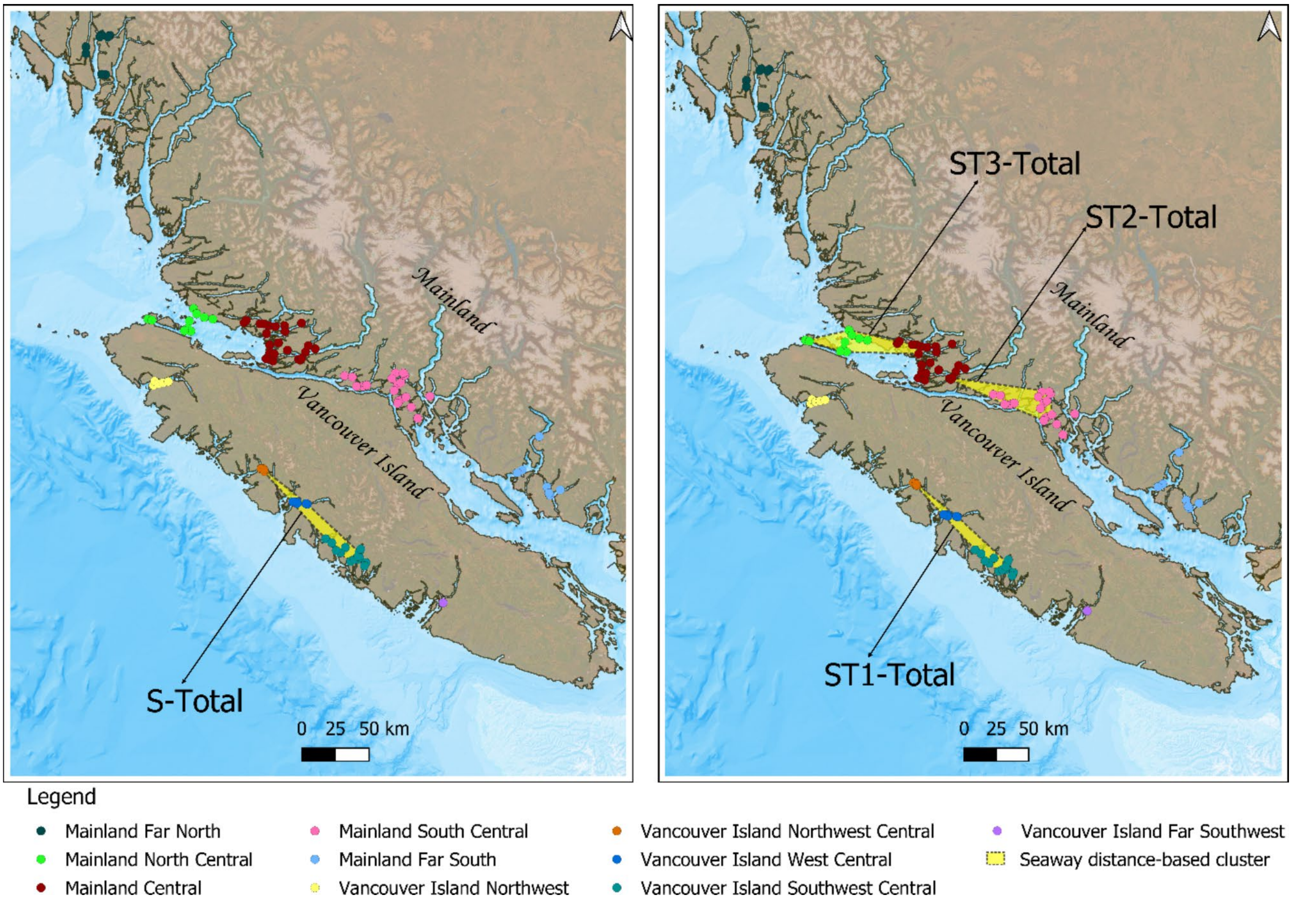

Fig. 8. Space (left) and space-time (right) of total mortality events (MEs) across farmed Atlantic salmon (*Salmo salar*) sites in British Columbia (BC) from June 2011 to June 2022. In the graph, S-Total represents the spatial cluster, while ST1-Total, ST2-Total, and ST3-Total are the space-time clusters. The map was created using QGIS software version 3.30.1 with data on salmon sites obtained from Fisheries and Oceans Canada (DFO).

MEs. The strict regulations from DFO to control sea lice in the pre-migration (February) and out-migration window (March- June) may likely be responsible for the seasonal pattern of mortalities from treatment[9]. In British Columbia, mechanical sea lice removal treatment only started in 2018, whereas medicinal and non-medicinal bath treatment began in 2014 and 2015, respectively[68]. The treatment-attributed MEs have been more pronounced since 2020, which may be due to the result of the introduction of stricter DFO regulations in 2020, which include a 42-day timeline to reduce motile sea lice count below three after the event, the establishment of a premigration window in February, and stricter sampling and reporting requirements[69]. In recent years, there has been a rapid shift in sea lice management strategies on the west coast of Canada, with an increasing focus on treatments that involve fish handling. In British Columbia (BC), an Integrated Pest Management (IPM) approach is applied, where Atlantic salmon aquaculture companies rotate between in-feed medication, mechanical removal, and medicinal and non-medicinal bath treatment[68]. This strategy aims to prevent the development of resistance in sea lice populations while maintaining effective control measures. The availability of numerous treatment methods in recent years has expanded the scope of the IPM approach and has allowed companies to use appropriate tools for different situations. Similar to Canada, Norway has also experienced a shift in treatment strategies in recent years, with an increased emphasis on mechanical treatments over the use of chemotherapeutants[22]. The environmental impact of chemotherapeutants used for sea lice management, coupled with evidence of progressive sea lice resistance to these treatments in several salmon-producing countries such as Norway[70,71], Chile[72,73], Scotland[74,75], and Eastern Canada[76,77], are among the key factors driving the shift toward mechanical treatments. Mechanical and bath treatments for sea lice in farmed Atlantic salmon are anecdotally known to be associated with high mortality. However, our findings provide the first empirical evidence of the increased risk of sea lice treatment-related MEs from BC.

MEs related to HABs were reported from almost all the AMUs in BC. Previous studies have documented the recurring events of HABs throughout the Pacific coastal regions[78,79]. However, the sites on the Northwest, West, and Southwest Central coasts of Vancouver Island were identified to be at higher risk of having HABs-related MEs. The evidence of a large mass of relatively warmer water on the off-coast of the North Pacific Ocean at different times between 2011 and 2022 was found to favor the bloom of harmful algae[80–82]. The impacts of HABs on aquaculture have increased over the past several decades in correlation with climate change[83,84] and other non-climatic factors like water quality degradation, precipitation and nutrient runoff from land, and increasing aquaculture operations[85–88]. From 2009 to 2012, the salmon aquaculture industry in British Columbia incurred an estimated 16.14 million CAD in direct losses due to HAB-related mortality events, with additional annual losses of 4 to 8 million CAD from production declines and bloom mitigation efforts[89]. The space-time analysis detected clusters during summer and early fall months, suggesting that warmer months favor the growth of harmful HABs. However, some algal taxa also have optimum growth at lower temperatures[85]. Interestingly, we observed a similar pattern in the annual occurrence of low-DO and HABs-related mortality, with both MEs showing an increasing pattern starting in 2014, peaking in 2019, and declining in the subsequent years. Increasing water temperature is likely a common link between these events, which favors the growth of most HAB species[80] and decreases DO concentrations[54,55] in net pens. Additionally, the decay of HABs has been shown to significantly deplete DO concentrations[90]. Applying an accurate forecasting model to identify the occurrences of marine heat waves could support the implementation of management strategies such as reducing fish densities, using aerators or oxygenation systems, minimizing feed waste (to prevent HABs), fallowing, and other emergency response plans.

One limitation of the dataset we used in our study was related to the definition of MEs. In our study, all the MEs were more prevalent among second-year class fish (larger fish). Before June 30, 2022, mortalities involving 4,000 kg of biomass, or 2% of the stock inventory, reported within 24 h were considered as MEs. Additionally, mortalities of 10,000 kg or more, or losses equal to 5% of the stock inventory over a 5-day period, were also classified as MEs. Under these criteria, larger fish were more likely to exceed the weight-based threshold than smaller ones. Utilizing such absolute measures may have led to the overreporting of events involving larger fish. Additionally, the dataset lacked information on mortality counts and biomass at the site level, which prevented us from determining whether the weight-based or number-based threshold for a mortality event had been triggered, as well as the scale and severity of the events.

Overall, for all the events discussed above, the sites in the Northwest, West, and Southwest Central coasts of Vancouver Island were found to be at higher risk of experiencing MEs compared to the sites of other AMUs. The exposure of these sites to the open Pacific Ocean, with its fluctuating water temperatures, ocean currents, and varying precipitation, may be one of the reasons for the higher incidence of MEs in these areas. Salmon production sites in these regions had higher risks of reporting MEs during Spring and summer, suggesting that warmer months increase the vulnerability of farmed fish. The complex relationship between temperature, HABs, low-DO, and marine heatwaves and their detrimental effects on fish survivability, particularly during summer, has been documented in countries such as Norway, Chile, Australia, and others[17,91–94]. The increased mortality rates in BC are primarily attributed to low-DO, HABs, and sea lice treatments that involve fish handling. Environmental factors like HABs are associated with salmon mortalities in other salmon-producing countries like Chile[95]. Likewise, sea lice treatments involving fish handling are becoming a leading cause of fish mortality in both BC and Norway[17,22].

Besides the major MEs, there are other events that contributed to the total MEs. Among these, infectious diseases and non-infectious diseases are the most notable. They constituted only a small proportion of total mortality events, suggesting that disease management is effective across aquaculture sites in BC. Additionally, mechanical factors related to fish transport and handling accounted for 9.45% of the total MEs, 86.79% ($n=46/53$) of which are associated with fish handling. These handling events differ from treatment-related fish handling and are related to harvesting, net pen cleaning, and other farm activities. Water quality and jellyfish are other environmental factors contributing to a small portion (5.35%) of the total MEs. Nearly 89% ($n=8/9$) of jellyfish-related MEs were reported from Vancouver Island's Southwest Central coasts, suggesting that the abundance of jellyfish in this region could be different from others. Jellyfish contact causes direct traumatic damage to gill tissues, impairs their function, and predisposes fish to secondary infection[96].

Conclusion

The total number of MEs in BC has been increasing significantly, particularly since 2013. The Northwest, West, and Southwest Central coasts of Vancouver Island were at increased risk of reporting MEs compared to AMUs in the Mainland and northern parts of Vancouver Island. Low-DO, sea lice treatment, and HABs were the primary drivers of these MEs. The effects of climate change and marine heatwaves are likely contributing to increasing salmon mortalities in Canada and other salmon-producing countries. In recent years, sea lice treatments involving fish handling have become the leading cause of MEs in salmon aquaculture in BC, Canada. This highlights the urgent need for adaptive sea lice management strategies to effectively control sea lice while minimizing treatment-related MEs. In contrast, infectious and non-infectious disease-related MEs were minimal, suggesting that disease management is effective across salmon aquaculture sites in BC. This study provides essential insights into the spatial and temporal variation of MEs, which can be crucial in applying targeted intervention strategies to reduce the burden of mortality loss. Additionally, our study demonstrates the value of publicly available data for research to identify gaps and provide empirical evidence for policymakers. Finally, we suggest that future studies should explore the potential underlying factors associated with the clustering of mortality events in space and time in BC.

Data availability

All the data used in this study are publicly available on the Open Government Portal of Canada (https://search.open.canada.ca/data).

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Author contributions

K.K.T. conceptualized the study. S.J. conducted the analysis and wrote the original draft. S.J., B.J., S.S., H.S., D.P., C.W.R., and K.K.R. reviewed and edited the manuscript. K.K.T. and B.J. managed the funding and supervised the study.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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