Received: 5 October 2022 | Revised: 15 February 2023 | Accepted: 5 March 2023
DOI: 10.1111/raq.12811

REVIEW

REVIEWS IN Aquaculture

A global review of protected species interactions with marine aquaculture

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Abstract

As marine aquaculture expands around the world, there is increased concern for impacts to protected species. Documented cases of marine mammal, sea turtle, seabird, and shark interactions with aquaculture installations do exist but are challenging to find. This extensive review summarises the state of knowledge of protected species interactions with marine fish and shellfish aquaculture installations. Although seaweed aquaculture was beyond the scope of this review, some of the findings for shellfish and finfish aquaculture may be relevant. The potential impacts of farms including habitat exclusion, entanglement, entrapment, collisions, and behavioural modifications are the primary risks posed to protected species by marine aquaculture facilities and operations. In addition, indirect effects from habitat impacts of farm operations may be of concern in some areas as well as the cumulative impacts of multiple small or large farms in the same general vicinity. Decades of farm innovations and best management practices have been driven by industry, natural resource managers, conservation organisations, and international conservation agreements. This review is useful for informing industry planning and permitting to develop aquaculture in the open ocean. This work will help advance the science of conservation by synthesising the state of knowledge and provide managers and industry with more insight to protect the most vulnerable species.

KEYWORDS
aquaculture interactions, marine cage, marine mammals, mussel longline, protected species, sea turtles

1 | INTRODUCTION

The increasing demand for seafood and marine aquaculture technological innovations of the last three decades provide an opportunity to increase global production of protein-rich, nutritious seafood in the ocean.[1–5] A study by the United Nations Food and Agriculture Organization (FAO) identified significant marine aquaculture growth potential with high opportunity for farming within exclusive economic zones.[1] In addition, increased seafood production can benefit from vast coastlines that span from polar to tropical climates with suitable depths, current speeds, and temperatures; mature gear technologies; a diverse number of feed alternatives[6]; access to ports; a stable legal and economic system; skilled labour; and substantial seafood market demand.[1–4,7]

To assess the potential effects aquaculture activities could have on protected species, regulatory authorities rely on the best available scientific information, which includes but is not limited to peer-reviewed scientific data and publications. Herein, we summarise historical records of protected species interactions with marine aquaculture operations globally. Many new data are presented and together represent the most comprehensive review of documented interactions to inform resource conservation and risk assessment associated with marine aquaculture development. This information will be valuable as a starting place for coastal managers conducting environmental review of marine aquaculture or in their role providing technical advice or consultations on aquaculture activities that might impact endangered and threatened species, marine mammals, and important marine habitats. This review summarises the current state of knowledge regarding documented interactions of marine mammals, sea turtles, seabirds, and sharks with aquaculture farms worldwide.

Over the past 30 years, protected species interactions with aquaculture have been documented in a wide variety of literature including government agency documents, non-governmental reports, journal publications, and books. Our review included scientific papers; government reports and databases; industry organisation documents; company sustainability and investor reports; certification program requirements, published data, and reports; newspaper articles and press releases; operational commercial farms; regional fishery management organisations; stranding and entanglement response organisations; and international commissions and conventions. Keyword searches were also conducted using common scientific literature databases including Web of Science, ProQuest Aquatic Science Fisheries Abstracts, Elsevier Science Direct, JSTOR, and Google Scholar. Early reviewers and colleagues also provided relevant publication recommendations. Professional contacts from aquaculture farms supplied unpublished data. The reviewed documents originated from research conducted globally, cover a range of cultured species, include many new and practical farm management approaches, and address ecological processes at multiple scales. Less accessible documents or sources may have been missed due to limits on information sharing, language barriers, or policy relevance. Noteworthy is that all countries do not have the same protections for these species, reporting incidents is therefore not required in all countries; thus, significant data gaps were expected.

There are no conventions for delineating coastal and offshore marine aquaculture.[8–13] Generally, coastal farms are visible from the shoreline, moored at shallower depths, typically between 10 and 50 m, and may experience significant wave exposure. Coastal farms include operations found in large embayments like lochs and fjords, and provide some protection from open ocean conditions. We considered offshore farms to include aquaculture operations beyond 3 miles from shore. Many offshore farm sites are located at water depths greater than 40 m, and are more exposed and subject to ocean swells, strong winds, and strong ocean currents with significant wave heights up to 3–4 m. These farms are generally large-scale commercial enterprises requiring significant capital investment due to the technology costs.

Aquaculture farm design and engineering have advanced the capability to withstand dynamic offshore environments and increase production capacity.[2,3,12,14–17] Offshore, open ocean waters provide space for aquaculture expansion, increased protein production, reduced social conflict, and lower exposure to terrestrial sourced pollution.[2,18–20] The water depth, currents, and ocean circulation provide optimal environmental conditions for growing diverse marine species and the potential to reduce some of the negative environmental impacts of coastal fish farming.[2,9,21–25] In this review, many of the animal encounter reports took place in traditional coastal farms. The risk of the same type of interactions should be considered as aquaculture development moves offshore. And while some environmental concerns are alleviated, the challenge of monitoring farms for protected species interactions may be compounded because of the remoteness of offshore farming.

2 | MARINE AQUACULTURE GEAR

2.1 | Longline mussel aquaculture

Coastal and offshore mollusc aquaculture production is predominately mussels (Mytilidae), sea scallops (Pectinidae) and oysters (*Crassostrea* spp.).[5] Globally, the primary cultivation species are mussels, of which 40% of modern world mussel production occurs in China.[5] Other significant mussel producers include Canada, Chile, New Zealand, Spain, France, and Italy. Farmed mussel culture operations employ different technologies depending on the location in intertidal, shallow subtidal environments, or waters deeper than 20 m. As mussel aquaculture expands away from user conflicts and some environmental concerns inshore to more exposed offshore, high-energy environments, submerged high-tension longline designs are superior (Figure 1).[27–32] Mussel farms employ both floating and submerged configurations depending on the physical environment conditions (Figure 1). Coastal and offshore commercial scale longline mussel farms deploy both spat (shellfish larvae) collection and grow-out ropes in multiple backbone lines arrayed in parallel rows with individual lines (droppers) vertically suspended or a long continuous looped line.[33] Single droppers are 3- to 10-m long.[33,34] Continuous droppers are up to 10-m long and are looped at intervals along the mainline. Collectively, the culture rope may be up to 5-km long at a single farm.[30,33–36] In an exercise to quantify the cumulative length of lines in a Prince Edward Island embayment, McKindsey et al.[37] estimated the total backlines to be over 500 km and socking material and product to be 2250 km within a 7 km^2 area.

Mussel longline configurations are supported by a set of floats and secured by mooring lines.[29,34,35,38,39] The longlines are typically 150–300 m in length with arrays spaced 10–20 m apart and the configuration anchored 5–20 m below the surface by two or four mooring lines and suspended by two corner floats.[30,32,40] Vertical lines tether mussel longline arrays to the seafloor using screw anchors, deadweight anchors, or hydraulic expansion anchors.[29,34,35] Longlines and anchor lines may be made of durable synthetic line with diameters approximating 36 mm.[23,38] Vertical lines connected to anchors and horizontal longline orientations are maintained in the water column by buoys, which prevent the lines from becoming entangled. To alert traversing vessels, radar-reflecting surface buoys are attached to the end of each longline. Additional floats added along the longline compensate for their weight and maintain the longline geometry.[35] Submerged longlines are deep enough (5–20 m) to avoid interaction with navigation. Mussel farm infrastructure components that pose potential risk for entanglement and injury include anchor lines, horizontal backbone longlines, vertically suspended and looped grow lines, suspended nets, and surface buoy marker lines.[26] The slack

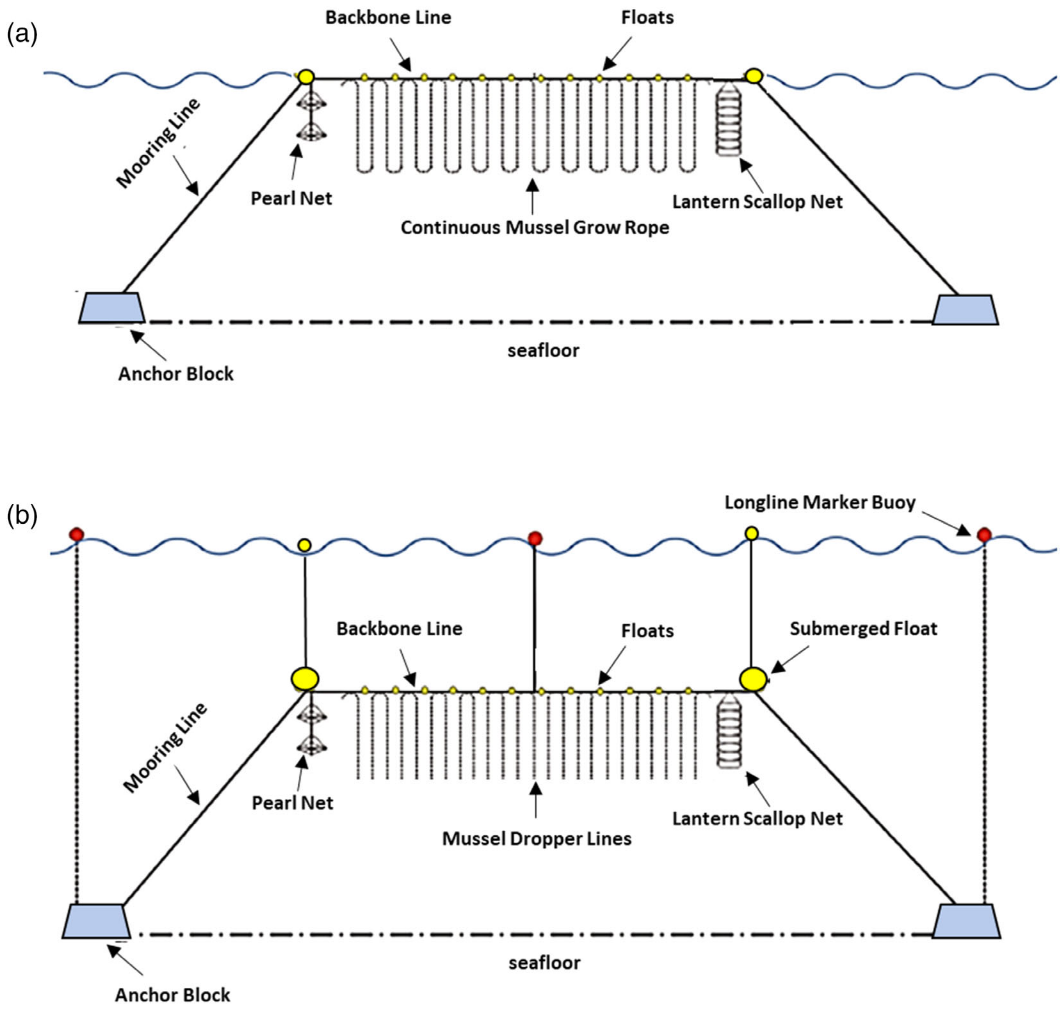

FIGURE 1 Representative schematics of surface (a) and submerged (b) offshore longline systems used for suspension culture of mussels, pearl oysters, and scallops. View (a) shows a single looped grow rope configuration. View (b) shows individual dropper lines suspended from the backbone.[26]

spat-collecting lines, grow-out lines, and surface marker buoy lines have specifically been implicated in documented entanglement cases.[36,41–43]

2.2 | Finfish aquaculture

Technological innovation continues to expand opportunities for marine finfish aquaculture farms to move further offshore with rigid or flexible frames capable of floating or being submerged below the surface.[9,11,13,44–46] Floating rigid frames (Figure 2a) are made of large rubber and high-density polyethylene collar cages.[9,11,46–48] Square steel cage systems (Figure 2b) provide a rigid platform and infrastructure from which holding pens (nets) can be aligned in any configuration and are secured by one mooring line each.[47] Submersible cage systems, such as the SeaStation (Figure 2c) and futuristic geodesic designs (Figure 2d) are engineered to withstand the harsh, high-energy conditions of the open ocean.[16,17,31] Pen diameters can range from around less than 10 m up to 100 m (up to 200 m for tuna ranching) depending on the production goals of the farm and the site requirements. Cages can be lowered and raised in the water column by mechanical systems or air compressors.

A traditional open cage comprises a cylindrical net with bottom weights to spread the bag, jumping net fixed above the net bag to prevent fish escapes, cage collar for net bag spread and buoyancy to keep the bag in the correct water column position, and a mooring system.[11,17] Finfish cages and antipredator netting are made of rigid, synthetic materials engineered to tolerate ocean conditions for several years.[11,13,17,48] Net used in cage aquaculture are most commonly made with nylon. Rigid polyethylene terephthalate (PET), copper, and stainless steel mesh are also used. Compared with nylon, these relatively inflexible materials maintain cage structure better in heavy currents.[11,46,49] Weights or heavy bottom ring/sinker tubes at the bottom of the net bag help maintain their shape[45] but also increase the dynamic forces from waves (stretch and slack) acting on the net bag.[11,13,17,50,51] To prevent bowing or folding in currents, antipredator nets are stretched taut and are deployed with space between them and the fish containment cages. Tensioned deployment reduces entanglement risk and prevents predators from biting or pushing into

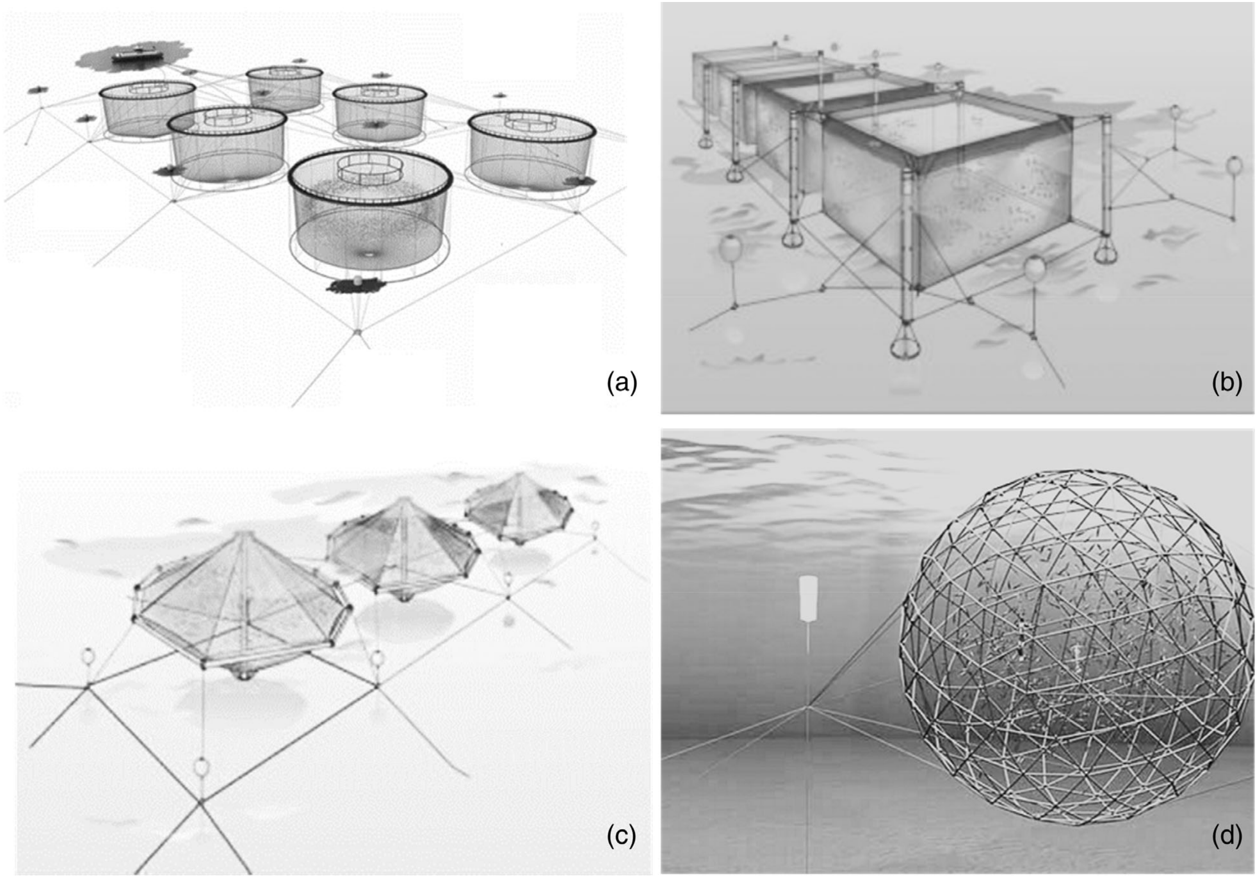

FIGURE 2 Examples of marine cages for finfish production. (a) Floating surface cage system, (b) square steel cage system, (c) submersible cage system, and (d) the submersible geodesic cage.[16,17,31,47]

nets to access fish. Depending on the target species for exclusion, antipredator mesh sizes range from 3.8 to 20.0 cm (bar length).[11,26,48]

Offshore finfish aquaculture infrastructures employ anchoring systems similar to those found in mussel farms.[29] Ropes are used for both the mooring lines and grid system lines and are most commonly made of polysteel with a tensile strength more than 25% higher than polypropylene. Polyester or nylon ropes are also used; however, they stretch when placed under load, which can compromise the mooring grid.[11] Cages are tethered in arrays by bridling systems on a farm site (Figure 3) and often secured by orthogonal moorings. In many cases, double anchors and more durable lines require sufficient flexibility to ensure that wind and water forces on net structures do not fully stretch the lines and generate a full load.[11,14,46,52] For some cages (typically submersibles), single point mooring systems are designed with each cage anchored individually with a single line. The cage can rotate in an arc defined by the length of the mooring line. In deep water, a single mooring and anchor line may be attached to several aquaculture cages. Cage locations and farm boundaries are marked with navigational surface buoys[11] that could pose a risk for primary or secondary animal entanglements if the lines are slack.

High-performance netting materials are often used in offshore aquaculture environments to contain fish, exclude predators, and prevent predation. Some netting materials and their related hardware pose potential entanglement risk, resulting in injury, stress, or death to marine mammals, sea turtles, birds, and sharks.[25,26,48,53–59] Finfish operations can attract some piscivorous animals because wild fish aggregate to the structural habitat provided by cages or are attracted to excess feed loss from the cages.[25,55,60,61]

3 | PROTECTED SPECIES AND MARINE AQUACULTURE

3.1 | Marine mammals

Marine aquaculture and marine mammal interactions have occurred throughout the world.[26,55,58] Events are documented in Australia and Tasmania,[60] New Zealand,[36,43] United States,[62] Canada,[63] Argentina,[64] Chile,[57,60,65,66] Iceland,[67] Scotland,[68] Norway,[69] Italy,[70] Turkey,[71] and South Korea.[72] Pinnipeds (seals, sea lions, and walruses) and cetaceans (porpoises, dolphins, and whales) are the groups most commonly documented to have direct physical interactions because they are more broadly distributed and must surface to breathe. The primary risks posed to marine mammals by aquaculture facilities and operations are habitat exclusion, entanglement, and behavioural alterations (attraction, avoidance, or food preference).[26,36,43,58,73–75]

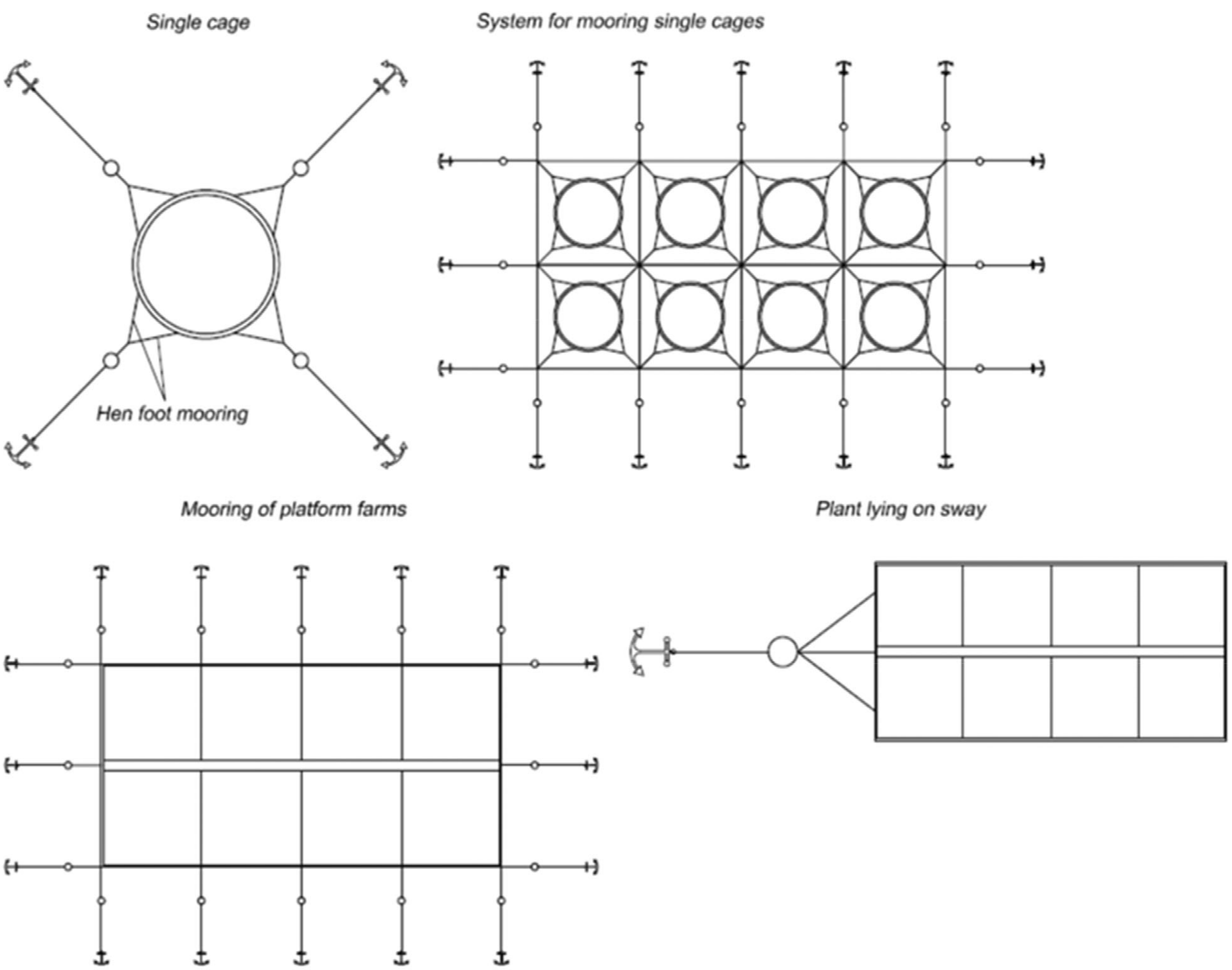

FIGURE 3 Various systems for mooring ocean cages: single point moorings for individual cages, multi-cage grid systems commonly used for nearshore cages and platform farms, tension leg moorings that allow the cage to rotate in an arc typically used for submerged cages. *Source*: Lekang.[17]

3.1.1 | Habitat modification, exclusion, or competition for space

Marine mammals can be excluded from their habitats depending on the size and concentration of farms, farm operations (including vessel traffic), and behaviour of a particular marine mammal species.[43,53,58,60,65,76–78] While some marine mammals may not be spatially excluded from farm areas, limited mobility in the vicinity may result in individuals being forced into suboptimal foraging habitat. Species may alter their behaviour, and be deterred from traversing or feeding if aquaculture structures present a navigation obstacle. Animals may not only avoid the farm, but also the broader area; thus, minimising spatial overlap with home ranges, foraging habitats, critical breeding areas, and migration routes is prudent for farm site selection. In some cases, farm structures may not have a major impact as sited; however, as multiple farms are constructed within an area, cumulative impacts over time to individuals and populations are possible.[79,80] These anthropogenic landscapes can present both risks and benefits for both prey and predators.[81–83] Prey may use structures for safe harbour to escape predators and alternatively, farm structures may aggregate prey and provide novel foraging opportunities.[84]

Mussel farms

Several studies in Admiralty Bay, New Zealand, have focused on potential dolphin habitat exclusion in nearshore waters where mussel farms are located. During 5 years of observations in a bay with numerous mussel farms, dusky dolphin (*Lagenorhynchus obscurus*, Gray 1828) groups entered farms (located <200 m from shore) in only eight of 621 observations.[85] Compared with unfarmed areas in the Bay, the dolphins avoided farm areas and were able to navigate through the lanes between the mussel lines. Coordinated dolphin feeding behaviour appeared limited by the presence of the farms.[85,86] Duprey[84] reported similar findings in the same area; only two of the 332 groups of dusky dolphins observed were inside a mussel farm and of the nine groups of bottlenose dolphins (*Tursiops truncatus*, Montagu 1821) seen, none entered farms. A study of dusky dolphin behaviour similarly found the animals increased foraging behaviour adjacent to the farms but did not enter the farms.[87] Thus, mussel farms may act or be perceived by dolphins as three-dimensional (3D) obstructions that impede navigation and foraging capabilities at and below the surface.

Clement[43] suggested there is a low habitat exclusion risk to marine mammals at both offshore mussel spat collection sites and grow-out operations in New Zealand, which is consistent with earlier reports on environmental impacts of the industry.[42,60,88] Clement[43] cautioned as long as mussel farming expansion does not overlap with breeding, migrating, and feeding habitats of protected species, few negative interactions are expected. Although pinnipeds have been attracted to nearshore mussel farms because they occasionally consume benthic organisms typically associated with mussel farms, including crabs and fish,[89] they do not commonly feed on shellfish and may be less likely to visit offshore mussel farms.[55,62] Kemper et al.[60] evaluated known negative interactions of marine mammals with aquaculture in the southern hemisphere, and found most occur at finfish farms and involve pinnipeds attracted to the gear seeking food.

In southern Chile, both Peale's dolphins (*Lagenorhynchus australis* Peale, 1848) and Chilean dolphins (*Cephalorhynchus eutropia* Gray, 1846) observed in extensively farmed areas (shellfish and finfish) avoided direct interaction with farms.[57,60,65,66] While Peale's dolphins were never observed closer than 100 m to mussel farms, Chilean dolphins were observed feeding on schooling fish adjacent to farms and in open spaces between dense sets of growth lines. Seven Chilean dolphins crossed under shellfish lines and floats; however, the clearance between the lines and seafloor was unknown. In mussel farm areas, Ribeiro et al.[57] reported Chilean dolphins were present with less than 30% coverage of mussel farms but notably absent in areas with greater than 60% coverage. In this region, habitat exclusion due to high density of aquaculture was considered a concern because it restricted essential habitat access.

In Europe, shellfish production is second to Asia[5] and little research has addressed impacts to protected species.[90] In Bantry Bay on the southwest coast of Ireland, Roycroft et al.[89] assessed impacts of mussel culture on common seals (*Phoca vitulina* Linnaeus, 1758). The mussel farms used 15 m vertical grow lines suspended from floating longlines in nearshore, sheltered, deep water (up to 20 m). Seal abundance was the same at sites with and without mussel farms, and no negative interactions were reported. Along the northwestern coast of Spain, mussel farms influence habitat uses and foraging behaviour of bottlenose dolphins.[91,92] The shellfish culture method may impact animals differently due to the gear configurations and materials used. In contrast to longline systems, rafts support mussels grown on ropes tied to rectangular floating platforms. Each individual raft has a maximum of 500 ropes (no longer than 12 m) and covers an area of up to 500 m^2.[93] Over 2 years of consecutive fieldwork, Díaz López and Methion[91] observed increased numbers of bottlenose dolphins at mussel farm locations and in waters surrounding aquaculture zones. They postulated this positive relationship was due to the available high-quality prey from large aggregations of fish around mussel rafts. Their observations were different than previous studies that observed other coastal cetacean species avoiding mussel longline aquaculture zones, which resulted in habitat loss and the possibility of negative population impacts.[55,57,76] Building on this study, Methion and Díaz López[92] investigated the influence of the shellfish aquaculture industry on the specific foraging behaviours of bottlenose dolphins. The mussel rafts provided a physical structure that attracted forage fish species, in comparison to adjacent areas to the farms. Pelagic and demersal fish species aggregated around the rafts for shelter and to feed directly on the line-associated organism communities. Because their prey was concentrated in these farms, the dolphins were able to forage more efficiently by shortening their dive times which increased oxygen intake and gave them the ability to regulate their mode of swimming speed.

Marine finfish farms

Marine mammals can be attracted to the caged fish as well as the presence of wild fish that congregate around fish farms.[25] Off the coast of Italy, bottlenose dolphins were observed feeding on wild fish in the vicinity of marine fish farms, but did not target the caged fish.[94] Bottlenose dolphins are regularly observed foraging near fish farm cages in the northern Mediterranean.[70,73,95–99] Bottlenose dolphins modified their social structure and altered hunting tactics in response to increased prey densities around fish farms.[70,94] In a 5-year study of gilthead sea bream (*Sparus auratus* Linnaeus, 1758), European sea bass (*Dicentrarchus labrax* Linnaeus, 1758), and meagre (*Argyrosomus regius* Asso, 1801) cages off the coast of Italy, Díaz López[73] observed known individual dolphins exhibit habitat use patterns and farm fidelity. Dolphin occurrence near the farm varied with time of day, season, and year. Dolphins near farms typically foraged on wild fish but also fed on discarded or escaped farmed fish during harvesting operations. Ninety-nine observation months over 9 years at these cages, Díaz López[100] witnessed bottlenose dolphins habituating to fish harvesting operations where discarded fish were easy prey. Piroddi et al.[97] suggest bottlenose dolphin abundance increased around fish farms in Greece because the farms facilitated prey capture. Bonizzoni et al.[99] observed more bottlenose dolphins in areas within 5 km of fish farms and less at areas more than 20 km from farms. Dolphins did not appear to avoid farm structures or noise from farm activities and were thought to be foraging, often within 10 m or less of the fish cages. Interviewed farm employees revealed dolphins were not considered a threat and acoustic deterrent devices are not used in the area. Farmers in Italy, Spain, Malta, Greece, and Israel claim the animals negatively impact their businesses because of depredation on cultured fish as well as inducing stress on those fish, which heightens the importance of understanding the interactions and developing consistent mitigation measures.[73]

In the Bay of Fundy, eastern Canada, feeding harbour porpoises (*Phocoena phocoena* Linnaeus, 1758) were not displaced by an Atlantic salmon farm, except during short periods of feed delivery or cage cleaning.[101] In the same region, Jacobs and Terhune[102] observed harbour seals (*Phoca vitulina* Linnaeus, 1758) were not attracted to areas with salmon farms. Cetacean species observed in coastal waters of Scotland include harbour porpoises, minke whales (*Balaenoptera acutorostrata* Lacépède, 1804), killer whales (*Orcinus orca* Linnaeus, 1758), and bottlenose dolphins.[68,103–106] There are no reports of these species interacting with aquaculture gear; however, harbour seals and grey seals

(*Halichoerus grypus* Fabricius, 1791) are considered primary predatory species of finfish aquaculture sites.[107]

Kemper et al.[60] evaluated known negative interactions of marine mammals with aquaculture in Australia, Tasmania, New Zealand, and Chile and found that most occur at finfish farms and involve pinnipeds attracted to the gear seeking food. Sepúlveda et al.[108] used stable isotopes to derive dietary data from foraging South American sea lions (*Otaria flavescens* Shaw, 1800) around salmon farms in southern Chile. They integrated sea lion movement patterns, based on satellite telemetry, with dietary data to characterise the impacts of an abundant and predictable source of non-native prey on their foraging ecology. There was large variability in individual sea lion spatial ranges and their degree of overlap with salmon farms. Based on isotopic analyses, farmed salmon were one of the most important prey in the study area; however, the authors explained that these data were potentially confounded by the possibility of sea lions consuming widely-distributed feral salmon in the area with the same isotopic ratios. In addition, the degree of spatial overlap did not correlate with the relative contribution of salmon in their diets. Their results suggest that even if an individual animal forages around salmon farms, it does not necessarily prey on the cultured fish. In a recent review of pinniped and salmon farm interactions over 50 years of industry expansion, Heredia-Azuaje et al.[109] ascertained although the primary threat to pinnipeds is intended and unintended killing, breeding or foraging habitat alterations may also induce behavioural or social change in impacted areas.

Chilean dolphins are endemic to Chile and are listed as near threatened on the IUCN Red List of Threatened Species.[110] According to Ribeiro et al.,[57] Chilean dolphin movement patterns and habitat use did not seem influenced by or directly altered by the presence of salmon farms. Heinrich and Reeves[110] also found no significant association identified between areas of intense habitat use and distance to salmon farms by Chilean dolphins. However, in the fjords of southern Chile, salmon farm structures are commonly close to the shore, and Chilean dolphins have been observed avoiding farm cages.[57,66,111] While active avoidance minimises direct interactions with the aquaculture gear, Chilean dolphin habitat selection is limited to shallow waters and thus water depth is a principal environmental feature that shapes their distribution.[111] This close association with shallower water depth may, therefore, put them at heightened risk of negative impacts from aquaculture operations sited at inshore locations. This may also be true for other *Cephalorhynchus* species including Hector's dolphin (*C. hectori* P.-J. van Bénéden, 1881), Commerson's dolphin (*C. commersonii* Lacépède, 1804), Heaviside's dolphin (*C. heavisidii* Gray, 1828), and Peale's dolphin, which show the same general habitat requirements.[66,111] Heinrich et al.[66] further refined the broadly sympatric Chilean and Peale's dolphin coastal water habitat requirements using species distribution models (SDM). Chilean dolphins preferred shallow (<30 m depth) turbid waters within 500 m of shore and river mouths near shellfish farms. Peale's dolphins were also observed in shallow waters but occurred over a broad range of conditions along open and exposed coastlines. With the expansion of aquaculture in these shallow, coastal habitats,[112] populations of these near-threatened species[110] become fragmented and isolated, and thus more vulnerable to additional anthropogenic stressors including gillnet fisheries, boat traffic, and tourism.[111] Minke whales (*B. acutorostrata*) have been seen interacting with finfish farms in Chile, although no specific information was documented.[60,113]

Based on an ecosystem modelling approach in the Ionian Sea, increased productivity from fish farm nutrients has contributed positively to bottlenose dolphin populations in the region.[97] As an explanatory variable, the number of fish farms was the main factor used to reconstruct the observed trends in dolphin biomass and distribution from 1997 to 2008. Rapid transfer of nutrients through the food web in oligotrophic waters has been shown to increase commercial fish biomass and fish farms are known to act as attracting devices for forage fish.[26]

3.1.2 | Entanglement

Physical interactions between marine mammals and offshore aquaculture farms increase the risk of entanglement in structures such as antipredator nets and mooring lines.[26,41,43,114] The potential for marine mammals to become entangled and drown is a predominant concern,[55] especially given the frequency of entanglements in commercial fishing gear[115–118] and marine debris.[111,119] Entangled animals have lower reproductive success, which results in population level effects, especially for small populations.[120] In addition, injuries from entanglement can reduce movement, impede feeding ability, cause internal injuries from struggling, constrict blood flow, sever appendages, and cause infections.[121] Animals burdened by dragging gear may be disconnected from social interactions and communications. While spatial overlap of farms and habitats increases the risk of interacting, marine mammals can be attracted to the structures that house potential prey or seek out aggregating wild fish near the farm sites, which increases the opportunity for entanglement.[55,60,98,122,123]

Marine mammal interactions with marine aquaculture gear may depend on several factors. Young, naïve animals are typically more at risk of entanglement, compared with adults because of their inquisitive nature and inexperience.[124,125] Whales and dolphins that use echolocation to navigate their environment and feed (Odontocetes) may be better able to detect and avoid 3D farm structures compared with species that do not echolocate (Mysticetes); however, if they are attracted to the abundance of prey in and surrounding cages they can still become entangled. Larger, less agile species with flippers and fins that extend out from the body[42] and species with feeding strategies that involve engulfing huge volumes of water (e.g., baleen whales including right, minke, and humpback whales) are considered more susceptible to entanglement in ropes and lines.[67] Species or individuals that roll when encountering entangling gear may be more likely to become severely wrapped.[126] Marine mammal perception of structures in the ocean and use of visual, auditory, or other sensory cues to elicit risk-averse behaviour is not well understood.[124,125] Not all countries mandate marine mammal protection and aquaculture farms may not be required to report interactions. Most of the global marine aquaculture occurs in countries with no reporting. Thus, entanglement data are relatively sparse and rarely quantitative for both shellfish and

TABLE 1 Documented cetacean entanglements or entrapments at mussel farms.

Location	Species common name	Scientific name	Number	Year	Gear type	Outcome	Citation(s)
Argentina	Southern right whale (juvenile)	*Eubalaena australis*	1	2011	Suspected mussel farm spat line	Unknown[a]	64
Western Australia	Humpback whale (calf)	*Megaptera novaeangliae*	1	2005	Mussel farm spat line	Released	43,67,127–129
Iceland	Harbour porpoise	*Phocoena phocoena*	1	1998	Mussel farm spat line	Fatal	67
Iceland	Humpback whale (juvenile)	*Megaptera novaeangliae*	1	2010	Mussel farm spat line	Fatal	67
Iceland	Minke whale	*Balaenoptera acutorostrata*	1	2012	Mussel farm head rope	Released itself[a]	67
New Zealand	Bryde's whale	*Balaenoptera edeni brydei*	1	1996	Mussel farm spat line	Fatal	36,43,67,88
New Zealand	Bryde's whale	*Balaenoptera edeni brydei*	1	Prior to 2003	Mussel farm spat line	Fatal	36
New Zealand	Humpback whale (calf)	*Megaptera novaeangliae*	1	2011	Mussel farm line as a result of primary craypot entanglement rescue operation	Released[b]	
South Korea	North Pacific right whale	*Eubalaena japonica*	1	2015	Mussel farm spat line	Released itself	67,72,130
South Africa	Bryde's whale	*Balaenoptera edeni brydei*	1	2019	Mussel farm spat line	Released itself	131

[a]Unconfirmed event.
[b]https://www.newshub.co.nz/environmentsci/mussel-farmer-frees-trapped-humpback-whale-2011070917.

finfish aquaculture farms in many countries and the global extent of the problems are poorly known.

Mussel farms

It is unclear whether entanglement occurs because mammals are attracted to or unaware of shellfish-farming gear.[58] Lloyd[36] reported two fatalities of Bryde's whales (*Balaenoptera edeni brydei* Anderson, 1879) entangled in mussel spat collection lines in New Zealand (Table 1). In 1996, a Bryde's whale was found dead with the spat line lodged tightly through the base of the animal's mouth indicating that the entanglement occurred with a high level of force.[36,43,67,88] There are no additional details about the second Bryde's whale fatality mentioned in Lloyd.[36] Bryde's whales are designated Threatened-Nationally Critical in New Zealand[132] and since these two reported incidents, no other entanglements have been documented. In 2011, an entanglement occurred because of a rescue operation when a humpback whale (*Megaptera novaeangliae* Borowski, 1781) calf was dragging craypot gear tied around its fluke.[133] The New Zealand Department of Conservation workers tied buoys to the whale as the sun was setting so they could follow the whale and locate it in the morning when they had better visibility. The next morning a mussel farmer discovered the whale entangled in mussel ropes by the buoy lines. He and his crew cut the lines off the whale and freed it without the offered assistance of trained responders, and unfortunately, this was achieved by winching the tail of the whale out of the water[133] (Table 1). In 2005, a humpback whale calf in Western Australia was cut free from a mussel spat line after catching it in its mouth and rolling[43,67,127–129] (Table 1). In a report on southern right whale (*Eubalaena australis* Desmoulins, 1822) entanglements in Argentina from 2001 to 2011, there is one unconfirmed case of a juvenile right whale that may have involved mussel spat collection lines[64] (Table 1). The whale was sighted during a whale-watching cruise and was not re-sighted during the search effort and the fate is unknown. Two fatal marine mammal entanglements in mussel single dropper spat collection lines were reported in Iceland[67] (Table 1). In 1998, a harbour porpoise was found entangled, and in 2010 a juvenile humpback whale entanglement was reported. In 2012, a mussel farmer in Iceland suspected a minke whale was entangled in headropes and droppers but it freed itself without gear attached. Although the farmer had not actually seen the whale, he assumed it happened because the gear was in disarray and slime-coated, similar to what is left on his gillnets after a whale had been caught.[67] In 2015, a young male North Pacific right whale (*Eubalaena japonica* Lacépède, 1818) was entangled by a mussel spat line in South Korea (Table 1). Divers cut the ropes but had to cease operations due to low visibility at night. When they returned the next morning, the whale was nowhere to be found and assumed released.[67,72,130]

Similar to mussel longline construction, pearl oysters (*Pinctada maxima*) are held in net panels just below the surface and attached to surface longlines anchored at each end (Figure 1). This allows the

TABLE 2 Documented cetacean entanglements at oyster pearl farms.

Location	Species common name	Scientific name	Number	Year	Gear type	Outcome	Citation(s)
Western Australia	Humpback whale	*Megaptera novaeangliae*	1	1998	Pearl farm rope	Released	128,129
Western Australia	Humpback whale	*Megaptera novaeangliae*	1	2004	Pearl farm rope	Released	128,129
Western Australia	Humpback whale	*Megaptera novaeangliae*	1	2008	Pearl farm rope	Released	128,129
Philippines	Short-finned pilot whale	*Globicephala macrorhynchus*	Not quantified		Pearl farm rope		135–137
Philippines	Pantropical spotted dolphin	*Stenella attenuata*	Not quantified		Pearl farm rope		135,136

panels to move with the tide and the oysters to feed in as close as possible to their natural state.[134] Pearl oyster farm ropes in Western Australia have been implicated in three humpback whale entanglements in 1998, 2004, and 2008; all animals were released alive[128,129] (Table 2). In the Philippines, short-finned pilot whales (*Globicephala macrorhynchus* Gray, 1846) and pantropical spotted dolphins (*Stenella attenuata* Gray, 1846) entangled in pearl farm lines[135,136] (Table 2) although no details about specific events or the cumulative number of animals impacted have been documented.

Offshore finfish farms

From 1990 to 1999, fatal entanglements of 17 short-beaked common dolphins (*Delphinus delphis* Linnaeus, 1758) and 11 Indo-Pacific bottlenose dolphins (*Tursiops aduncus* Ehrenberg, 1833) in southern bluefin tuna (*Thunnus maccoyii* Castelnau, 1872) ranching operations using large mesh (>15 cm) antipredator nets have been documented in South Australia[53,60] (Table 3). In 1993, a humpback whale broke through the walls of a tuna ranching operation and was trapped in the net pen for 2 days before it was successfully released[53,60] (Table 3). In an International Whaling Commission Scientific Committee National Progress Report,[138] the fatal entanglement of a bottlenose dolphin in a yellowtail kingfish (*Seriola lalandi* Valenciennes, 1833) cage in 2008 was documented with no further information (Table 3). Twenty-one unspecified seal and sea lion interactions were reported at yellowtail kingfish farms and two seal interactions reported in southern bluefin tuna ranching operations from 2014 to 2016. All reported pinniped interactions resulted in the animals releasing themselves or being released alive[155] (Table 4). Over the past 20 years, improvements in the tuna ranching industry with operations and best practices have eliminated marine mammal entanglement mortalities.[159] Predator nets are no longer used by the tuna industry and additional measures have been taken such as switching to pellet feed and reducing waste, better siting practices, reduced tuna mortalities and prompt carcass removals.[159]

Atlantic salmon (*Salmo salar* Linnaeus, 1758) net pens are the most abundant aquaculture gear in Tasmania. Before 1991, a southern right whale collided with the side of an Atlantic salmon net pen but was released, most likely after getting tangled in mooring lines, not preying on the caged fish[153] (Table 3). Bottlenose and short-beaked common dolphins have drowned in antipredator nets that were not enclosed at the bottom; trapping the dolphins between the main cages and the antipredator nets[60,154] (Table 3). Before 2000, 36 Australian fur seals (*Arctocephalus pusillus* Wood Jones, 1925), one New Zealand fur seal (*Arctocephalus forsteri* Lesson, 1828), two leopard seals (*Hydrurga leptonyx* de Blainville, 1820), and one southern elephant seal (*Mirounga leonina* Linnaeus, 1758) died in Atlantic salmon aquaculture farms[60] (Table 4). Tassal Group is the largest Atlantic salmon producer in Tasmania. Since achieving the Aquaculture Stewardship Council certification in 2014 across its Atlantic salmon farm operations in Tasmania, it has publicly released information about wildlife interactions at all of its sites within 30 days of occurrence on its sustainability dashboard website.[160] These interactions are also documented in its annual Sustainability Reports.[161] From 2010 to 2021, 70 accidental Australian fur seal deaths were recorded in their salmon net pens (Table 4). From 2014 to 2020, there have been no interactions with sharks, whales, or dolphins at their farms. Two New Zealand fur seals became entangled and drowned in finfish antipredator nets in New Zealand prior to 2007[43,56] and another two in 2014 (Table 4). In New Zealand, fish farms use antipredator nets to deter pinnipeds; however, these nets have been implicated in small cetacean entanglements.[78] Three dusky dolphins and one Hector's dolphin have been fatally entangled.[56,78,84,85,148] Four bottlenose dolphin deaths occurred before 2013[43] (Table 3). Huon Aquaculture[162] reported 18 seal deaths in 2021 on their sustainability dashboard.

A Bryde's whale measuring 6 m in length was rescued from being trapped in a fish farm in Brunei Bay near Pulau Pelompong Brunei-Maura in May 2000[145,146] (Table 3). The whale was injured and had a partially severed fluke, not because of the fish cage, but because two fishermen tied a rope around the base to help pull the whale to deeper water. The rescuers were able to move the whale to deeper water and watch it swim away, reportedly struggling to orient itself from the damaged tail.[136,145,146]

Sea lion mortality in Chile salmon farms is rampant due to shooting, poisoning, clubbing, and some incidental entanglement.[60,156,157] In Southern Chile, there is a well-known negative interaction between South American sea lions and salmon farms. The high concentration of vulnerable prey results in the threat of predatory attacks at the cage which contributes to farmed salmonid escapes.[156,163] Pinniped

TABLE 3 Documented cetacean entanglements or entrapments at marine finfish farms.

Location	Species common name	Scientific name	Number	Year	Gear type	Outcome	Citation(s)
Australia	Bottlenose dolphin	*Tursiops truncatus*	1	2008	Kingfish cage	Fatal	138
South Australia	Humpback whale	*Megaptera novaeangliae*	1	1993	Tuna ranching operation	Released	53,60
South Australia	Short-beaked common dolphin	*Delphinus delphis*	17	1990–1999	Tuna ranching operation	Fatal	53,60
South Australia	Indo-Pacific bottlenose dolphin	*Tursiops aduncus*	11	1990–1999	Tuna ranching operation	Fatal	53,60
British Columbia Canada	Harbour porpoise	*Phocoena phocoena*	4	2007	Net pen	Fatal	139
British Columbia Canada	Humpback whale	*Megaptera novaeangliae*	1	2013	Net pen	Found dead at farm	139
British Columbia Canada	Humpback whale	*Megaptera novaeangliae*	2	2016	Net pen	Fatal	139
British Columbia Canada	Humpback whale	*Megaptera novaeangliae*	1	2016	Net pen	Released	139
British Columbia Canada	Humpback whale	*Megaptera novaeangliae*	1	2018	Net pen	Released[a]	139
Chile	Chilean dolphin	*Cephalorhynchus eutropia*	1	2007	Net pen	Fatal	59,140
Chile	Humpback whale (calf)	*Megaptera novaeangliae*	1	2007	Net pen	Fatal	141,142
Chile	Chilean dolphin	*Cephalorhynchus eutropia*	1	2011	Net pen	Fatal	59
Chile	Chilean dolphin	*Cephalorhynchus eutropia*	4	2015–2017	Net pen	Fatal	59
Chile	Humpback whale (adult)	*Megaptera novaeangliae*	1	2017	Net pen	Released	59
Chile	Sei whale	*Balaenoptera borealis*	1	2020	Salmon net pen	Fatal[b]	
Iceland	Minke whale	*Balaenoptera acutorostrata*	1	2005	Net pen	Fatal	67,143,144
Brunei	Bryde's whale	*Balaenoptera edeni brydei*	1	2003	Finfish cage	Released	136,145,146
Italy	Bottlenose dolphin	*Tursiops truncatus*	3	2005	Coastal fish farms	Fatal	70
New Zealand	Hector's dolphin	*Cephalorhychus hectori*	1	1987	Net pen	Fatal	147
New Zealand	Dusky dolphin	*Lagenorhynchus obscurus*	7	1999–2018	Net pen	Fatal[c]	56,78,84,85, 87,147,148
New Zealand	Hector's dolphin	*Cephalorhychus hectori*	1	2005	Net pen	Fatal	56,147,149
New Zealand	Bottlenose dolphin	*Tursiops truncatus*	4	Prior to 2013	Net pen	Fatal	53
Norway	Humpback whale	*Megaptera novaeangliae*	1	2009	Net pen	Released	144,150
Norway	Minke whale	*Balaenoptera acutorostrata*	1	2005	Net pen	Fatal	67,143,144
Norway	Minke whale	*Balaenoptera acutorostrata*	1	2014	Net pen	Released	151
Norway	Humpback whale (calf)	*Megaptera novaeangliae*	1	2015	Net pen	Released[d]	151
Norway	Minke whale	*Balaenoptera acutorostrata*	1	2015	Net pen	Fatal	151

TABLE 3 (Continued)

Location	Species common name	Scientific name	Number	Year	Gear type	Outcome	Citation(s)
Norway	Harbour porpoise	*Phocoena phocoena*	1	2018	Net pen	Fatal[e]	
Norway	Minke whale	*Balaenoptera acutorostrata*	1	2019	Net pen	Unknown[f]	151,152
Tasmania	Southern right whale	*Eubalaena australis*	1	Prior to 1991	Salmon net pen	Released	153
Tasmania	Bottlenose dolphin	*Tursiops truncatus*	2	Prior to 1998	Atlantic salmon sea cage	Fatal	60
Tasmania	Bottlenose dolphin	*Tursiops truncatus*	3	1998–2000	Atlantic salmon sea cage	Fatal	60
Tasmania	Short-beaked common dolphin	*Delphinus delphis*	6	1998–2003	Atlantic salmon sea cage	Fatal	60,154
Tasmania	Dolphin	Unidentified species	2	2012	Atlantic salmon sea cage	Fatal[g]	

[a]https://www.cowichanvalleycitizen.com/news/trapped-humpback-whale-freed-from-salmon-farm-near-tofino/.
[b]https://salmonbusiness.com/whale-found-tangled-and-trapped-in-rope-dies-at-salmon-farm/.
[c]https://www.stuff.co.nz/marlborough-express/news/69187299/dolphins-die-on-nz-king-salmon-farms.
[d]https://www.fiskeridir.no/Akvakultur/Erfaringsbase/Knoelhval-i-merd.
[e]https://www.cermaq.com/wps/wcm/connect/cermaq-no/cermaq-norway/baerekraft/asc-rapportering/.
[f]https://www.fishfarmermagazine.com/news/whale-of-a-time-for-escaped-salmon/.
[g]https://tassalgroup.com.au/wp-content/uploads/sites/2/2018/01/Tassal-Sustainability-Report-2012-13.pdf.

control nets set near Chile salmon farms are considered the principal entanglement threat to cetaceans.[110,164] In 2007, a Chilean dolphin was found entangled in salmon anti-sea lion nets[140] and a humpback whale calf was fatally entangled in an antipredator net at a Chilean salmon farm[141,142] (Table 4). An adult humpback whale was released from entanglement in an antipredator net that was in the process of being installed at a salmon farm.[59] Near the southern tip of Chile, a 15-m sei whale (*Balaenoptera borealis* Lesson, 1828) was believed to have died after it became entangled in a net at the salmon farm (Table 3). The whale's body was almost entirely entangled with different length ropes and a metal chain was wrapped around its fluke.[165] Chilean dolphins share coastal habitats with salmon farms and are most likely feeding on small schooling or benthic wild fish attracted to waste feed at the farms.[59,66] In a study using predictive SDM, Heinrich et al.[66] partitioned fine-scale habitat use by Chilean dolphins and demonstrated potential overlap with mussel and salmon farms, with mussel farms showing higher probability of interactions. Because of the proximity of Chilean dolphin populations to farms,[66] they may be vulnerable to entanglements and entrapments; however, these events are seldom recorded so it is not clear whether there are no interactions or interactions are not documented.

In Norway, minke and humpback whale interactions with Atlantic salmon farms have been documented. Minke whales have been entangled in fish farm pens in Iceland and Norway. A minke whale was fatally entangled in an Iceland fish farm pen in 2005[67,143,144] (Table 3). In 2014, a 6-m minke whale swam through the upper part of a net wall and into a cage.[69] The fish farmers lowered a small part of the cage into the water, which created an opening for the whale to swim out. No further damage to equipment or whale was observed. In 2015, a small minke whale broke into the cage and had to be euthanized to prevent further damages and fish escapes.[69] In 2019, a 9-m-long minke whale broke through a cage, tearing a large hole in the net, which enabled a small number of fish to swim free. The whale was released and the net was sealed but there was no further information on the whale.[152] The same news article mentions an interaction with a minke whale at a different farm earlier that year but we were unable to confirm the report. Two humpback whales were entangled and released from fish cages, one in 2009[144] and a 9-m calf in 2015[69] (Table 3). The small calf swam into the net and its fluke became entangled in a rope, which made a small wound in the blubber. The farmers released the rope, attached another rope around the fluke, and pulled it out of the cage. The whale was released and observed swimming with other whales shortly after the incident. A harbour porpoise drowned after being entrapped at a salmon farm in 2018. At a Scottish salmon farm in 2014, a juvenile male humpback whale drowned after being trapped under a net pen[166,167] (Table 3). It was noted that humpback whales are not usually observed around the farms and the farmers surmised most likely the young whale was inquisitive and naïve.

Marine finfish aquaculture has expanded in most Mediterranean countries over the last two decades and depredation attempts by bottlenose dolphins attracted by farmed fish pose a risk of negative interactions. The antipredator net barriers used to protect the fish cages from attacks by airborne and underwater predators present an entanglement risk. Observations of incidental catch of bottlenose dolphins in fish pens on the northeastern coast of Sardinia[70] and of monk seals (*Monachus monachus* Hermann, 1779) in Turkey[71,158] (Table 4) are the result of inexperienced calves and loose predator barriers. A long-term

TABLE 4 Documented accidental entanglements and entrapments of pinnipeds at marine finfish farms.

Location	Species common name	Scientific name	Number	Year	Gear type	Outcome	Citation(s)
South Australia	Seal	unspecified	2	2014–2016	Southern bluefin tuna feedlot	Released	155
South Australia	Seals and sea lions	unspecified	21	2014–2016	Yellowtail kingfish sea cages	Released	155
British Columbia Canada	California sea lion	*Zalophus californianus*	41	2011–2021	Net pen	Fatal	139
British Columbia Canada	Harbour seal	*Phoca vitulina*	50	2011–2021	Net pen	Fatal	139
British Columbia Canada	Northern fur seal	*Callorhinus ursinus*	1	2021	Net pen	Fatal	139
Chile	South American sea lion	*Otaria flavescens*			Net pen	Fatal	59,60,156,157
Chile	South American fur seal	*Arctocephalus australis*			Net pen	Fatal	60,157
Faroe Islands	Grey seal	*Halichoerus gryphus*	10	2015–2019	Net pen	Released[a]	
New Zealand	New Zealand fur seal	*Arctocephalus forsteri*	2	Prior to 2007	Net pen	Fatal	43,56
New Zealand	New Zealand fur seal	*Arctocephalus forsteri*	2	2014	Net pen	Fatal[b]	
Tasmania	Southern elephant seal	*Mirounga leonina*	1	1998	Atlantic salmon sea cage	Fatal	60
Tasmania	Leopard seal	*Hydrurga leptonyx*	2	Prior to 1998	Atlantic salmon sea cage	Fatal	60
Tasmania	New Zealand fur seal	*Arctocephalus forsteri*	1	Prior to 1998	Atlantic salmon sea cage	Fatal	60
Tasmania	Australian fur seal	*Arctocephalus pusillus*	36	1998–2000	Atlantic salmon sea cage	Fatal	60
Tasmania	Australian fur seal	*Arctocephalus pusillus*	70	2010–2021	Atlantic salmon sea cage	Fatal[c]	
Tasmania	Seal	Unspecified	18	2021	Atlantic salmon cage	Fatal[d]	
Turkey	Monk seal	*Monachus monachus*	1		Fish farm	Fatal	71,158
USA California	California sea lion	*Zalophus californianus*	2	2005	Fish holding pen attached to dock	Fatal	Jaclyn Taylor, NOAA Fisheries, pers. comm. 20 February 2022
USA Hawaii	Hawaiian monk seal	*Monachus schauinslandi*	1	2017	Marine fish cage	Fatal[e]	Jaclyn Taylor, NOAA Fisheries, pers. comm. 20 February 2022
USA Washington	Harbour seal	*Phoca vitulina*	8	1996–1998	Net pen	Fatal	Jaclyn Taylor, NOAA Fisheries, pers. comm. 20 February 2022
USA Washington	California sea lion	*Zalophus californianus*	33	1996–1998	Net pen	Fatal	Jaclyn Taylor, NOAA Fisheries, pers. comm. 20 February 2022

[a]https://www.bakkafrost.com/media/1666/a71_y2016_w52.pdf.
[b]https://www.stuff.co.nz/marlborough-express/news/69187299/dolphins-die-on-nz-king-salmon-farms.
[c]http://tassalgroup.com.au/our-planet/reports/sustainability/.
[d]https://dashboard.huonaqua.com.au/.
[e]https://governor.hawaii.gov/newsroom/latest-news/dlnr-news-release-federal-and-state-agencies-investigate-death-of-hawaiian-monk-seal/.

bottlenose dolphin distribution and behaviour study was conducted off the northeast coast of Sardinia, Italy, in the vicinity of a marine fish farm with sea bass, gilthead sea bream, and meagre reared in 21 floating cages arranged in three rows of seven.[73] In 2005, three animals were fatally entangled in 15 cm mesh antipredator nets (Table 3). Díaz López and Shirai[70] estimated one bottlenose dolphin fatal entanglement per month in fish cages with loose antipredator netting and zero for those with taut antipredator netting. During the entire study period (2004–2009), the estimated annual dolphin mortality was 1.5 per year based on five animals found entangled in nets.[73] In the Turkish Aegean Sea, farmers from 11 out of 25 surveyed sea bass and sea bream fish farms reported individual monk seals were observed taking fish and damaging nets, mostly at night-time feedings during the winter months.[71] A range of non-lethal deterrents was ineffective but antipredator nets were the only successful method to avoid fish loss.

In Canada, public reports on authorised pinniped control activities at British Columbia salmon farms are available on the Fisheries and Oceans Canada (DFO) Public Reporting on Aquaculture - Pacific Region database (DFO PAC-AQUA-MMI).[139] From 2011 to 2016, there were 249 authorised deaths of California sea lions (*Zalophus californianus* Lesson, 1828). From 2011 to 2015, 78 harbour seal deaths were authorised, and two Steller sea lions (*Eumetopias jubatus* Schreber, 1776) in 2011. The database also provides information about the numbers of known accidental marine mammal drownings at fish farms from 2011 to 2020. Animals often become tangled underwater in the cage netting or other farm gear. During the time-period 2011–2021, 41 California sea lion, 50 harbour seal, and 1 northern fur seal (*Callorhinus ursinus* Linnaeus, 1758) accidental drownings were reported in Canadian Atlantic salmon fish farms (Table 4). Three dead humpback whales were discovered at Atlantic salmon farms and two trapped humpback whales were and successfully released. In 2013, a humpback whale was found dead at a farm but the necropsy report did not include the cause of death. In November 2016, two humpback whales drowned in net pen gear; a juvenile breached the predator net of a net pen and the other was entangled by an anchor line, supporting an empty net pen.[26,139] That same year, a third humpback whale was entangled at a fallowed farm and released alive. In 2018, a humpback whale was discovered swimming in an empty sea cage and not entangled. Rescuers removed two panels from the antipredator net and the whale swam out of the net pen[139] (Table 3).

Review of the US NOAA Fisheries Marine Mammal Stock Assessments database identified 41 unintentional pinniped fatalities: eight harbour seals and 33 California sea lions in Atlantic salmon net pens in Washington State from 1996 to February 2021 (Jaclyn Taylor, NOAA Fisheries, pers. comm. 20 February 2022). In over 30 years of Atlantic salmon net pen farms operating in Puget Sound, Washington State, there have not been any documented incidents of cetacean entanglements in predator exclusion nets (Jaclyn Taylor, NOAA Fisheries, pers. comm. 20 February 2022). In 2005, two California sea lions were fatally entangled in predator nets of juvenile white seabass (*Atractoscion nobilis* Ayres, 1860) holding pens in the Channel Islands off the California Harbour.

Off the coast of Hawaii farm workers at an almaco jack (*Seriola rivoliana* Valenciennes, 1833) fish farm reported over 550 marine mammal observations from 2010 to 2016, and over 2500 from 2017 to 2020.[168,169] Bottlenose dolphins, humpback whales, and Hawaiian monk seals (*Monachus schauinsland* Matschie, 1905) were frequently observed near the farm and in proximity to the cages. Individual animals with distinguishing features were frequent visitors to the site but did not take up permanent residency. Pantropical spotted dolphins, rough-toothed dolphins (*Steno bredanensis* Cuvier, 1828), and false killer whales (*Pseudorca crassidens* Owen, 1846) have all been observed in the area or in other offshore waters of the Kona Coast, but have not been reported from the farm site.[168] Dolphins observed at the farm site were reported to forage on wild fish, play, mate, follow boats, and approach divers and cages (Jennica Hawkins, Ocean Era, pers. comm. 9 September 2021). Unfortunately, in 2017 at the same farm, an endangered Hawaiian monk seal drowned in a partially decommissioned sea cage (Table 4). The 10-year-old male seal was discovered dead in a submerged empty fish cage in which farm workers removed a side panel to allow a shark to swim out the previous day. Other than that incident, from 2010 to 2022, no entanglements, injuries, or mortalities occurred despite being located less than one mile from the Hawaiian Islands Humpback Whale National Marine Sanctuary. There was one fatality report of a juvenile North Atlantic right whale (*Eubalaena glacialis* Müller, 1776) entangled in undefined aquaculture gear in the Western North Atlantic Ocean in 2000.[26,170] Although, the lack of standardised gear investigation protocols at the time produced an incomplete investigation and there is no direct evidence that aquaculture gear was involved (David Morin, NOAA Fisheries, pers. comm. 22 December 2020).

Noteworthy, given anthropogenic and environmental threats to sirenians worldwide,[171–173] in the Philippines, local fishers have mentioned instances of dugong (*Dugong dugon* Müller, 1776) entanglement in the ropes of pearl farms and grouper culture cages.[174] Aside from these anecdotes, we have not found validated documentation of manatee (*Trichechus* sp.) or dugong interactions with marine fish cage culture, yet at sites within their habitat range potential impacts to these animals should be considered.[55]

3.1.3 | Underwater noise disturbances

In addition to aquaculture farm construction and decommissioning, finfish and mussel farm operations produce underwater noise from vessels, feeding systems, generators, aerators, net cleaning equipment, and acoustic deterrents.[175] There is evidence that underwater noise disturbances can alter the behaviour of marine mammals, cause temporary or permanent injuries, or cause death, trigger a stress response, cause habitat displacement or avoidance, and disturb underwater acoustic cues for communication, navigation, and foraging.[43,68,175–182]

There are many factors that influence underwater noise, including the number of pens, the operations on the farm, the characteristics of the habitat, and the proximity to other sound-generating sources.

Coastline configuration and habitat characteristics including water depth and sediment type impact noise sources and propagation.[182] Whales may be more sensitive to increased noise production along migration routes,[43,183–185] while pinnipeds demonstrate tolerance and do not avoid underwater noises.[179] Moreover, dolphins exhibit curiosity in response to underwater noises.[43,186,187] Although not always effective on pinnipeds, the use of Acoustic Deterrent or Harassment Devices (ADDs and AHDs) to prevent pinniped predation has resulted in killer whale, harbour porpoise, and dolphin displacement from areas with active devices.[43,175,176,178] Harcourt et al.[188] tested the effectiveness of widely used commercial acoustic alarms to deter migrating humpback whales from entanglement hazards including fish trap or pot lines. They detected no evidence of deterrence. The whales did not speed up, slow down, or alter their course within the predicted audible range of the alarm.

3.1.4 | Vessel traffic

Depending on the size of the farm operation and the size of transportation vessels, vessel traffic around aquaculture farms can produce noise, impose a navigation hazard, alter animal behaviour, exclude animals from habitats, and pose a collision risk. Vessel noise may contribute to stress and disrupt cetacean echolocation signals, and thus reduce communication and foraging efficiency.[182,189,190] Worldwide, vessel collisions with marine mammals have become recognised as a significant source of anthropogenic mortality and serious injuries.[191–195] Schoeman et al.[194] found most scientific publications focus on collisions between large vessels and large whales. Their extended review discovered that at least 75 marine species are vulnerable to vessel collisions, including smaller whales, dolphins, porpoises, dugongs, manatees, whale sharks, sharks, seals, sea otters, sea turtles, penguins, and fish.

While marine mammal behaviour changes in response to vessel traffic have been studied,[181,196,197] documented cases of direct vessel traffic effects on protected species around aquaculture farms are difficult to find. Vessel traffic related to aquaculture affects Chilean dolphins by altering behavioural responses such as changes in swimming reorientation rate and speed.[198] While individual farms may have very little vessel traffic, areas with multiple farms may have a cumulative effect. The impacts of vessel noise and collision impacts on blue whales (*Balaenoptera musculus* Linnaeus, 1758) in northern Chilean Patagonia is significant considering the aquaculture fleet is an order of magnitude larger than any other sector including cargo, transport, artisanal fishery, and industrial fishery fleets.[195] Using density predictions from previous SDM, spatially explicit predictions of behavioural responses to vessel presence, and vessel tracking data, they estimated the relative probability of vessels encountering whales and identify areas where interaction is likely to occur. Given the size of finfish and mussel culture operations in Chile, the projected industry growth,[115] and known presence of several marine mammal species, vulnerable protected species are at risk of collision with vessels associated with aquaculture activities.

3.1.5 | Attraction to artificial lighting

Overhead lighting at fish farms provides navigational and personnel safety, and farm security. Submerged artificial lighting is commonly used at higher latitudes to slow cultured fish maturation, increase growth rates, reduce fish densities near the surface, and evenly distribute the fish in cages.[199–201] Overhead and submerged lighting around finfish farms may attract marine mammals to caged prey or aggregated wild fish and cause trophic level disruptions.[55,60,71,122,201–204] The effect of lighting on marine mammals is not only localised, as animals may be attracted from longer distances, especially at night.[163] In addition, sound and light attract animals more than light alone. Light shielded from all but essential directions minimises wild animal behaviour disruption around finfish cages. Spotlights above pens positioned high above the surface will diffuse penetration through the water column.[201]

3.1.6 | Risk management and depredation mitigation

Marine mammals can damage aquaculture gear, resulting in economic loss to the farm from equipment replacement costs and escaped fish from net breaches,[62,71] and such interactions may cause serious injury or death to imperilled species. Predatory pinnipeds are often considered a nuisance because of the net damage they incite by preying on the farmed fish.[60,68,71,156,205–207] Torn nets not only allow for fish escapes, resulting in economic loss for the farmers, but also present an additional entanglement hazard to other animals. In addition, farmed fish are also impacted by the stress-inducing predatory behaviour, which can indirectly effect fish growth and survival[109] and result in lost biomass production. Thus, deterring pinnipeds from salmon net pens in the United States,[62,208] Canada,[63] Scotland,[103,209] Australia,[210] and Chile[141,156,163] has been a constant battle for decades.[109] Until recently, authorised kills have not only been legal but also tolerated as an effective control measure by salmon farmers in some countries[62,63,68,109]; although, reliable, quantitative mortality data is lacking.[109] An extensive review of pinniped interactions with salmon farms in Canada, published by Jamieson and Olesiuk,[63] described non-lethal intervention methods, the effects of lethal deterrents to sea lion and seal populations, as well as the financial impacts to the industry. Although farm stock or gear damage may be a few thousand dollars for an individual farm, multiple cases can amount to millions of dollars in 1 year for a country. The growth of the fish farming industry and concurrent pinniped population expansion has increased the number of interactions, and previously accepted lethal control methods are less viable due to ecosystem conservation objectives and regulatory protection. In many cases, public support for aquaculture is decreased when there is news of marine animals being harmed or culled.

To reduce marine mammal depredation or avoid injuries and lethal interactions, aquaculture operations use a suite of methods: harassment, aversive conditioning, non-lethal removal, lethal removal, population control, and exclusion.[5,41,71,109,209,211,212] Harassment by chasing, explosives, and ADDs is effective in the short term but tend to be less efficacious over time as animals become acclimated to the noise.[60] ADDs emit sound underwater at a range of frequencies to deter predation on the stocked fish by causing auditory discomfort. Noise harassment devices may actually become attractants to habituated individuals who associate the unpleasant sound with an easy prey source over time.[43,186,187] The effectiveness of noise deterrents and their secondary impacts to non-target animals is uncertain.[68,163,178,211,213,214] In a controlled experiment to assess the influence of an ADD on free-range bottlenose dolphin behaviour by Díaz-López and Mariño,[215] dolphins were not deterred from the farm, especially when food was present. ADDs and underwater explosive devices used to prevent pinniped predation have resulted in killer whale, minke whale, harbour porpoise, and dolphin displacement from areas with active devices.[43,103,176,178,216–220]

In Scotland and British Columbia, Canada, harbour porpoises avoided salmon farms when ADDs were active but returned quickly when they were deactivated.[176,178] In farms where active ADDs had been deployed for some time, animals were observed foraging. In New Zealand, Hector's dolphins, avoided acoustic gillnet pingers, and based on this observation, Stone et al.[221] suggested using similar devices at salmon farms to deter pinnipeds could also impact non-target mammals. Killer whales in British Columbia avoided marine farm areas where ADDs are in use[216,222] but whales in a nearby farm without ADDs remained stable during this same period. Six years after deployment, the local killer whale abundance returned to previous levels after the devices were removed.[216] In the Bay of Fundy, ADDs deployed near aquaculture facilities did not elicit startle responses, cause measurable avoidance behaviour, or change haul-out behaviour of pinnipeds over many years.[211] Salmon farm managers surveyed in Scotland questioned the effectiveness of ADDs and do not use them at all farms.[178,209] Despite daily sightings of seals near farms, the authors suggested seal predation on farmed fish decreased over the previous decade and less than a quarter of salmon farms reported major problems with seals. Because specific individuals allegedly were responsible for the most damage, improving individual recognition techniques was a priority for farm management and reduced interactions. In a review of commercial ADDs, Götz and Janik[213] concluded main problems were reduced efficiency over time and noise pollution that impacted communication, hearing—including permanent damage, and behaviour of non-targeted animals where ADDs were employed. They also suggested ADDs used to deter pinnipeds from farms operate at the same frequencies received by odontocetes with more acute hearing sensitivity and may explain large-scale habitat exclusion in the vicinity of these units. Findlay et al.[217] quantified the cumulative impact of multiple farms using ADDs along the Scottish west coast and demonstrated ADDs are a significant and chronic source of underwater noise disturbance. Using species-specific frequency-dependent hearing sensitivity, deterrent devices can be modified to target one taxon and minimise impact to others. Götz and Janik[223] targeted grey seal acoustic startle reflex with transducers that emitted short, isolated noise pulses at low duty cycles, and elicited avoidance responses by the animals within 250 m of the units. This Targeted Acoustic Startle Technology reduces the avoidance response to a defined area and decreases noise pollution.[223]

In addition to the ADDs, Terhune et al.[211] reviewed other non-lethal interventions or aversive conditioning such as harassment by boat or with noise (such as underwater seal firecrackers), predator models or sounds, acoustic devices, and relocation. Seal bombs and shooting are most effective if used before animals acclimated to finfish cages and established a permanent interest in the farm.[224,225] Physical predator models and sound devices (imitating killer whales, for example) are also not effective.[60,103,156] Electric fences have been used to prevent pinnipeds from hauling out on farm structures in the Canada and the US Pacific Northwest.[48,224,226] Capture and relocation of destructive animals is time-consuming, expensive, and minimally effective.[211]

Until recently, pinniped lethal removal from aquaculture farms was common practice and authorised in many countries with large-scale Atlantic salmon farms, including Canada, Chile, Norway, and Scotland. Before the spring of 2020, Fisheries and Oceans Canada (DFO) authorised farm licence holders[227] to lethally remove nuisance seals that posed eminent danger to the aquaculture facility or to human life, if all other non-lethal deterrent efforts failed. In Chile, all marine mammals are protected by law from intentional killing and accidental mortalities in fishing operations are legally required to be reported.[228] Despite this law, strict adherence to the regulation and accountability is lacking. In 2021, rules governing the interaction between marine mammals and aquaculture require antipredator nets be installed at salmon farms and detailed plans for dealing with sea lions must be included in farm operational management plans.[229] In Scotland, shooting seals was licenced to aquaculture operations until June 2020 when the Scottish Parliament approved an amendment to the Marine Scotland Act of 2010,[230] banning intentional killing of seals to protect cultured animals.[231] Animal welfare concerns have driven these changes. Importantly, under the US seafood import rule,[232] exporting countries must implement a regulatory program comparable in effectiveness to US policy. Beginning in January 2023, such programs must be implemented in which intentional marine mammal kills are prohibited, marine mammal population assessments include bycatch estimates, bycatch limits are quantified, and bycatch reduction measures are implemented.[59,232,233] Because the United States is a major importer of Atlantic salmon from Canada, Chile, Norway, and Scotland, documenting marine mammal interactions at farms is now imperative to comply with US seafood import requirements.[59,234] Under this import rule, exporting countries must implement a regulatory program in which intentional marine mammal kills are prohibited, stock assessments are conducted, bycatch estimates are quantified, and bycatch limits are imposed.[232]

Other farm management practices including the addition of false bottoms to avoid predation under the cages, increased net tension, removal of fish carcasses, and installing antipredator nets are accepted as best practices. Advances in antipredator cage technology, routine net maintenance to avoid fish escapes, minimal use of lights at night, and feed management to reduce waste are farm practices that likely decrease the potential for negative interactions. Successful pinniped deterrence is achieved using physical exclusionary barriers, including rigid net materials for fish cages or the installation of rigid exclusionary nets around finfish farms to reduce injury and siting cages offshore, away from haul-out sites and rookeries.[48,55,62,71,114] Exclusion nets must be strong enough to resist chewing or tearing and should be properly tensioned to prevent entanglement.[25,114] Innovative net materials, like the Fortress Pen, patented by Huon Aquaculture and made from Kevlar and woven nylon, the same material as bulletproof vests, provides high net visibility and a robust barrier to seal entry. Farms located distant (>20 km) from haul-out sites tended to have fewer pinnipeds trying to forage on farmed fish.[55] In South Australia, predation by New Zealand fur seals and Australian sea lions (*Neophoca cinerea* Péron, 1816) at southern bluefin tuna farms was considered a continuing problem for tuna farmers in Port Lincoln, causing a significant cost to the industry.[153,235] Fur seals were most commonly seen around the farms and in the cages, but the sea lions were aggressive predators that also stressed and damaged the tuna. The fur seals were too small to be a threat to the tuna and fed mostly on the tuna feed and other small fish around the cages. Although fencing was the best method used to deter seals, the most frequent entry method to the tuna cages for seals was jumping over the fences. Frequent cage maintenance, hole repairs, and tuna carcass removal was effective in minimising seal and sea lion attacks.[235]

3.2 | Sea turtles

There are seven species of sea turtles worldwide, including green (*Chelonia mydas* Brongniart, 1800), hawksbill (*Eretmochelys imbricata* Fitzinger, 1843), Kemp's ridley (*Lepidochelys kempii* Garman, 1880), leatherback (*Dermochelys coriacea* Vandelli, 1761), olive ridley (*Lepidochelys olivacea* Eschscholtz, 1829), loggerhead (*Caretta caretta* Linnaeus, 1758), and flatback (*Natator depressus* Garman, 1880). All species except for flatback, which is data deficient, are classified as vulnerable, endangered, or critically endangered.[236] To date, there are few reported incidents of sea turtle injuries or mortalities at aquaculture sites.[237,238] Interactions have been reported at mussel farms in Newfoundland, Canada, and Chile, and pearl and seaweed farms in the Philippines. Sea turtles are observed as incidental visitors around marine fish cages but not perceived as predatory threats to the farmed fish.[239,240] Because they are protected in many countries as threatened or endangered species, the primary concern with sea turtles is the threat of entanglement with nets, lines, or other floating equipment at aquaculture farms, although vessel traffic around farms could also cause collisions.[238,241–244] Relatively little is known about how sea turtles may be impacted by marine fish cage farms and after an exhaustive search, we were unable to find published reports of harmful interactions.

3.2.1 | Entanglement

Sea turtle entanglement reports at aquaculture farms are rare; however, from commercial fishery gear observations, they are vulnerable to entanglement in both horizontal and vertical lines.[237] Leatherback turtles and cheloniid turtles behave differently in response to lines used in commercial fishery gear,[237,238] and thus, the vulnerability and mechanics of entanglement are likely different among mussel farm gear types. Uncertainty remains about the entanglement risk posed by high-tension horizontal backbone lines at mussel longline farms because there have been no published reports of entanglements. While tensioned lines may decrease entanglement risk for small cetaceans and cheloniid sea turtles, there is still concern that large whales and leatherback turtles may be at risk for entanglement and/or injury if they collide with these lines at mussel farms.

There are three known incidents involving leatherback sea turtles entangled in mussel ropes in Notre Dame Bay, Newfoundland, Canada (Table 5). In 2009, one turtle was found dead and rolled up in the mussel farm lines.[237,245] Two individuals were reported entangled in mussel spat collection lines, one leatherback was found dead at depth in 2010. In 2013 the second was found alive at the surface and released after being disentangled around the head and flippers.[67,237,246] One leatherback was entangled in vertical line anchoring gear associated with a shellfish aquaculture site in the Greater Atlantic Region in US waters in 2014 and released[26] (Kate Sampson, NOAA Fisheries, pers. comm. NOAA NMFS Sea Turtle Disentanglement Network database [STDN]; Table 5). On June 11, 2022, a 900-lb leatherback was entangled off Nantucket, Massachusetts, USA in research aquaculture gear for bay scallop spat collection (David Morin, NOAA Fisheries, pers. comm. 20 July 2022; Table 5). The turtle was found in 3 feet of water entangled around the neck twice and both flippers with two complete sets of gear including four cinder blocks, six surface buoys, and 48 m of line. The turtle was completely disentangled and released alive. At an almaco jack farm in Hawaii, sea turtles have not been observed around the fish cages. Because green sea turtles are common in the nearshore waters of the main Hawaiian Islands, it is likely they occasionally swim through the farm area despite no recorded sightings.[168] Additional records of sea turtle and aquaculture farm interactions were not confirmed in this investigation. In Chile and the Philippines, turtles interact with aquaculture farms, primarily mussel, pearl, and seaweed, but are considered a nuisance and therefore are harvested, intentionally killed, and are not protected or reported.[59,137] Aquaculture gear impacts to sea turtles are understudied and need to be considered in future entanglement and mitigation actions.[237] Entanglement injuries can result in reduced feeding efficiency, impaired locomotion, exertional myopathy, compromised blood flow and necrosis, infections, and prolonged, debilitating health complications or death.[237,247]

In the United States, NOAA Fisheries held a workshop in 2008 to address sea turtle species distribution in the Northeast US, interactions with vertical lines in fixed gear commercial fisheries, injury assessments, and disentanglement techniques.[248] The participants suggested some sea turtles become entangled in vertical lines by chance, because of general curiosity, or as they forage. Participants agreed that fishing gear is often set in areas where turtles forage and thus present an opportunity for entanglement. In an analysis of leatherback turtle interactions with fixed gear fisheries over almost two decades of observations, Hamelin et al.[237] determined turtles are vulnerable to both horizontal and vertical lines. Slack lines pose the greatest entanglement threat because the lines wrap tightly, multiple

TABLE 5 Documented sea turtle entanglements at shellfish farms.

Location	Species common name	Scientific name	Number	Year	Gear type	Outcome	Citation(s)
Newfoundland Canada	Leatherback sea turtle	*Dermochelys coriacea*	1	2009	Mussel farm	Fatal	237,245
Newfoundland Canada	Leatherback sea turtle	*Dermochelys coriacea*	1	2010	Mussel farm spat line	Fatal	67,237
Newfoundland Canada	Leatherback sea turtle	*Dermochelys coriacea*	1	2013	Mussel farm spat line	Released	67,237,246
USA Greater Atlantic Region	Leatherback sea turtle	*Dermochelys coriacea*	1	2014	Shellfish farm vertical anchor line	Released	NOAA Fisheries STDN, unpublished data[a]
USA Nantucket, Massachusetts	Leatherback sea turtle	*Dermochelys coriacea*	1	2022	Bay scallop spat collection gear	Released	D. Morin, NOAA Fisheries, pers. comm. 20 July 2022

[a]NOAA Fisheries Sea Turtle Disentanglement Network (STDN) database.

times around flippers as turtles try to escape. Because they are unable to free themselves, they can drown if held under water and their survival depends on human intervention to remove the lines.[237] These conclusions are validated in an analysis of 15 years of entanglement reports in fixed gear fisheries off Massachusetts, USA.[238] The leatherback entanglements at mussel farms occurred in spat collector lines that are typically not anchored to the substrate. Fixed gear that is highly weighted may pose an immediate threat to leatherbacks when they are entangled at depth because they cannot surface to breathe.[237,238]

3.2.2 | Underwater noise disturbance

Underwater noise disturbances from aquaculture farm construction, operations, or decommissioning could potentially alter the environmental soundscape and impact sea turtles in the vicinity of these activities. While underwater noise impacts to marine mammals are well-studied,[177,179–182] impacts to sea turtles are relatively uncertain.[249,250] It had long been assumed sea turtles do not vocalise and little is known how sea turtles use auditory cues to avoid predators, locate prey, or navigate their environment.[251,252] Experimental studies have verified sea turtles can detect sounds both in air and underwater[253] and recent research on green sea turtles by Charrier et al.[252] suggests acoustic intra-specific communication may exist. Sea turtles inhabit different ocean habitats throughout their life history.[254] Juveniles and adults spend most of their time in the inshore environment, which is typically noisier than the open ocean pelagic habitat where hatchlings feed and grow. The location of the underwater noises from farms and associated vessels could differentially impact important sea turtle behavioural and ecological functions.

3.2.3 | Vessel traffic

In addition to underwater noise, vessel traffic around aquaculture farms can create a navigation hazard and pose a collision risk. Sea turtles are most susceptible to vessel strikes when they surface to breathe, feed, bask, mate, and orient themselves to their surroundings.[255] Sea turtles rely primarily on visual cues to detect vessels[256] and may have limited ability to manoeuvre in the water column to avoid collisions, depending on the vessel size and speed. Inclement weather and reduced light at night decreases visual acuity and increases the collision risk. All seven species of sea turtles have been injured or killed by vessel strikes.[194] It is unknown what proportion of sea turtles struck by vessels survive their injuries. It is difficult to quantify the impact of vessel strikes on sea turtles because their bodies are negatively buoyant and sink, so fatal vessel collisions may go undetected and unreported. There is good evidence from sea turtle stranding data from Florida, USA, that postmortem vessel strikes are rare and the vast majority of stranded animals with vessel strike injuries were hit antemortem and died as a result.[257] Schoeman et al.[194] provide detailed mitigation measures to improve vessel safety around marine animals to prevent collisions.

3.2.4 | Risk management

Given the potential significant impact of entanglement on sea turtles in aquaculture gear, detailed accounts at mussel and finfish farms are paramount to understand the frequency and severity of encounters. To reduce negative interactions, best farm management practices include the use of rigid netting material for the cage, keeping mooring lines taut, and removing any loose lines or floating equipment around the farm. Building on the 2008 NOAA Fisheries sea turtle workshop,[248] NOAA Fisheries and a representative from Fisheries and Oceans Canada met to develop a summary of relevant information and a matrix of gear research ideas.[258] Many fisheries gear modifications presented in the matrix to minimise turtle entanglements provide possible modifications to vertical lines used in aquaculture and could be explored further. In addition to gear modifications, minimising marine debris reduces the potential for turtles to ingest trash associated with farm operations. Because ADDs used to deter marine mammals are outside the frequency turtles detect underwater,[251,259] they would likely not be effective at keeping sea turtles away from gear. However, low frequency acoustic alerts targeting sea turtle sensitivity ranges, have been used in gillnet fisheries in Baja, Mexico and showed a 60% reduction in turtle bycatch per unit effort (Dow Piniak, NOAA Fisheries, pers. comm. 9 May 2022). Dodge et al.[238] recommended the need for maintaining a trained and active disentanglement network for bycatch mitigation, which is critical not only for turtles, but marine mammals as well. Coordination with these disentanglement networks is paramount for marine aquaculture farms where vulnerable species are present.

3.3 | Seabirds

Marine aquaculture farms across different regions may interact with species of albatross, cormorants, gannet, loons, pelicans, auks, gulls, petrels, storm petrels, shearwaters, diving ducks, penguins, and terns, among others. Depending on the geographic range of these seabird species, the potential for overlap with aquaculture farms is an imperative siting consideration.[260] Both mussel farms and finfish farms attract seabirds.[36,109,261–264] Marine aquaculture farms may exclude seabirds from important habitats including migratory routes and feeding grounds, or may cause benthic disturbances that cause high turbidity and reduce foraging success, altered prey availability, foreign object ingestion, entanglement, and collision with farm structures.[261,263,265,266] Disturbances to breeding colonies may result in nest abandonment, reduced breeding success, and localised population depletion.[263,267]

3.3.1 | Habitat modification, attraction, or exclusion

The attraction and aggregation of forage fish around farm structures as well as the farmed mussels and net fouling organisms can provide enhanced feeding opportunities for marine diving birds.[58,114,224,225,261,263,266] In Washington State, diving birds feed on colonising epifauna that accumulates on farm structures.[239,268] Environmental changes to benthic communities in proximity to fish farms could potentially disrupt diving bird feeding preferences.[266] Flocks of diving ducks such as the black scoter (*Melanitta nigra* Linnaeus, 1758) or common eider (*Somateria mollissima* Linnaeus, 1758) can substantially impact mussel biomass by predation at farms.[30,224] Small fish commonly consumed by birds are attracted to net pen structures, residual feed, and farm lighting.[204,269,270] Seabirds are also attracted to lights around net pen facilities, which put them at risk of collision.[261–263,271] Increased bird populations around farm structures may add large amounts of nutrients to the surrounding water, affecting fouling organisms on nets.[114,261] Adding nutrients to the water column can also cause algal blooms and alter birds' ability to locate prey due to increased water turbidity.

Floating farm structures may provide roosting locations close to foraging grounds and afford protection from terrestrial predators.[56,262,266,272] However, the refuge and increase in foraging efficiency could also alter foraging behaviour, resulting in changes in the food web or disturb breeding colonies. Habitats available for surface feeding birds (gulls, terns, shearwaters) can also be reduced because of the physical structures of mussel and finfish farms,[36,56,262] and the presence of added activity and boat traffic around these farms disrupts seabird breeding and feeding behaviour.[262,263]

A study in southwest Ireland[89] found no adverse effects on seabird species richness or overall abundance at nearshore mussel farms (14–17 m deep). More birds, namely cormorants and gulls, were present in mussel farm areas. The farm provided structure for perching and source of food from epifauna growing on above-water structures. Neither benefit would be expected at submerged offshore mussel farms, which do not include rigid structures suitable for perching. In a comparison of seabird activity budgets between three areas of nearshore mussel farms and three control sites in Bantry Bay, Ireland, Roycroft et al.[265] concluded the impact of mussel suspension culture appeared to be positive or neutral on seabirds at the study site. Aguado-Giménez et al.[264] observed the spatiotemporal variability of piscivorous sea birds over a year at eight fish farms in the western Mediterranean and recorded seasonal differences in bird density and assemblages. Bird density increased from fall to winter and decreased in spring and summer, which was partially explained by season and distance to breeding/wintering grounds. In Admiralty Bay, New Zealand, Fisher and Boren[273] surveyed king shag (*Leucocarbo carunculatus* Gmelin, 1789) foraging distribution and habitat use around mussel farms. Although a few observations of this behaviour have been reported, they did not observe birds foraging in the farms. The birds perched on farm structures to rest, roost, and preen. In Chile, Jiménez et al.[274] observed higher seabird abundance at salmon pens compared with their control sites and found salmon farming had no significant effect on avian species richness. The primary species included diving piscivores, perching piscivores, omnivores, and carrion eaters but did not include herbivores, invertebrate, or surface feeders.

3.3.2 | Entanglement

Entanglement poses the biggest threat to seabirds in both mussel[42,275] and finfish aquaculture operations[48,68,262]; however, entanglement data resulting in injury or mortality are rarely available. Seabirds are at risk of becoming entangled in lines or nets, colliding with structures while flying, and ingesting debris, all of which may result in injuries or death.[25,56,261,262] Ingestion and entanglement of marine debris from associated farm activities could block seabird digestive tracts and cause serious injury or death.[261,262,276,277] In 2003, Lloyd[36] reported there were no published accounts of seabird entanglements in New Zealand aquaculture. More recently, both Huon Aquaculture[162] and Tassal Group[278] report bird releases and mortalities at their Tasmanian salmon farms in real time on their sustainability dashboards.

Incidental seabird bycatch during commercial fishing operations is recognised as a global problem, but there are no official reports of seabird deaths as a result of entanglement in fixed lines of the type found in mussel farms or spat catching areas.[276,277] In Marlborough Sound, New Zealand, adult and young Australian gannet (*Morus serrator* GR Gray, 1843) have been found entangled in rope ties from mussel farms incorporated into their nests.[36,272] At finfish farms, diving birds become entangled in underwater fish containment nets and drown. Predator exclusion nets can also entangle birds, resulting in limb injuries or death. Seabirds are considered a low predatory risk to the live farmed fish but may scavenge mortalities or take fish during transfer or harvest.[21,239,242,268]

3.3.3 | Risk management

Richman[279] recommended deterrent methods to reduce sea duck depredation at mussel farms. She noted, although loud sounds frighten birds, they can become desensitised and habituated. Visual devices like streamers, reflective mirrors, and model predators, are minimally effective. Human activities, boat chasing, and falconry are effective but labour intensive. Exclusionary nets are effective for small nearshore mussel farm sites but less practical for large offshore farms. And while shooting is highly effective at the individual level, it requires permits and may be socially unacceptable.

Net material and size play an important role in entanglement risk. Nets with large meshes, small diameter twine, or transparent monofilament are more likely to cause seabird entanglement.[280] Fortunately, offshore marine fish farms do not require small diameter, transparent nets for any component of the cage design and farming operation. Research conducted by Nemtzov and Olsvig-Whittaker[281] examined 101 netted marine cages using 11 different net types varying in mesh size, material, colour, and thickness. They studied the influence these net design features had on bird mortality. Bird mortality was largely a function of net visibility.[281] Fewer birds were entangled in nets with dark-coloured netting, meshes ranging from 20 to 30 mm, and made of woven nylon 1.8–2.0-mm thick.

Enclosing predator nets at the bottom of cages and using top nets over cages to exclude birds, ensuring nets are kept taut, and frequent maintenance decrease the number of entanglements and subsequent mortality in exclusion nets.[261,280,281] Exclusion nets can be an effective solution; however, they cannot be used everywhere and thus must be used discriminatingly.[280] Any change in cage design must consider the method by which avian predators forage.[153] Net pen site selection to avoid overlap with home ranges, critical breeding grounds, and foraging habitats is prudent.[241,244,261,262] Siting farms in areas with strong currents to disperse nutrients away from fish cages and minimising feed waste reduce the potential for negative interactions fostered by aggregating prey.[261,262] The light type and direction are important to abate collisions with net pen structures that could result in injury or death.[261,262] Curtailing the growth of biofouling on nets and keeping them taut reduces the risk of attraction and entanglement. Debris removal and continuous monitoring diminish the risk of ingestion or entanglement.[261,262] It may be possible to reduce the negative impacts caused by human disturbances at seabird breeding grounds by situating aquaculture farms away from seabird colonies and nearby foraging areas.[263]

3.4 | Sharks

Consistent with the FAO Code of Conduct for Responsible Fisheries,[282] the International Plan of Action for the Conservation and Management of Sharks[283] provides guidance for member nations to develop their own shark conservation management plans. Under the Convention on Migratory Species intergovernmental treaty, 49 Member States and 12 Cooperating Partners signed a Memorandum of Understanding on the Conservation of Migratory Sharks in 2010, amended in 2018 (https://www.cms.int/sharks/en).[284] Backed by the United Nations Environmental Program, this memorandum is a legally non-binding international instrument. The agreement is to achieve and maintain a conservation status for migratory sharks based on the best available scientific information, considering the listed species' socioeconomic value in various countries. Given the recent global interest in shark population declines and the need to implement conservation efforts,[285–288] the potential impacts of offshore aquaculture to sharks are important to evaluate.[26,147,289,290]

Aggregating fish around farms attract sharks to finfish farms in Puerto Rico,[291] Hawaii,[292] the Bahamas,[293] Canary Islands,[294] Latin America,[226] the US Pacific Northwest,[239] New Zealand,[56,290] and Australia.[25,147,289,295] In addition to wild fish attracted to farms, sharks are likely attracted to multiple stimuli associated with fish farms, including live fish in cages, the presence of dead fish at the bottom of cages, the odour trail generated during feeding, farming operation sounds, and the physical structures.[58,147,289,290] Sharks damage farm structures and cause economic impacts to the farms through fish escapes and predation as well as decreased production from cultured fish under regular attack.[151]

3.4.1 | Shark presence at offshore farms

Four species of sharks frequent New Zealand King Salmon farms including spiny dogfish (*Squalus acanthias* Linnaeus, 1758), bronze whalers (*Carcharinus brachyrus* Günther, 1870), blue sharks (*Prionace glauca* Linnaeus, 1758), and seven-gill sharks (*Notorynchus cepedianus* Péron, 1807) because they are primarily attracted to dead fish at the bottom of the cages.[290] In Australia tuna lots and yellowtail kingfish and mulloway (*Argyrosomus japonicas* Temminck & Schlegel, 1843) cages, interactions with pack-hunting bronze whalers are a more significant issue than opportunistic, solitary hunting white sharks (*Carcharodon carcharias* Linnaeus, 1758); however, white sharks attract more attention because they are a higher profile species and protected under the Environment Protection and Biodiversity Conservation Act of 1999.[289] According to the Tuna Boat Owners' Association in Australia, interactions with white sharks and bronze whalers tend to occur in specific areas and at individual farms, during fish transfer from towing to farm pontoons in the grow-out cycle, and in seasonal patterns.[289]

In the Mediterranean Sea, white sharks have been sighted near tuna farms. In Norway, spiny dogfish are attracted to dead fish in the bottom of salmon cages.[290] A telemetry study of sandbar (*Carcharhinus plumbeus* Nardo, 1827) and tiger sharks (*Galeocerdo cuvier* Péron & Lesueur, 1822) near almaco jack cages off Hawaii found sharks aggregated near the cages with some individuals recorded for the 2.5-year study.[168,292] From June to August 2008, shark bites of various sizes were discovered in the webbing of one cage and were immediately repaired. In 2009, a small Galapagos shark (*Carcharhinus galapagensis* Snodgrass & Heller, 1905) breached the cage and was caught and released unharmed. In response to these net breaches, the farm changed the cage mesh material to deter sharks and prevent further damages.[168] Off Réunion Island, video monitoring documented 190 bull shark (*Carcharhinus leucas* Müller & Henle, 1839) observations over 1 month under a sea cage fish farm. Many sharks were re-sighted and at least three individuals displayed site attachment throughout the month-long study.[296] The authors reported that no sharks were observed attacking the cage to access the farmed fish.

3.4.2 | Threats to gear and workers

In Norway, spiny dogfish bite through holes to prey on caged salmon and are a well-known challenge for fish farmers in some areas.[151] In southeastern Tasmania, large sharks were recorded twice as the cause of large (1.5 m) tears in fish farm containment nets; one of these attacks was by a thresher shark (*Alopias vulpinus* Bonnaterre, 1788).[153] Yellowtail kingfish farms in Australia are frequented by bronze whalers, which tend to aggregate in groups of 4–14 fish. The sharks typically break through the bottom of the nets but have also broken through the sidewalls.[289] In South Australia, aquaculture cages have been identified as an entanglement threat to white sharks.[297] The sharks will break into aquaculture cages in search of food, posing a risk to the farmed stock and cage operators.[295]

Increased encounters with sharks could occur if the animals are attracted to net pens and share space with recreational or commercial divers.[298] Because of these threats, dangerous species are sometimes lethally removed from marine farm areas. For safety reasons, some farm managers have killed sharks before removing them from cages. Before 2001, within a 5-year period, there were nine confirmed white sharks captured in tuna ranches, of which six were killed and three were already dead.[299] In Australia, an estimated 20 white sharks a year are killed at marine aquaculture farms,[295,299] and in response to the need for better conservation practices, live-release methods have been developed in South Australia.[289] In New Zealand, culling in and around farms happens infrequently and according to anecdotal information, shark mortalities from entanglement or entrapment are rare.[290] In South Africa, a salmon farm situated inside an ecologically significant white shark congregation area closed after eliciting major negative public reactions.[300] In the first year of operations (2005) at a fish farm in Hawaii, cage divers were not removing all moribund fish from the cages. An aggressive tiger shark took up residency at the farm to feed on the dead fish and displayed agonistic behaviour causing divers to exit the water for safety. To protect the employees from future attacks, the shark was killed. Because using this long-term mitigation strategy was unacceptable, the farm worked in collaboration with state agencies to develop a shark management plan, which included relocation, as recommended by catch and release research.[168] After that incident, the tiger and sandbar sharks observed around the farm posed minimal threat to the farm workers. Another time, a humpback whale carcass floated near the farm, drawing a swarm of tiger sharks around the fish cage. The farm workers were able to drag the dead whale offshore so it would not wash up on the beaches or pose risk to the farm operations (Jennica Hawkins, Ocean Era, pers. comm. 1 December 2020).

3.4.3 | Dietary shift

Sharks are strict carnivores and consume a wide range of prey including plankton, invertebrates, teleosts, elasmobranchs, birds, reptiles, and marine mammals. In most shark species, prey type and size may change with shark ontogenetic shifts, expanded ranges, and improved hunting skills.[301,302] Generally, sharks feed opportunistically on the most abundant prey item, primarily fish.[302,303] Sharks can be attracted to fish farms because wild fish often aggregate around the farm structures.[8,56,61,122,269,270] The nutritional value of these wild fish could change if their diets primarily consist of uneaten feed pellets from farmed fish, as compared with their natural prey sources. Although many aquafeeds are most commonly composed of fishmeal and fish oil, many manufacturers are moving to more sustainable plant-based ingredients, which modify the fatty acid composition and fat content levels of tissues of wild fish that feed on the lost pellets.[6,304] In addition, antibiotics in some feeds have the potential to accumulate in the tissues of the wild fish and result in liver damage, acute toxic effects, bacterial resistance, and immune system suppression.[298]

Octopus, molluscs, and crustaceans are prey for small bottom-dwelling and bottom-feeding sharks.[302] Benthic macro-invertebrate communities can change in the presence of aquaculture farms because of crop and biofouling organism drop-off and the deposition of farmed fish faeces and uneaten food pellets.[56,305–308] If preferred prey items are not available, sharks may be forced to alter their diets and scavenge dead fish accumulating in cages and uneaten feed beneath farms.[289,290,298] Depending on the shark species and their foraging habits, these farm-induced dietary changes raise concern about the potential effect of farms on the biology of these predators, their trophic interactions, and ecosystem function at different spatial and temporal scales.

3.4.4 | Risk management

As the marine aquaculture industry moves into offshore sites, the potential economic and ecological risk of large-scale fish releases due to sharks tearing nets may be a concern depending on net types and locations used.[8] Technological improvements in aquaculture cage materials like strong PET monofilament and semi-rigid and tightly stretched net walls make cultured fish resistant to predator attacks.[47] The semi-rigid net structure is designed with self-closing properties that prevent fish escape and thermo-formed double twisted mesh to prevent unravelling. The degree to which sharks are attracted to farms to feed on wild fish, farmed fish, or sunken pellets, and the resulting behavioural or ecological impacts are unknown. Although farming offshore may reduce exposure to coastal predators such as pinnipeds and coastal cetaceans, exposure to predatory sharks may increase. In addition, sharks that spend a significant amount of time close to the surface like whale sharks (*Rhincodon typus* Smith, 1828) and basking sharks (*Cetorhinus maximus* Blainville, 1816) may be more vulnerable to vessel strikes and entanglements in slack buoy lines.[107,309,310] The risk of sharks interacting with offshore farms can be managed through site selection to avoid known aggregation areas of local predators, the use of robust containment barriers, and continuous monitoring and removal of dead or injured fish.[9,26,289,299]

3.5 | Marine debris

Similar to fishing gear, lost or discarded aquaculture gear from a facility can contribute to marine debris.[312,313] Potential sources of marine debris from aquaculture operations include rope, nets, buoys, feed bags, plastics, cardboard, wood, rags, tools, syringes, plastic bags, paper waste, oil filters, scrap metal, and general human trash (wrappers, cups, cans etc.). While it may be difficult to determine the origin of buoys, lines, or loose ropes, other debris, such as feedbags, may be more easily traced to aquaculture activities. Marine wildlife is impacted by marine debris through ingestion, entanglement, bioaccumulation, and habitat effects[119,314,315]; and the relative contribution of aquaculture gear is uncertain.[312] Fishing nets, line, rope, and other debris entangles, disfigures, and drowns wildlife by encircling or ensnaring the animals. Infection and debilitation could occur if animals get lacerations or other wounds from debris.[314,316] A marine species' mobility is reduced when it becomes entangled in debris. The animal may suffer from starvation, suffocation, exhaustion, and increased risk of predation due to restricted movement.[314,317] Marine debris can be inhaled accidentally, but often animals feed on it because it resembles their food.[318,319] The materials may accumulate in the animal's stomach and cause malnutrition or starvation once ingested. Sharp objects can damage the mouth, digestive tract, or stomach lining, resulting in nutrition loss, infection, sickness, starvation, and even death.[320,321] In addition, ingested items may block air passages and cause suffocation. Consumption of some debris items may also result in the release of harmful chemicals. To prevent farm waste from becoming marine debris, waste management and accountability are imperative. Detailed site waste management plans will provide specific instructions for the fate of supplies (i.e., ropes, netting, plastics, cardboard, paper, steel drums, chemical containers, scrap metals) to prevent or minimise waste production, control waste, and responsibly recycle, reuse, or dispose waste. Gear at abandoned and derelict farm sites poses a threat to wildlife and habitats when left behind. Debris caused by catastrophic events (e.g., hurricanes or typhoons) that compromise the structural integrity of farm gear pose a threat to marine mammals, sea turtles, seabirds, and sharks. Detailed company recovery plans should emphasise immediate remedial action and specify technology and resources that will be used to rapidly recover equipment.

4 | CONCLUDING REMARKS

The growth of coastal and offshore aquaculture worldwide is drawing attention to the potential environmental impacts, including impacts to protected species. Despite an increased understanding of how protected species may be affected by marine aquaculture farms over the last decade, questions remain. The research and data analysed for this assessment indicate interactions and entanglements with marine shellfish longline gear and finfish cages worldwide pose some level of risk for protected species in coastal and offshore environments (see Table 6 for a summary of stressors and mitigation measures). This study focused on validated, credible reports of interactions and entanglement. We acknowledge that global systems for aquaculture regulation and resource conservation are highly varied and generally reflect the socioeconomic development, industrialisation, and political systems of a nation or region. For countries without regulations, oversight, and accountability, the extent of coastal and offshore aquaculture interactions with protected species is unknown or it is believed that voluntary reports (self-reports) underestimate interactions. It is important to note that offshore aquaculture, aquaculture with exposure to the weather and ocean climate, generally requires a level of technologically advanced infrastructure, sophistication, and investment available in developed countries. As a product of becoming a developed country with a mature economy, these countries generally have established environmental policies to protect natural elements from agricultural and industrial processes. This study did not include marine aquaculture in coastal environments that has been observed to be rapidly expanding in many developing countries and has put enormous pressure on natural resources and environmental sustainability (e.g., Shandong Province, China—the world's most productive region for farmed shellfish).[322,323]

Marine aquaculture siting and sustainable development belongs in an ecologically responsible framework, taking into consideration all potential interactions and effects on vulnerable species and their habitats. Spatial planning and siting of farms to avoid and minimise interactions with populations of protected marine species is an effective strategy for minimising negative interactions.[324] Our review of historical cases around the world suggests that while it appears that aquaculture does not indicate significant impacts to marine mammals, sea turtles, seabirds, and sharks from documented marine aquaculture entanglement events, additional monitoring to verify is warranted. It is unclear if the low incidence is because farms are relatively benign and pose little risk, or because the number and density of farms and the detection level for harmful interactions are considerably low. Furthermore, low frequency entanglements of critically endangered species can result in a significant impact.

Improved information about home ranges, movements, and behaviours of protected marine species in response to aquaculture farming could help inform aquaculture development and provide better understanding of risks to wildlife.[325] Understanding non-lethal effects of disturbance on protected species physiology or behaviour and the potential population level repercussions is key to a comprehensive risk assessment and understanding cumulative effects.[79,80,326,327] (Figure 4).

TABLE 6 Summary of marine aquaculture stressors, sources, and impacts on protected species, including potential solutions and mitigation measures.

Stressors	Sources	Impacts	Vulnerable species	Potential solutions/mitigation measures	Key references
Habitat modification, exclusion, or competition for space	Farm construction, operations, and maintenance activities	Behavioural change, modified access to foraging and reproduction areas, reduction in fitness, death	Cetaceans, pinnipeds, turtles, seabirds, sharks	• Conduct a farm risk assessment prior to structures being placed in the water. Include proximity to critical, sensitive, or protected species and habitats, as well as a description of potential impacts on biodiversity. • Site farms in areas that minimise the likelihood of overlap with the migration routes or critical breeding and feeding habitats of protected species. Locate farms away from haul-out sites and rookeries. • Reduce fish feed waste to minimise attraction to farms and the time protected species and marine life spend near pens. • Log marine mammal presence and behaviour around farms including night-time feeding activity around lighted areas. Report incidents to the appropriate authorities and keep records of entanglements and mortalities.	26,36,43,55,57,58,60–63,65,66,68,70,73,76–80,84–87,89,91,92,94–103,107–111,147,168,204,239,241,244,261–265,268,269,271,274,289,290,292
Physical gear interaction, entanglement, or entrapment	Buoy lines, anchor lines, exclusion nets, cage mesh	Behavioural change, injury, death	Cetaceans, pinnipeds, turtles, seabirds, sharks	• Minimise the number of vertical lines in the water to reduce entanglement risks. • Enact a predator avoidance plan including gear maintenance and repair schedules. Keep all anchor and backbone lines properly tensioned and nets maintained (cleaning, repairing holes). • Consider antipredation measures as preventative and only second as a cure to problems. • Exclusion measures including predator nets, top nets, electric fences, and other deterrents should be installed at the start of the farming operation. This practice will prevent training potential predators to locate a food source and develop predatory behaviours around the farm. • Enclosing predator nets at the bottom of fish cages will prevent mammals and diving birds from getting trapped and potentially drowning. • Develop a communication plan and coordinate with local wildlife authorities trained in rapid animal rescue response in case an animal is trapped or entangled in farm gear. • Practice good husbandry techniques at fish farms to ensure the health of the fish and prevent predation. Remove mortalities from cages and surrounding area and keep food sealed in containers to avoid attracting wildlife to the site.	9,26,36,43,53,55,56,58–60,64,67,70–72,78,84,87,88,105,128–131,135–158,208,237,245,246,266,272,280,281,289,290,299,309–311

TABLE 6 (Continued)

Stressors	Sources	Impacts	Vulnerable species	Potential solutions/mitigation measures	Key references
				• Include a farm decommissioning strategy in the operating plan to maximise efficient gear removal, eliminate marine debris, and minimise opportunities for animal entanglement.	
Underwater noise	Vessels, feeding systems, generators, aerators, net cleaning equipment, acoustic deterrents	Behavioural change, trigger stress response, communication disruption, disrupt foraging efficiency, cause habitat displacement or avoidance, temporary or permanent injury, death	Cetaceans, pinnipeds, turtles	• Reduce vessel speed in the vicinity of animals. • Minimise the noise levels at the source (e.g., feeding systems, generators, equipment at the lowest operable noise level). • Separate the noise-producing activity spatially and/or temporally from the sensitive species. • Avoid or minimise the noise-producing activity within close proximity to sensitive habitats, defining appropriate clearance distances where necessary. • Assess the ambient soundscape environment pre-construction. Test, measure, and monitor noise produced by equipment during construction, operation, and maintenance periods. Compare with the sound frequency and levels at which key marine species produce and receive sound. Practice adaptive management to minimise adverse impacts to resident or transient species in the farm vicinity.	26,43,68,175–180,182–190,208,211,213,217,223
Artificial light	Lights for navigation, personal safety, farm security, submerged lights for fish growth, maturation schedules, reduce fish densities, and evenly distribute fish in cages	Behavioural change	Cetaceans, pinnipeds, turtles, seabirds, sharks	• Limit the use of underwater lighting. Only use appropriate submerged lighting for beneficial outcomes. • Lights should be shielded from all but essential directions. Spotlights should be positioned high above the water so penetration is maximised and reflection is minimised. • Restrict lighting on moored vessels at night to the minimum required for safe operation	55,60,71,122,163,199–204,261–263,271
Presence of vessels	Required for construction, operations, and maintenance	Vessel collision resulting in injury and/or death, navigation hazard, habitat modification, behavioural change, reduction in fitness	Cetaceans, turtles, surface-dwelling sharks (i.e., basking and whale sharks)	• Reduce number of vessels used during operations and maintenance as possible. • Train vessel crew as lookouts to spot and identify animals in the vicinity. • Operate vessels at slow speeds when performing work within and around the farm. Travel at speeds necessary for safe and efficient navigation, i.e., at speeds necessary to maintain steerage if towing equipment, but not so fast that objects in the water cannot be avoided.	191–195,255–257

(Continues)

TABLE 6 (Continued)

Stressors	Sources	Impacts	Vulnerable species	Potential solutions/mitigation measures	Key references
				• When animals are sighted, maintain a minimum approach distance between the vessel and the animal. • Avoid excessive speed or abrupt changes in direction until the animal has left the area. • Reduce speed and shift the engine to neutral when an animal is sighted in the vessel's path or in close proximity to a moving vessel and when safety permits. Do not engage the engines until the animals are clear of the area. • Traverse the same designated vessel transport channels to and from the farm.	
Marine debris	Rope, nets, buoys, feed bags, plastics, cardboard, wood, rags, tools, syringes, plastic bags, paper waste, oil filters, scrap metal, and general human trash	Entanglement or ingestion resulting in sickness, starvation, injury, infection, reduction in fitness, death	Cetaceans, pinnipeds, turtles, seabirds, sharks	• Design a site waste management plan to prevent or minimise waste, control waste, and responsibly recycle or dispose waste. This plan should include specific instructions for the fate of supplies (i.e., ropes, netting, plastics, cardboard, paper, steel drums, chemical containers, scrap metals). Evaluate and renew plan annually. • Source uniquely manufactured farm gear or employ gear marking to allow the materials to be tracked back to specific farms. For example, rope designed with unique patterns can be used so that it can be identified (and quantified) as belonging to a certain farm if it is lost as marine debris.	119,312–321

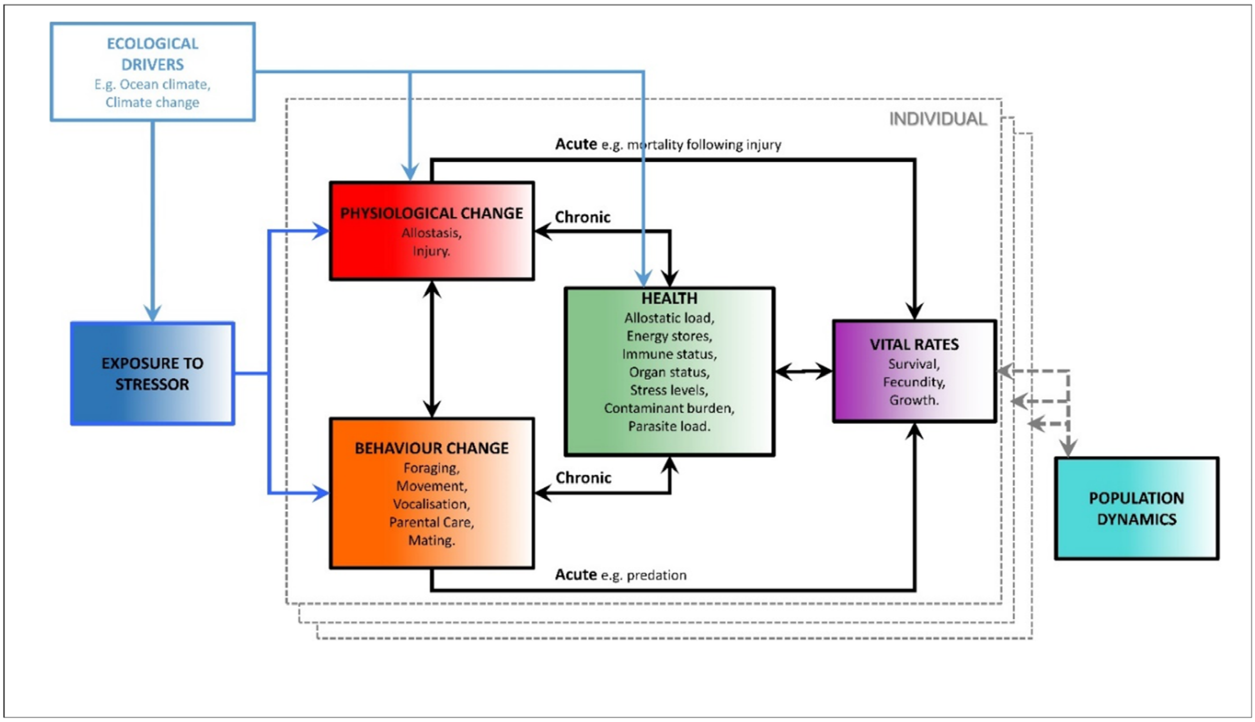

FIGURE 4 "The Population Consequences of Disturbance (PCoD) conceptual framework, modified from National Academies.[79] The boxes within the dashed grey boundary line represent the effects of exposure to a stressor and a range of ecological drivers on the vital rates of an individual animal. The effects are then integrated across all individuals in the population to project their effects on the population's dynamics" (reproduced from Pirotta et al.[80]).

There is also a great need for understanding ecosystem shifts and impacts on species abundance and distribution. For example, aquaculture may influence species composition locally (e.g., attracting of predators) thus influencing local movements of protected species around the farm.

There are technological, monitoring, and siting approaches that may provide risk reduction for protected species interacting with aquaculture farms. In the United States, mitigation measures are commonly explored during pre-application and permitting processes. Practices that warrant more attention include adaptive monitoring, smart design using entanglement simulator technologies,[328] use of breakaways and tension sensors, and innovative deterrent technology. Animal morphology and interactions with fishing gear can inform how mechanics and behaviours such as swimming speed, tail-beat frequency, water column placement, feeding position, veer away, roll, and startle reflex, increase the probability of aquaculture gear entanglement. Identifying how animals use visual and acoustic senses to detect farm structures will advance technical solutions to avoid interactions. Quantitative data on the properties of mooring lines and cages such as tensile strength, bending stiffness, elongation, friction, and wear due to internal and external damage define variables and parameters for developing models. Engineering advances and interaction simulation models can improve aquaculture gear design to minimise entanglement events and reduce injuries and fatalities.

This extensive review highlights interactions between aquaculture farms and vulnerable species, underscores the potential risks involved, and identifies critical areas of research to incite collaborative research. Addressing the potential for protected species interactions with aquaculture infrastructure and gear, improved monitoring protocols, event documentation, as well as mitigation strategies is imperative for responsible aquaculture growth in the ocean. This summary, including best farm management practices and monitoring, will globally inform industry planning, the regulatory processes, and robust species conservation strategies.

AUTHOR CONTRIBUTIONS

Gretchen E. Bath: Investigation; writing – original draft; methodology; validation; writing – review and editing; formal analysis; project administration; data curation. **Carol A. Price:** Investigation; conceptualization; writing – review and editing. **Kenneth L. Riley:** Funding acquisition; writing – original draft; writing – review and editing; project administration; resources; supervision. **James A. Morris:** Conceptualization; funding acquisition; writing – original draft; writing – review and editing; project administration; resources; supervision.

ACKNOWLEDGEMENTS

Support for this work was provided by the NOAA Fisheries, Office of Aquaculture and the NOAA National Ocean Service, National Centers for Coastal Ocean Science. The authors are grateful to the following people (in alphabetical order) for sharing their expertise and their thorough reviews of this review paper: Dr. Tomma Barnes, Dr. Ann Bowles, Langley Gace, Scott Lindell, David Morin, Penny Ruvelas, and several reviewers in the NMFS Office of Protected Resources and

Protected Species Divisions in the US regions. The authors appreciate the insightful reviews provided by three anonymous experts who helped improve the manuscript quality.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

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

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How to cite this article: Bath GE, Price CA, Riley KL, Morris JA Jr. A global review of protected species interactions with marine aquaculture. *Rev Aquac*. 2023;1-34. doi:10.1111/raq.12811