A Review of Aquaculture Gear Characteristics and Impacts on Entanglement Risk for Protected Species

by
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Abstract

Entanglement in fishing gear is the cause of death for hundreds of thousands of marine mammals and sea turtles every year. There are relatively few documented cases of protected species entanglement in aquaculture gear, but events are likely underreported. Interactions with aquaculture are expected to increase in the United States as demand for seafood drives industry growth, new technologies enable farming further offshore, and clarified regulatory processes reduce barriers to entry. Despite this, little attention has been paid to how characteristics of aquaculture gear impact entanglement risk. This research a) catalogs the gear elements thought to influence detection, contact, entanglement, entanglement sustainment, and/or injury severity, and b) summarizes the state of knowledge on how each identified characteristic influences entanglement risk. I find that many of the characteristics are correlated and/or interact in their influence on entanglement. By highlighting relevant gear elements, this review supports future research into system-specific strategies for mitigating entanglement risk.

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Executive Summary

Growing demand for seafood, clarified regulatory processes, and new technologies are driving a rapid expansion in the offshore culture of finfish, shellfish, and macroalgae. Accompanying the growth in the industry are mounting concerns over interactions between protected species and aquaculture systems. Entanglement in fishing gear is one of the leading human-driven causes of mortality in marine mammal populations globally. Other protected species, like sea turtles, are also vulnerable to entanglement, which can impact species' population dynamics through lethal and sub-lethal effects. Compared to reported entanglements in fishing gear, entanglement events in aquaculture gear are relatively uncommon. However, these events are likely underreported and can be expected to increase as the offshore aquaculture industry expands. Up to this point, little attention has been paid to how characteristics of aquaculture gear influence entanglement risk for protected species.

The purpose of my research is to a) collate the state of knowledge on how aquaculture gear characteristics impact entanglement risk for protected species, b) identify knowledge gaps, and c) provide recommendations for future research on aquaculture-protected species interactions. First, I catalog the elements thought to influence gear detection, gear contact, entanglement, entanglement sustainment, and/or injury severity. Then, I summarize the literature on how each relevant characteristic affects entanglement risk. Given the paucity of research on entanglement in aquaculture operations, my review focuses on the literature describing bycatch mitigation in commercial fisheries, which are then related back to aquaculture. A disadvantage of this approach is that fishing gears are often not directly comparable to aquaculture systems. However, a review of the fisheries literature is useful for identifying key characteristics and generating hypotheses for future research in aquaculture entanglement.

I find that many of the identified characteristics are correlated and/or interact in their influence on entanglement risk. In some cases, changing gear characteristics involves trading off risk at different stages of a potential entanglement event. Importantly, entanglement risk varies among systems, sites, and species. Accordingly, it is not within the scope of this report to prescribe strategies for risk reduction. To provide robust recommendations for mitigating entanglement risk, future research will need to focus on particular settings and species, and

caution should be taken in generalizing findings to dissimilar settings. Based on the review of the literature, I provide the following recommendations:

- Increased monitoring of farms (*e.g.* observers, acoustic monitoring, or gear instrumentation), particularly at newly introduced sites
- Marking gear, such as rope, with distinct signatures that can be traced to particular activities or sites
- Standard protocols for documenting entanglement events, with a common database to organize and share information
- Development of new tools to simulate protected species interactions with aquaculture systems
- Requiring the following information on permit applications for review by permitting agencies: gear specifications such as diameter, breaking strength, material type, condition, color, and the presence/absence of knots, along with details on how the gear was configured with other components

Introduction

Background

Marine aquaculture, or mariculture, systems are used for the production of shellfish, finfish, and macroalgae in offshore waters of the United States. These systems employ gears like nets, lines, buoys, and other floating equipment that can pose an entanglement risk to marine organisms like marine mammals and sea turtles. Compared to entanglements in fishing gear, documented entanglements in aquaculture gear are rare (Young 2017). Due to a lack of negative data – that is, data on the absence of interactions with protected species – it is unclear why reported entanglements are relatively uncommon. It may be because aquaculture poses little entanglement risk, or because farm density is so low that detection of harmful interactions is limited (Price et al. 2017). In any case, events are likely underreported. Protected species interactions in the U.S. can be expected to increase as demand for seafood drives industry growth, new technologies enable farming further offshore, and clarified regulatory processes reduce barriers to entry (Young 2017; Exec. Order No. 13921, 2020).

Despite the lack of scientific reporting on the frequency, severity of injuries, or mortality rates associated with aquaculture-related entanglements (Price et al. 2017), anecdotal reports show that such interactions can result in serious injury and mortality. There have been several confirmed instances of marine mammal and sea turtle mortality in shellfish and finfish farms (see Table 1 for summary). For example, there have been two reports of Bryde's whale entanglements in New Zealand shellfish farms that proved fatal (Lloyd 2003). Three leatherback turtles have been reported entangled in mussel farm lines in Newfoundland with only one surviving (Price et al. 2017). In 2016, three humpback whale entanglements occurred at salmon farm sites in British Columbia, Canada, two of which resulted in mortality (Price et al. 2017). Given the relatively slow growth and low fecundity of marine mammals, interaction with fishing and aquaculture operations is among the most serious threats to their species and population survival (FAO 2018; Read 2008). For marine mammals, entanglement can lead to death by drowning and a host of other complications like impaired locomotion, reduced foraging ability, tissue infection, and necrosis, which in turn can lead to death (van der Hoop et al. 2016b). Potential Biological Removal (PBR) is defined as "the maximum number of animals, not including natural mortalities, that may be removed from a marine mammal stock while allowing that stock to reach or maintain its optimum sustainable population" (16 USC § 1362). For species with low levels of PBR, like the North Atlantic Right Whale, the loss of even one individual to entanglement can have drastic consequences for their population dynamics (NOAA Fisheries 2019).

Table 1 – Global cases of protected species infractions with aquaculture gear referenced in Price et al. 2017

Location	***Species***	***Year***	***Gear Type***	***Outcome***	***Citation***
Australia	Humpback Whale (calf)	2005	Mussel crop line	Released	Clement 2013
	Humpback Whale	1982–2010	Mussel farm	Unknown	Groom & Coughran 2012
	Humpback Whale	1982–2010	Abalone	Unknown	Groom & Coughran 2012
	3 Humpback Whales	1982–2010	Pearl	Unknown	Groom & Coughran 2012
New Zealand	Bryde's Whale	1996	Spat line	Fatal	Lloyd 2013; Clement 2013
	Bryde's Whale	Unknown	Unknown	Unknown	Lloyd 2013; Clement 2013
South Korea	North Pacific Right Whale	2015	Mussel farm	Released	IWC 2015
Argentina	Southern Right Whale	2011	Unconfirmed aquaculture gear	Unknown	Bellazi et al. 2012
Iceland	Humpback Whale (juvenile)	2010	Spat line	Fatal	Young 2015
	Harbor porpoise	1998	Spat line	Fatal	Young 2015
North Atlantic Ocean	North Atlantic Right Whale	Unknown	Unspecified aquaculture	Unknown	Johnson et al. 2005
California, USA	Grey whale	Unknown	Unknown	Unknown	Lloyd 2003 (unconfirmed)
Canada	Humpback Whale	2016	Salmon farm	Fatal	P. Cottrell, Fisheries and Oceans Canada
	Humpback Whale	2013	Fish farm	Fatal	Fisheries and Oceans Canada (DFO)

	Leatherback sea turtle	2009	Mussel farm	Fatal	Ledwell & Huntington 2010
	Leatherback sea turtle	2010	Spat line	Fatal	Scott Lindell
	Leatherback sea turtle	2013	Spat line	Released	Scott Lindell

Purpose

A comprehensive assessment of the risks of aquaculture to protected species will need to have multiple components to be comprehensive. Marine spatial planning (MSP) is needed to identify overlap between potential sites and species distributions. Review of operational considerations, like the amount of boat traffic or schedules for cleaning finfish cages, can provide information on potential negative interactions, including entanglement, habitat exclusion, and underwater noise disturbance. A separate necessary component is a review of risks posed by gear types and specifications. These exist for wild-caught fisheries yet are lacking for aquaculture (e.g. Cox et al. 2007). Compared to the body of research on commercial fishery gears, there has been very little research on how characteristics of aquaculture gear influence entanglement risk.

The purpose of this research is to catalog the elements of aquaculture gear that are thought to influence entanglement likelihood and/or severity. I also summarize the state of knowledge on whether and how each proposed characteristic impacts risk for protected species. Gear elements might influence the likelihood of gear detection or contact with gear, the likelihood of entanglement given contact, the severity of injuries, the likelihood of mortality, or some combination of those factors. By providing a starting point for a list of important gear metrics, the research will inform the NOAA guide aimed at describing aquaculture gears used in offshore waters of the United States. The research findings may also support the regulatory agency's role in formulating Best Management Practices (BMPs) for aquaculture operations and in issuing Programmatic Environmental Impact Statements (PEIS) for pre-permitted Aquaculture Opportunity Areas (AOAs). Additionally, communicating the research to prospective aquaculture entrepreneurs can provide clarity on the gear specifications and technical details of interest to regulatory agencies on permit applications. Finally, by identifying knowledge gaps and research needs, this document can serve as a useful launching point for future research in aquaculture entanglement.

Methods

The primary method involved in this research is a literature review, along with expert interviews with protected species biologists, fisheries bycatch experts, and ocean engineers. Sources for this research include published field and laboratory studies, bycatch mitigation trials, conference proceedings, peer-reviewed academic articles, agency white papers, University theses, government reports, and meta-analyses of bycatch studies. Sources were collected using the Duke Libraries search function, Google Scholar, and by following references cited in the peer-reviewed academic journal publications and in the grey literature. Since the literature on entanglement in aquaculture systems is so sparse, the majority of the research presented within focuses on the extensive literature on protected species bycatch in commercial fisheries. This is satisfactory because some gear and gear components used in fisheries are analogous to those used in aquaculture. It is therefore useful to relate findings from the fisheries literature back to aquaculture. However, there are potential roadblocks since fishing and aquaculture do have large differences, so caution is noted to prevent assuming false equivalency due to this gap in the literature.

Generally, fixed fishing gears are more analogous to aquaculture systems than mobile gears, like trawls, encircling nets (purse seines), dredges, or hook and line methods (Gabriel et al.

2005; Price et al. 2017). While similarities and differences between commercial fishing and aquaculture gear will be discussed in greater detail in a later section, it is useful to draw a few comparisons in advance. Anchoring systems and buoy lines can be entanglement hazards in fixed fishery gears, like gillnets, traps, and pots (Knowlton et al. 2016). These systems bear some resemblance to structures used at marine farms (Price et al. 2017). However, anchor systems used for aquaculture facilities tend to rely on heavy gravity or plow anchors, thick metal cables or high tensile strength lines, and high tension (Ögmundarson et al. 2011). They are not considered to pose high entanglement risk, although they could pose risk of injury to animals in the event of a collision (Price et al. 2017). Buoy lines used to mark the boundaries of farm sites are similar to those used to mark gillnets, traps, and pots, which are hazardous to wildlife (Price et al. 2017). However, gillnets, which by design are intended to ensnare animals, do not compare well to the taught, heavy, multifilament nets used in fish farms (Gabriel et al. 2005). Despite the imperfect analogies, relating findings from the commercial fisheries literature to aquaculture provides useful insights into the mechanisms affecting entanglement.

Scope

For several reasons, it is beyond the scope of this work to generalize about important thresholds for entanglement risk or provide recommendations on low-risk gear configurations. For one, entanglement risk seems to be site- and species-specific. An insight from the literature on commercial fisheries bycatch is that mitigation methods that effectively reduce bycatch for a species in one region may not be effective for other population segments (FAO 2018). Importantly, risk depends on the morphology and behaviors of particular species. To provide a few examples, the tendency of some marine mammal species to roll upon making contact with gear in the water column has implications for whether, how, and where they become entangled

(Howle et al. 2018). Pinnipeds are known to manipulate nets at finfish farms in attempts to depredate on fish, but they may be less likely to interact with shellfish farms since they do not commonly feed on shellfish (Kemper et al. 2003). The size of whale individuals and species can influence their likelihood of breaking free of entangling gear (Knowlton et al. 2016). Given the many species- and site-specific elements that influence entanglement, it was not feasible or appropriate to prescribe entanglement mitigation measures as part of this research effort.

Another reason for avoiding prescriptive claims is that many of the identified characteristics are correlated with each other or interact in their influence on entanglement risk. Additional attention will be paid to this issue in the discussion section. The relevant point is that the influence of certain characteristics on entanglement risk will depend on other gear parameters in that system. Also, changes to gear characteristics can involve trading off risk at different stages of a potential entanglement event. For example, high tension may reduce the likelihood of rope looping and becoming entrained on an animal, but it might also increase the severity of lacerations.

Due to the limitations of the project scope, the focus was restricted to two taxa of protected species: marine mammals and sea turtles. It is worth noting that other groups of protected species, like sharks and sea birds, have also been known to become entangled in aquaculture gear (Price et al. 2017). The three main types of mariculture – shellfish, finfish, and macroalgae – were considered. However, attention mostly focused on shellfish and finfish farms because no reports of entanglement in macroalgae farms were uncovered during the review process, which may simply reflect the limited extent of the developing industry.

In addition to the gear characteristics described in this literature review, several other characteristics were identified as relevant to assessing entanglement risk. These characteristics were not reviewed in detail given that their influence on entanglement risk is assumed to be system-specific (i.e. not generalizable across systems, as is true of the reviewed gear elements). These gear elements are buoyancy, scope, profile, buoy volume, anchor type, and material type. The buoyancy of rope or line can affect the amount of slack line present in the water column, and slack line poses entanglement risk to marine mammals and sea turtles (NOAA 1997). The scope of vertical lines refers to the ratio of the length of a line to the depth to which it descends. Reduced scope is associated with tighter lines and less looping, which may reduce the probability of ropes entangling animals (FAO 2018; California Dungeness Crab Fishing Gear Working Group 2018). The profile of aquaculture gear refers to the area it occupies in the water column, which can influence the likelihood that animals come into contact with gear (FAO 2018). The quantity and volume of buoys used to suspend aquaculture systems influence the upward force on gear and accordingly the vertical profile and/or tension on gear (SMRU et al. 2001). More or larger buoys can also increase the stress on an animal in the event of entanglement by creating drag (van der Hoop et al. 2016a). Certain anchor types, like helical anchors, are more likely to keep a line under tension and reduce erratic movement, thus reducing risk of entanglement (Benjamins et al. 2014). Finally, material type, which refers to the type of synthetic or natural fibers used in gear, can impact entanglement risk by influencing other relevant characteristics, like breaking strength and material stiffness (reviewed below).

Literature Overview

Breaking Strength

Breaking strength refers to the highest tensile force that an object (e.g. rope, line, or netting) can withstand before rupture. Line diameter, manufacturing process, use of weak links, weak rope, or knots, and polymer type influence breaking strength. Additionally, mechanical stress, abrasion, UV exposure, and other aging may reduce strength over time (Knowlton et al. 2016). This gear characteristic is relevant in assessing entanglement risk for large whales because it influences the likelihood that entangled whales can escape gear. Higher breaking strength gear poses a greater risk that an entangled animal will be unable to free itself. Entanglement can cause drowning and severe injury, impair feeding success, impose high energetic costs, and elicit stress responses that compromise the health or reproductive success of baleen whales (Knowlton et al. 2016; Moore et al. 2013; Cassoff et al. 2011; Pettis et al. 2004). Entanglement duration is a critical determinant of whale survival (van der Hoop et al. 2016b). Research by Knowlton et al. (2016) suggests that adopting reduced breaking strength (RBS) ropes could decrease the number of life-threatening entanglements for species like the endangered humpback and North Atlantic right whales. Specifically, the researchers find that broad adoption of ropes with breaking strengths of less than 7.56 kN could reduce the number of life-threatening entanglements for large whales by at least 72%.

Substantial research effort has focused on the frequency and severity of large whale entanglements in pot/trap and gillnet fisheries along the east coast of North America. In a review of 70 entanglement events (30 right, 30 humpback, 8 minke, and 2 fin whales) involving 132 different ropes, Knowlton et al. (2016) found that whales with larger body size tended to be entangled in ropes with higher breaking strength. The ropes that entangled right whales and those that entangled humpbacks had significantly higher breaking strengths than ropes that entangled minke whales, the smallest species in the study (Knowlton et al. 2016). Additionally, the breaking strength of ropes found on adult right whales was significantly higher than the breaking strength of those found on juvenile right whales (Knowlton et al. 2016). Ropes entangling adult right whales were also significantly stronger than those found on both adult and juvenile humpbacks, a species with “less girth and strength” than right whales (Knowlton et al. 2016).

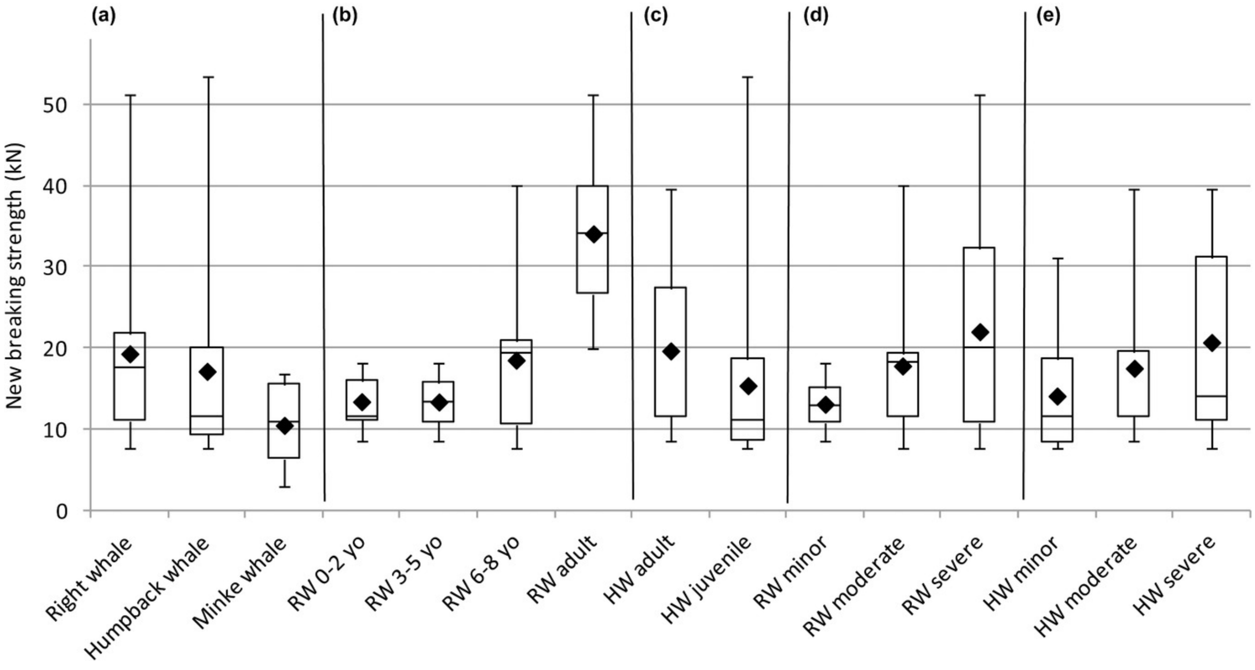

Figure 1: Relationship between breaking strength and entanglement in fishing ropes by species, age class, and severity of injury. Source: Knowlton et al. 2016

These results suggest that smaller, weaker whales are more likely to die in strong ropes and go undetected (Knowlton et al. 2016). Similarly, the fact that larger whales were less frequently observed in weak ropes suggests they can break free of weaker gear – no adult right whales were found in ropes with a breaking strength of less than 20.02 kN, whereas juvenile right whales and smaller species were commonly encountered in weaker ropes (Knowlton et al. 2016). The load-bearing requirements of a rope-, line-, or net-based marine activity determine the minimum operable breaking strength. Accordingly, the use of RBS rope may not be as relevant in addressing entanglement risk for smaller whale species, calves of large whale species, or other taxa like sea turtles (Knowlton et al. 2016).

Results of the 2016 Knowlton study suggest that breaking strength may also influence the severity of entanglement-related injuries. Analysis revealed a trend between breaking strength and injury severity for right whales. However, differences in breaking strength were only significant when comparing minor to severe injury cases (Knowlton et al. 2016). No such relationship was detected for humpbacks (Knowlton et al. 2016). The authors also note that in the 1990s, fishing rope construction shifted toward stronger materials and more durable ropes. This change coincided with and may explain an increase in the frequency of moderate to severe injuries for right whales (Knowlton et al. 2016). Beginning around 1992, the advent of co-extruded floating ropes, like *Polysteel*, and blended sinking ropes allowed heavier traps to be fished in deeper water offshore. These changes in rope strength and the spatial distribution of gear likely exacerbated entanglement risk and may have contributed to the trend in right whale injuries starting in the mid-1990s (Knowlton et al. 2016).

Weak Links

In addition to RBS rope, several types of rope modifications and attachments designed to reduce breaking strength have been proposed or implemented. These designs are intended to mitigate risk of life-threatening entanglement by lowering breaking strength at some or all portions of ropes. Weak links connect sections of rope and are intended to break at a target load (FAO 2018). They are generally comprised of hog rings or plastic rings (FAO 2018). Knots in ropes similarly function to reduce breaking strength at a specific location. However, there is concern that knots may increase the likelihood that ropes become lodged in baleen or wrapped around the appendage of a large whale, and their use is discouraged by NOAA Fisheries (FAO 2018). Other proposals for weak links include splicing pieces of manila into ropes, using breakaway buoys, and cutting then reassembling rope using braided sleeves (FAO 2018).

The efficacy of past management efforts to reduce takes of Atlantic large whales by requiring weak links in trap/pot and gillnet fisheries is uncertain (FAO 2018; Pace et al. 2014;

Knowlton et al. 2012; Knowlton et al. 2016). Under the Atlantic Large Whale Take Reduction Plan (ALWTRP), weak links were required between the vertical endlines and surface buoy systems of pot and gillnet gears and between gillnet panels (Knowlton et al. 2018; Pace et al. 2014). Analysis of gear retrieved from large whale entanglements suggests that gillnet weak links may be effective given that few gillnet panels have been observed in entanglement events (ALWTRT 2018). However, entangled whales have been observed carrying ropes with weak links after the enactment of the ALWTRP. Therefore, either the weak links did not function as intended or the links reduced some, but not all, entanglement risk (FAO 2018). Notably, a study by Pace et al. 2014 found no significant reduction in the incidence or severity of whale entanglements following the weak link requirements and other ALWTRP management measures for Atlantic U.S. fisheries.

The location of weak links within gear configurations likely influences entanglement risk. Further entanglement modeling and analysis could reveal where whales tend to encounter vertical lines and inform more effective placement of breakaway technology within gear configurations (ALWTRT 2018). It is hypothesized that RBS rope may be more effective in mitigating entanglement risk for large whales compared to weak links. Since weak links only reduce breaking strength at specific points, there is the likelihood that a whale will be unable to separate the rope. This largely depends on where the whale encounters the rope. As such, sections or entire lengths of RBS rope may improve the likelihood that a whale can escape entanglement (Knowlton et al. 2016).

Other Post-Entanglement Release Mechanisms

In addition to the devices described above, several other post-entanglement release mechanisms have been proposed. These devices are generally designed to release ropes either on demand, after a set amount of time, after a set amount time under tension, or under forces from a certain direction (FAO 2018). Mechanisms for release include line-cutting blades, dissolving metal components, and devices that hold rope secure for a set time using air or water compression (FAO 2018). Although some of these devices have been shown to function as intended, it remains to be seen whether they could reduce the number or severity of large whale entanglements. They are designed to work in largely the same way as weak links, so there is currently little support for their use in entanglement mitigation (FAO 2018).

Tension

Tension refers to the tautness of line, rope, or netting used in an aquaculture system. The degree of tension, or tensile force, is determined by the amount of weight and flotation used, the forces of tides, currents, and wind, and gear breaking strength (FAO 2018). There are several pathways by which tension may affect the likelihood or severity of entanglement. By increasing material stiffness, tension is thought to influence the likelihood that an animal can "bounce off" gear upon contact (FAO 2018). Generally, tensioned gear is thought to pose lower entanglement risk, as it is less likely to loop or wrap around an animal than slack gear (Price et al. 2017). Additionally, entangled animals may be better able to rupture and break free of gear that is pre-tensioned. Tension may also influence the detection of gear by reflecting water movement towards approaching animals (Gabriel et al. 2005). Conversely, evidence suggests that higher tension materials can inflict more severe lacerations in the event of contact or entanglement (Woodward et al. 2006). Gear tensioning is frequently proposed as a method for reducing entanglement risk (Moore & Weiting 1999; Keeley et al. 2009; FAO 2018; Price et al. 2017), but there is presently little empirical support for its efficacy.

The Atlantic Large Whale Take Reduction Team, a multi-stakeholder group that guides NMFS on how to reduce serious injury and mortality to three stocks of large whales, has introduced measures to increase vertical line tension in lobster pot gear off parts of the northeastern United States. These measures include requirements that gillnets be anchored and that lobster trap ropes have negatively buoyant surface ends (FAO 2018; 72 FR 57103). Due to limited records of entanglement or lack thereof, it is unclear whether these efforts have resulted in lower entanglement risk (FAO 2018). In an attempt to understand how entanglement in fixed fishing gear occurs, Howle et al. (2018) developed a realistic, interactive computer simulation of North Atlantic right whale entanglement events. The researchers found higher tension to be a factor that facilitated entanglement (Howle et al. 2018). However, that finding did not result from experimental manipulation of the simulated gear's tensile properties, but rather it depended on the interaction between tension and the depth at which the whale models made contact with the gear (Douglas Nowacek, personal communication). In a separate experiment, Baldwin et al. (2012) outfitted a fiberglass model of a North Atlantic Right Whale flipper to a lobster boat and drove the flipper into moored ropes under variable tension (FAO 2018; Baldwin et al. 2012). The researchers were interested in how tension influences both the likelihood and severity of entanglement. Their simulations involved three contact points along the flipper. Entanglement occurred at all but the outermost contact point, and "extreme sawing action" occurred at all locations along the flipper, for 22 out of 30 events (Baldwin et al. 2012). Essentially, higher tension ropes did not seem to effectively prevent entanglement in those field simulations.

Multiple studies have investigated the influence of gillnet tension on the bycatch of marine megafauna. In a 2001 study on harbor porpoise bycatch by the Sea Mammal Research Unit, researchers modified the vertical tension of gillnets by manipulating the amount of weight and flotation. They found no significant difference in bycatch rates between vertically tensioned and standard gillnets (SMRU 2008). A similar study was conducted to assess how vertical tension influences shark bycatch in North Carolina gillnet fisheries (Thorpe & Frierson 2009). Researchers reported a significant reduction in shark bycatch for vertically tensioned gillnets (Thorpe & Frierson 2009). Another experiment by Schnaittacher (2010) investigated how horizontal tension, as measured by the hanging ratio, influences small cetacean (harbor porpoise and common dolphin) and pinniped (harp and grey seals) bycatch in a New England gillnet fishery. The hanging ratio indicates "how the net is fastened to the head rope, with lower ratios indicating more slack in the net" (FAO 2018). Schnaittacher found no significant difference in cetacean or pinniped bycatch rates between gillnets with hanging ratios of 0.33 and 0.5 (Schnaittacher 2010).

Other research has focused on how rope tension influences the potential severity of entanglement injuries. For example, in a lab experiment by Woodward et al. (2006), researchers used "an apparatus to create an oscillatory motion of ropes along the leading edge of a whale fluke" to test how rope type and tension affect laceration severity (FAO 2018; Woodward et al. 2006). The researchers tested two rope types (polypropylene float and polypropylene-polyester sink) and manipulated tension by adding weights. They found that higher tension rope with a 9 kg weight created a deeper furrow (0.40 cm) than rope with a 4.5 kg weight (0.27 cm) (Woodward et al. 2006).

Separately, tension seems to influence the efficiency of anti-predator nets for fish farms, which in turn can affect entanglement risk for pinnipeds and cetaceans. Reports from Australian salmon farms describe fur seals manipulating anti-predator nets and breaking holes in cage nets to access dead and live fish (Kemper et al. 2003; Pemberton and Shaughnessy 1993). Seals can subsequently become entangled in the openings of the damaged nets. To access the cage nets, the fur seals either charged the anti-predator nets or used their positive buoyancy to lift them to the main nets. Thus, tensioning anti-predator nets can reduce billowing and may prevent pinnipeds or cetaceans from damaging nets and creating entanglement hazards (Kemper et al. 2003).

There is mixed evidence for gear tensioning as an effective method for mitigating entanglement risk. Intuitively, the tensioning of predator nets could indirectly prevent entanglement by inhibiting access to other entangling gears. Common sense also suggests that tensioning to avoid looping of rope or line would reduce entanglement likelihood. However, to the best of our knowledge, no studies have shown that higher tension reduces the likelihood of entanglement in rope or line, and studies show gillnet tensioning reduces risk in only some cases. While additional research might reveal ranges of tensile force within which tension influences entanglement risk, the current evidence is inconclusive.

Material Stiffness

Material stiffness refers to the bending resistance of a rope, line, or netting. It is sometimes referred to as “hardness” or “firmness” (FAO 2018). Stiffness is influenced by material or polymer type, the diameter of the rope or line, and the manufacturing process (e.g. the number of rope yarns per strand or the type of lay) (FAO 2018). Similar to tension, material stiffness is thought to influence the likelihood that gear can wrap around and entangle animals like sea turtles and small cetaceans. Stiffened gear might also mitigate entanglement risk in certain environmental conditions by creating less line and movement in the water column and reducing arcing off the bottom (McFee et al. 2006; McFee et al. 2007). While no published studies show that gear stiffness reduces whale entanglement, several suggest that stiffened rope, line, or netting can mitigate entanglement risk for sea turtles, manatees, and dolphins.

Studies by McFee et al. (2006) and McFee et al. (2007) investigated the movements of buoy lines common to the South Carolina crab pot fishery to "determine where and when bottlenose dolphins may be more susceptible to entanglement" (McFee et al. 2007). The latter study expanded on the first by comparing the movements of three buoy line types with varying stiffness: diamond-braided nylon, Esterpro, and calf line (McFee et al. 2007). Line movement was tracked using DSTmilli data loggers (McFee et al. 2006; McFee et al. 2007). Observers then used the logger data to rank their first and second choices of buoy lines posing the least entanglement risk. The observer choices were based on the following criteria: degree of arcing, erratic movement, sudden ascent or descent of loggers, arcing off the bottom, and relative amount of time to descend to the bottom or ascend from the bottom (McFee et al. 2007).

Results from the McFee et al. (2007) study showed that "stiffened line, in particular the medium lay Esterpro type, produced the more desirable results that could reduce risk of dolphin entanglement" (McFee et al. 2007). Nylon line, the least stiff material, was only chosen around 10% of the time (McFee et al. 2007). Bowles et al. (2003) also explored whether stiffened line, like calf line, reduces entanglement in crab pot gear. In their study of captive manatees, the researchers found that the number of entanglements was significantly lower in trials with stiffened lines (Bowles et al. 2003).

Several studies have investigated whether chemically enhanced gillnets can reduce bycatch of small cetaceans (Larsen et al. 2002; Trippel et al. 2003; Cox and Read 2004; Larsen et al. 2007; Bordino et al. 2013). Adding chemicals like barium sulphate or iron oxide to nets has been suggested to reduce entanglement risk by enhancing acoustic reflectivity of the nets;

however, evidence from the studies suggests that any bycatch reduction from the modifications are more likely attributable to the increased stiffness than to any improvement in detectability.

In a study by Trippel et al. (2003) in the Bay of Fundy, researchers found that barium sulphate enhanced nets significantly reduced harbor porpoise and seabird bycatch compared to conventional demersal gillnets. However, in a follow-up study, Cox and Read (2004) found no difference in the rates or occurrence of echolocation by harbor porpoises encountering the two types of nets. Larsen et al. (2002) similarly found a significant reduction in harbor porpoise bycatch while testing high-density iron oxide (IO) gillnets in the Danish North Sea. When the researchers tested the conventional and IO nets in seawater tanks, they found no significant difference in acoustic reflectivity between the two (Larsen et al. 2007). Thus, the chemically enhanced nets are thought to catch fewer porpoises due to their mechanical properties, specifically their increased stiffness or weight (Cox and Read 2004; Larsen et. al 2007).

Another study by Bordino et al. (2013) compared rates of franciscana bycatch in three types of gillnets – standard, barium sulphate-enhanced, and materially stiffened gillnets – in Argentina, Brazil, and Uruguay. The stiff nets were constructed of nylon twine, and they had "a slightly but significantly higher flexural stiffness (FS) than the reflective or control net[s]" (Bordino et al. 2013). The researchers found no significant difference in franciscana bycatch rates between the three net types (Bordino et al. 2013).

In 2004 and 2005, the National Marine Fisheries Service (NMFS) conducted a study in the Chesapeake Bay to assess whether modifications to offshore pound net leaders, long walls of mesh that extend from the seafloor to roughly the sea surface, could reduce sea turtle bycatch (Silva et al. 2011). The leader modifications involved replacing the top two-thirds of the traditional mesh leader with vertical ropes, reducing mesh size, and increasing line stiffness

(Silva et al. 2011). During the first field trial, seven sea turtles were found impinged or entangled in the unmodified leader and only one turtle, a leatherback, was found entangled in the modified leader (in the vertical lines) (71 Fed. Reg.). The gear was further modified in response to the leatherback entanglement by using hard lay line for the vertical lines to increase their stiffness (71 Fed. Reg.). In the second field trial, 15 turtles were entangled in the unmodified leaders, while no turtles were entangled in the modified leader (Silva et al. 2011). While the reduction in sea turtle bycatch from using the modified leader was significant, attributing the bycatch reduction to any one element of the modified leader (e.g. stiffness, mesh size, or panel type) is not possible given the study design. However, the results suggest that materially stiffened gear may be a promising avenue for future research in sea turtle bycatch reduction.

The modified leader design also seems to have reduced the number of bottlenose dolphin interactions in the same Virginia pound net fishery (NOAA 2014). Twisted twine marks on stranded dolphins provide evidence of pound net leader entanglement (NOAA 2014). Researchers can use that stranding data, along with counts of animals removed directly from pound net leaders, to estimate the frequency of bottlenose dolphin interactions with the gear (NOAA 2014). The data indicated a 64% decrease in the number of interactions in the two years before and after the modified leader requirements were enacted (11 dolphins in 2008-2009 versus 4 in 2010-2011) (NOAA 2014). Again, while the decrease in dolphin interactions appears to be correlated with the change in leader design, the bycatch reduction cannot be attributed to any one characteristic of the modified leader, including stiffness.

There is a lack of support for increased rope stiffness as an effective method for reducing entanglement risk for large whales. Lobster pot ropes used in Western Australia have a harder lay (i.e. are stiffer) than those used in the Eastern United States, but they still entangle southern right and humpback whales (FAO 2018). Stiff ropes have also been retrieved from entangled whales in the U.S. (FAO 2018). Howle et al. 2018 note that stiffened gear is not “a priority for preventing whale entanglements and may even result in more severe injuries if applied.” However, stiffness may yet be relevant for smaller whale species or calves, which can exert less force to overcome the stiffness properties than larger species or individuals (FAO 2018). Additionally, as evidenced by studies summarized above, material stiffness can influence entanglement risk for smaller marine megafauna, like sea turtles, cetaceans, and manatees.

Mesh Size

Mesh size is defined as the longest distance between two opposite knots or joints in the same opening of a net when extended along its longest axis (ICES 2005). It is well-established that mesh size influences the capture probability and size selectivity of fishing gear like gillnets (Gabriel et al. 2005; Northridge et al. 2017). The size of openings in a net influences whether an animal can pass all or part of its body through the gear and become entangled. Although smaller mesh size is frequently proposed as a bycatch reduction strategy in net-based fisheries, its adoption is often limited by tradeoffs in target catch number or size (FAO 2018). Since target catch tradeoffs are not of consideration for aquaculture systems, mesh size reductions may be a promising approach to reducing protected species bycatch. Several studies show mesh size to be a factor influencing the incidental catch of sea turtles, seabirds, and marine mammals.

Northridge et al. (2017) performed a meta-analysis of over 600 published and unpublished studies on protected species bycatch in gillnet fisheries. They note that the “majority of studies on the mechanisms of gillnet bycatch are not accessible through the mainstream published literature,” but rather can be found in technical papers, government reports, and university theses (Northridge et al. 2017). The researchers identified “28 environmental, operational, technical, and behavioral factors that may be associated with high or low bycatch rates” of marine mammals, seabirds, and turtles (Northridge et al. 2017). Each factor was then scored based on whether they found evidence of correlation with observed bycatch rates (Northridge et al. 2017). Of the 28 factors, only three – mesh size, water depth, and net height – were associated with trends in bycatch for all three taxa (Northridge et al. 2017).

Gillnet mesh size restrictions targeting a reduction in vaquita bycatch have been implemented in Mexico’s Gulf of California (FAO 2018; Rojas-Bracho et al. 2006). As an initial regulatory measure, gillnets with a mesh size greater than 10 inches were banned (FAO 2018). However, vaquita have reportedly been caught in gillnets with much smaller mesh sizes (FAO 2018; Rojas-Bracho et al. 2006). Later, as part of the Vaquita Refuge Program, gillnets with mesh sizes over 6-7.8 inches were banned (FAO 2018). Rojas-Bracho and Reeves (2013) report that the additional measures may reduce vaquita bycatch by as much as seven individuals per year (FAO 2018).

Dewhurst-Richman et al. (2020) conducted 663 interviews in Bangladesh to assess the influence of fishing net characteristics on seasonal bycatch rates of Ganges River dolphins. The researchers collected data on gillnets, long-shore nets, set bag nets, and seine nets, but they restricted their statistical analysis to gillnet bycatch due to the small number of bycatch events in other gear types. A logistic generalized linear model with binomial error structure was used to relate gear and set characteristics to the probability of dolphin bycatch per gillnet per season (Dewhurst-Richman et al. 2020). Models selected according to Akaike’s information criterion (AIC) consistently included mesh size as an explanatory factor (Dewhurst-Richman et al. 2020).

Based on the model results, the probability of bycatch declined with decreasing mesh size (Dewhurst-Richman et al. 2020).

Murray (2009) analyzed data collected by fisheries observers on the capture of loggerhead, green, Kemp's ridley, and leatherback turtles in commercial sink gillnet gear in the US mid-Atlantic. The data were used to relate factors like spatial and temporal distribution and fishing characteristics (e.g. mesh size) to loggerhead bycatch rates, as measured by the number of turtles per metric ton of fish landed (Murray 2009). Mesh sizes in the mid-Atlantic typically range between 5 and 35.6 cm (Steve et al. 2001). Based on the observer data, entangled turtles were captured in mesh sizes between 9.1 and 30.5 cm (Murray 2009). According to the study, the "best-fitting model of loggerhead bycatch rates in the mid-Atlantic sink gillnet fishery from 1995 to 2006 describes bycatch rates as a function of latitude, [sea surface temperature], and mesh size" (Murray 2009). Of the three explanatory variables, mesh size explained the largest amount (20%) of the variation in bycatch rates (Murray 2009). Bycatch rates increased with increases in mesh size (Murray 2009).

López-Barrera et al. (2012) collected data from small-scale gillnet fisheries in Brazil to understand how gear characteristics influence the incidental capture of juvenile green sea turtles. The researchers used a Principal Component Analysis (PCA) to relate green turtle captures and gear characteristics, finding that mesh size and soak time had the strongest relationships to capture (López-Barrera et al. 2012). Separately, Wilcox et al. (2014) analyzed capture rates of turtles from nearly 9,000 ghost nets on Australia's northern coast. They found that nets with larger mesh sizes and smaller twine sizes had the highest probability of entanglement for marine turtles (Wilcox et al. 2014).

There is strong evidence that mesh size influences the likelihood of entanglement for at least some species of marine mammals, seabirds, and sea turtles. Restrictions on mesh sizes have been promulgated in some gillnet fisheries to reduce bycatch of marine mammals or sea turtles (e.g. Price 2008; Rojas-Bracho et al. 2006; Yeo et al. 2007). Unlike in gillnet fisheries, mesh sizes employed in aquaculture operations are not constrained by target catch considerations, thus controlling mesh size may be a viable solution to mitigating entanglement risk in those systems. Appropriate mesh sizes to limit entanglement will depend on the species in question, and additional sea trials and experiments may be needed to determine critical thresholds (Northridge et al. 2017).

Line Diameter

The diameter or thickness of rope or line used in aquaculture systems may influence entanglement risk through different causal pathways. Types of ropes used in aquaculture systems include spat lines, backbone ropes, and anchor lines, among others. Other factors held constant, thinner material may facilitate the release of entangled cetaceans, pinnipeds, or sea turtles due to reduced breaking strength. However, smaller rope and line diameters may also result in more severe lacerations at the same level of force exerted (Winn et al. 2008). Thinner ropes might also pose greater entanglement risk to species like dolphins due to higher flexibility (i.e. lower stiffness, or rigidity) and greater likelihood of looping. Essentially, rope diameter may influence entanglement risk both directly through its influence on laceration severity and indirectly through its influence on other gear characteristics. As line diameter increases or decreases, there may be tradeoffs between the various effects on entanglement risk.

According to the Knowlton et al. (2016) study on the effect of breaking strength on entanglement risk, the severity of injuries for entangled whales increased since the mid-1980s. The authors suggest the trend may be a result of changes in rope manufacturing in the mid-1990s that resulted in "stronger ropes at the same diameter" (Knowlton et al. 2016). Laboratory experiments have been used to test the hypothesis that line diameter influences injury severity. Winn et al. (2008) modified the apparatus used in the Woodward et al. (2006) study, described above, to compare the effect of rope diameter on epidermal abrasion for humpback and right whale tissue samples. The researchers conducted abrasion tests using 6.4 mm and 9.5 mm new float lines using a 31.8 kg load and a 3.1 m draw length. Statistical analysis of the effects of line diameter on abrasion was not possible due to the limited availability of tissue samples. However, they found that the smaller diameter line consistently cut "deeper into the humpback fluke tissue and had a greater length of epidermal removal for a given load and draw-length combination" (Winn et al. 2008).

Twine diameter has been identified as a factor correlated with target catch and bycatch rates in gillnet fisheries (Northridge et al. 2017). The "diameter and material of twine can influence visibility, elasticity, and flexibility, and therefore the efficiency of gillnets" (Gray et al. 2005). Minimum twine sizes have been established for mid-Atlantic large- and small-mesh gillnet fisheries under the U.S. Harbor Porpoise Take Reduction Plan (FAO 2018). The rules were established in response to analyses showing higher porpoise bycatch rates when using thinner twines (FAO 2018). López-Barrera et al. (2012) studied sea turtle bycatch in Brazilian small-scale gillnet fisheries and found that twine thickness was correlated with sea turtle capture. The researchers suspected that larger diameter twines may complicate "the escape of sea turtles by trapping them more thoroughly."

Importantly, the thin monofilament twine used in gillnet fisheries is not readily comparable to the thicker, tensioned multifilament materials used for aquaculture netting. Multifilament tends to be more rigid and more visible than monofilament (Gray et al. 2005). Nonetheless, the diameter of multifilament in netting may influence its detectability, entangling properties, and breaking strength and thus may influence risk through multiple stages of entanglement.

Rope diameter and breaking strength are closely related and may interact in their effect on entanglement risk (Figure 1; Knowlton et al. 2017). Partly as a result of this interaction, we might expect entanglement risk to respond nonlinearly to diameter. At small diameters, ropes may be more flexible and less visible, and there is greater potential for severe lacerations. As diameter increases, higher rigidity may reduce the risk of rope wrapping around an animal, but higher breaking strength may increase the risk of sustained entanglement. Of course, the significance of these relationships for different aquaculture configurations and vulnerable species is not known, so the reasoning outlined is largely speculative.

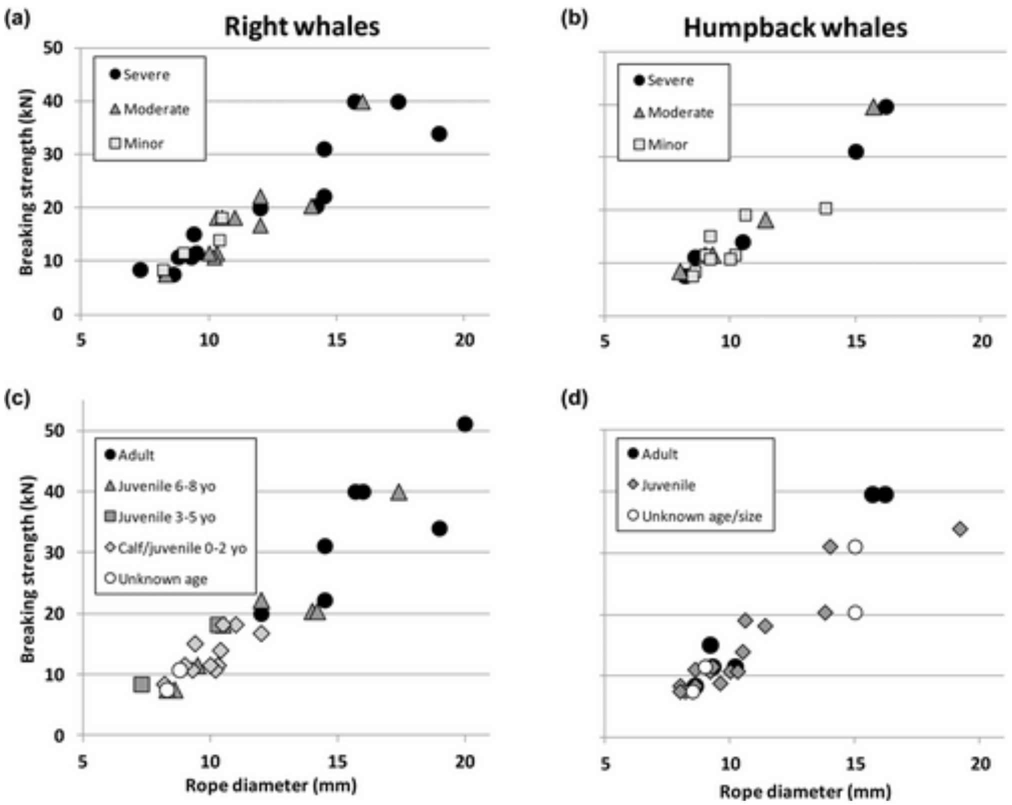

Figure 2: New rope breaking strength and diameter relative to (a) right whale injury severity, (b) humpback whale injury severity, (c) right whale age, and (d) humpback whale age. Source: Knowlton et al. 2016.

Visual Appearance

The visual appearance of gear encompasses the color, pattern, and luminosity of potentially entangling components like rope, line, or netting. Visual appearance can influence entanglement risk by affecting the ability of an animal to detect and avoid gear. Conversely, some visual properties attract animals to gear and may increase the potential for harmful interactions. The color and pattern of ropes in the water column have been shown to influence visual detection and avoidance of ropes by mysticete whales during daylight hours (Kot et al. 2011; Kraus & Hagbloom 2016). Research also shows that illumination can influence avoidance of gear by sea turtles (Wang et al. 2010; Wang et al. 2013; Southwood et al. 2008).

Cetaceans and pinnipeds only have one type of retinal cone photoreceptor, L-cones, which are most sensitive to long-to-middle wavelengths like green (Peichl et al. 2001). With only one cone (i.e. cone monochromacy), whales, dolphins, porpoises, and seals are essentially color-blind (Peichl et al. 2001). For whales, sound seems to be the primary mechanism for detection and communication (Kot et al. 2011), but vision is still thought to be important for finding prey and navigating (Kraus & Hagbloom 2016). Cetaceans "have adapted well to the spectral properties of a variety of aquatic photic environments, with light-gathering and enhancement mechanisms, high levels of resolution acuity, and special pupillary and retinal mechanisms to adjust to different light levels allowing for vision both above and below the water surface" (Kraus & Hagbloom 2016). Despite the inability of most cetacean species to discriminate color, the spectral signatures of objects in the water column may be important in influencing their apparent contrast against background light and therefore their detectability (Kot et al. 2011; Kraus & Hagbloom 2016).

In a study by Kot et al. (2011), researchers conducted field experiments to measure the behavioral responses of minke whales to different colored underwater ropes in the Gulf of St. Lawrence in Canada. They performed visual and acoustic monitoring of whale behaviors near experimental ropes and buoys, which were meant to simulate crab and whelk fishing gear (Kot et al. 2011). To quantify the behavioral responses, the researchers measured changes in velocity, bearing, and trajectory as whales approached the gear (Kot et al. 2011). The polypropylene ropes were all 1.5 cm in diameter and characteristic of the types used in commercial crab and whelk fishing (Kot et al. 2011). They conducted separate trials for yellow, orange, green, blue, white, and black ropes (Kot et al. 2011).

The researchers found that whales “decreased their swimming velocity and altered their bearing when passing near experimental ropes, especially during trials with white and black ropes” (Kot et al. 2011). There was a positive correlation between whale approach velocity and distance from the ropes for all the experimental ropes, and the correlation was strongest for the white ropes (Kot et al. 2011). Trials with black ropes showed the highest mean distance between approach and departure bearing (Kot et al. 2011). Results from the study suggest that minke whales can visually detect ropes underwater and that certain color ropes are easier to detect than others (Kot et al. 2011). Black and white are evidently “at the extremes of the monochromatic range in which whales can see” (Levenson et al. 2000; Kot et al. 2011), and they may contrast most with natural background hues during the day (Kot et al. 2011). Based on the study, Kot and colleagues recommend that high contrast ropes be used with fishing gear in coastal areas (Kot et al. 2011).

In a similar experiment, Kraus and Hagbloom (2016) studied NARWs in Cape Cod Bay to investigate whether changing the colors and visual properties of experimental “ropes” elicits different behavioral responses. They constructed 20 ft. rope mimics using two 10’ PVC pipes with roughly the same diameter as a 1” rope (Kraus & Hagbloom 2016). The researchers tested several colors, “including two that are common in most fisheries (black and green), two types of white rope (one white paint, and one glow in the dark white/green paint), and two colors that appear to occur in the spectral sensitivity for right whales (orange and red) that results in extremely high contrast” (Kraus & Hagbloom 2016). Trials using ropes with flashing or steadily illuminated LEDs were ultimately abandoned due to high rates of LED failure (Kraus & Hagbloom 2016). The researchers measured the distance at which whales first reacted to each type of experimental rope. Reactions included "noticeable changes in direction, submergence, closing the mouth, cessation of respiration, and change in fluke beat" (Kraus & Hagbloom 2016).

Due to challenges with weather, whale behavior, and technical issues, sample sizes of encounters with each rope mimic were fairly small (Kraus & Hagbloom 2016). Despite this, statistical analysis revealed a "significant difference in the distance of first change of behavior by right whales confronted with black and green ropes (n=8, mean distance = 2.625 m) vs red and orange ropes (n=7, mean distance = 6.21m) (Mann-Whitney U Test=55.5, p = 0.0018)" (Kraus & Hagbloom 2016). The authors note that right whales have photoreceptors that are tuned to a region of the spectrum to detect underwater background light but are insensitive to wavelengths greater than 650 nm, or the red region of the visible spectrum (Kraus & Hagbloom 2016). As a result, the red and orange ropes may have created a higher contrast image against the horizontal or upward visual axes and enabled the whales to detect the rope mimics at a greater distance (Kraus & Hagbloom 2016). Interestingly, the North Atlantic right whales' primary prey species, the calanoid copepod, transmits red light (Kraus & Hagbloom 2016). The Kraus and Hagbloom (2016) study provides additional evidence that the color of ropes can influence whales' ability to detect and avoid ropes during daylight conditions.

In contrast to the results of the Kot et al. (2011) study on minke whales, black and white ropes seemed to be detected at shorter distances by the NARWs compared to other colors (Kraus & Hagbloom 2016). Notably, Kot et al. (2011) found that "the correlation between whale velocity versus surface light level was relatively high for white ropes (R2= 0.79, N= 7; Fig. 6A) and black ropes (R2= 0.54, N= 12; Fig. 6B)," which suggests that detection of those colors is more contingent on background light conditions. In fact, during the Kraus and Hagbloom experiment, the researchers discovered using underwater cameras that both types of white rope mimics became invisible at relatively close distances (Kraus & Hagbloom 2016). Additional research is needed to determine whether gear color influences whale behavioral responses during night conditions.

Several studies have been investigated whether illumination of gillnets can reduce sea turtle bycatch. In one study by Wang et al (2010), researchers compared rates of sea turtle bycatch in a bottom-set gillnet fishery in Baja California, Mexico for trials at night with and without illumination. For each trial set, a control net with inactive LEDs or lightsticks was deployed along with an experimental net with active green LEDs or lightsticks at 10 m intervals (Wang et al. 2010). Nets illuminated by LEDs significantly reduced sea turtle bycatch by 40%, and nets illuminated by the chemical lightsticks also significantly reduced bycatch by 60% (Wang et al. 2010). In a follow-up study in Baja California by Wang et al (2013), ultraviolet lights were shown to reduce sea turtle capture rates by 39.7%. Similar research has also been conducted in a Peruvian gillnet fishery by Ortiz et al (2016). Those researchers also found that green LEDs reduced sea turtle bycatch, in this case by 63.9% (Ortiz et al. 2016). Although lights might decrease entanglement risk by enabling better detection, illumination may also have the side effect of attracting sea turtles towards gear (Southwood et al. 2008). Laboratory experiments have shown that juvenile loggerheads orient toward "chemiluminescent blue (peak 440 nm), green (peak 510 nm), and yellow (peak 550 nm) lightsticks, as well as flashing orange (peak 600 nm) light-emitting diode (LED) lightsticks" (Wang et al. 2007; Southwood et al. 2008). On the other hand, hatchling loggerheads from Florida nesting beaches show an aversion to light in the spectral range of 560 to 600 nm, although it is not known if this trait carries into adulthood (Witherington & Bjorndal 1991; Southwood et al. 2008). The tendency of certain spectral ranges to attract or repel sea turtles may vary by species and age class (Southwood et al. 2008).

Additional research may be needed to assess how visual properties of gear affect the detection and avoidance behaviors of other marine mammal taxa, namely dolphins and pinnipeds. However, species in both taxa seem to respond to aquaculture operations, so it is not clear that detection is a factor driving entanglement risk. For example, bottlenose dolphins in Western Australia have been documented changing course by several hundred meters to apparently avoid swimming through lines of a pearl farm (Kemper et al. 2003). Pinnipeds commonly depredate on finfish farms, in which case they are undoubtedly aware of the farms' presence (Kemper et al. 2003).

The visual appearance of gear does seem to influence gear detection for certain large whale species, but it is less apparent whether improvements in detectability are meaningful for enabling avoidance behavior. Additional research might inform us on whether the distances at which whales can detect gears of certain colors are sufficient to allow the whales to avoid contact. More research is also needed to determine whether certain spectral ranges can consistently repel sea turtles. Since many colors seem to attract turtles, caution should be taken that illuminated gear does not increase sea turtle-aquaculture interactions. For all the taxa discussed, additional studies are needed to determine how visual appearance influences gear detection and avoidance in both daylight and low light or night conditions. Monitoring of animal behavioral responses as they encounter farm sites would be useful in understanding abilities to detect and avoid aquaculture configurations.

Acoustic Reflectivity

Acoustic reflectivity refers to the tendency of materials used to deflect sound energy in water rather than absorb it. The acoustic properties of materials used in aquaculture systems may influence the likelihood or range of gear detection by echolocating cetaceans (FAO 2018). In underwater acoustics, target strength (TS) is a term that refers to the ratio of the intensity of a reflected sound wave to the intensity of the incident sound wave, measured in decibels (Johannesson 1983). By providing a measure of acoustic reflectivity, target strength is useful in describing how easily an object can be detected by an echolocating cetacean (or sonar). The target strength of gear can be altered through the use of passive acoustic deterrents, which are typically air-filled or metal components incorporated into the gear (FAO 2018). Passive acoustic deterrent devices should be distinguished from active acoustic deterrent devices (ADDs), like pingers, acoustic harassment devices (AHDs), and predator sounds, which produce sound to trigger behavioral responses in animals (Consortium for Wildlife Bycatch Reduction 2021). Active ADDs are "the most widely researched and implemented technique for deterring marine mammals interactions with fisheries" (FAO 2018). Accordingly, this research does not attempt to summarize the research on active acoustic deterrents. Rather, the objective is to review the state of knowledge surrounding how passive acoustic properties influence entanglement risk. Generally, research does not suggest that manipulating acoustic reflectivity is an effective approach to mitigating entanglement risk.

Dawson (1994) reviewed several experiments testing acoustic modifications to gillnets. From 1981 to 1986, researchers in Japan tested gillnets with three air-filled tubes interwoven into a central band to see if they would reduce porpoise bycatch (Snow 1988). Despite only a modest difference in target strength between the experimental and standard nets, they found that the modification reduced mean bycatch rates by 21% (Snow 1988). However, the reduction was "variable among years and not consistently significant" (Dawson 1994). In another Japanese study on porpoise bycatch, standard gillnets were modified with three multifilament threads intertwined in their central band (Snow 1988). The modifications increased target strength by about 10dB, but reductions in porpoise bycatch using the gears were not significant (Snow 1988; Dawson 1994). Separately, Harwood and Hembree (1987) modified gillnets with chrome-plated nickel bead chains to test whether they could reduce dolphin bycatch in a Taiwanese drift gillnet fishery in northern Australia. There was no significant bycatch reduction with the modified nets, and the bycatch rate was higher for the experimental nets during one of the trial years (Harwood & Hembree 1987). Overall, Dawson (1994) found that few studies on passive acoustic modifications used paired experimental trials or had significant statistical power to detect differences in bycatch rates between the experimental and standard nets. Furthermore, it was determined that none of the studies reviewed provided evidence of "unequivocal and large reductions in cetacean bycatch" (Dawson 1994).

As described above, studies by Trippel et al (2003) and Larsen et al (2002) investigated whether chemically-enhanced gillnets reduced rates of harbor porpoise bycatch compared to conventional gillnets. Although both studies found a significant reduction in bycatch using the enhanced nets, subsequent research showed a) no difference in the rates or occurrence of echolocation near gillnet types used in the Trippel et al (2003) study and b) no difference in acoustic reflectivity between nets used in the Larsen et al (2002) study (Cox & Read 2004; Larsen et al 2007). Thus, the reduction in bycatch associated with the chemically-enhanced nets is more likely attributable to changes in the profile or material properties of the nets (Larsen et al 2002; Larsen et al 2007; Cox & Read 2004). Also described above, a study by Bordino et al (2013) found no significant difference in the rates of franciscana bycatch in standard, barium sulphate-enhanced, and materially stiffened gillnets.

Laboratory and field studies have shown significant differences in the acoustic properties of some enhanced nets compared to conventional nets (Trippel et al 2003; Mooney et al 2004; Mooney et al 2007). For example, Trippel et al (2003) found that barium sulphate-enhanced nets were "three times more reflective than standard nets when ensonified with a 200 kHz multibeam sonar" (FAO 2018). Mooney et al (2004, 2007) simulated dolphin and porpoise echolocation clicks to investigate differences in target strength between barium sulphate-enhanced and iron oxide-enhanced gillnets and conventional nets. The researchers found that target strengths of chemically-enhanced nets were significantly greater than target strengths of conventional nets when the angle of incidence of the sound waves was near perpendicular (Mooney et al. 2004; Mooney et al. 2007). However, there was no difference in TS between the net types for angles of incidence greater than 40 degrees (Mooney et al. 2004; Mooney et al. 2007). For angles larger than 40 degrees, there was often no echo recorded at all (Mooney et al. 2007). Mooney et al (2004, 2007) used their observations of target strength at different sound levels and angles of incidence to estimate detection ranges for bottlenose dolphins and harbor porpoises. They note that the porpoises, which echolocate at lower sound levels than bottlenose dolphins, may not detect the nets until "they are at a relatively close range, and may have a more difficult time detecting any net" (Mooney et al. 2007).

The findings of Mooney et al (2004, 2007) and others suggest that the range of gear detection by echolocating cetaceans depends on their angle of approach. This raises concerns about the practicality of acoustically reflective nets as an approach to entanglement mitigation (Mooney et al. 2007). Acoustic reflectivity is only relevant to gear detection for echolocating cetaceans (Consortium for Wildlife Bycatch Reduction 2021). Furthermore, reflectivity can only affect detection if cetaceans are actively echolocating (Mooney et al. 2007). Finally, even for cetaceans that are actively echolocating, detection is influenced by the intensity of sonar emitted by the animal and by background noise levels (Mooney et al. 2007). Given these caveats and the lack of strong evidence for passive acoustic modifications reducing bycatch, changing the acoustic reflectivity of aquaculture gear does not seem to be a promising avenue for mitigating entanglement risk.

Discussion

Gear Modifications to Reduce Risk

In addition to the gear elements described above, there are several modifications and devices designed to decrease entanglement risk. These include acoustic deterrent devices (ADDs) (e.g. pingers), anti-predator nets or fencing, post-entanglement release mechanisms, lipid-soluble rope, camouflage, seal blinds, predator decoys, and olfactory deterrents, among others (FAO 2018). Some devices, like pingers, are well-studied (e.g. Gosch et al. 2017; Nowacek et al. 2003). Other devices, like time tension line-cutters, are still being developed and explored as bycatch mitigation methods (Consortium for Wildlife Bycatch Reduction 2021; Werner 2018). While some of these modifications have shown potential as entanglement mitigation strategies (FAO 2018), reviewing the efficacy of those devices is outside the scope of this project. Instead, this review focuses on the gear characteristics that are inherent to aquaculture systems.

Framework for Reviewing Entanglement Risk

In the process of characterizing how gear elements impact entanglement risk, it can be useful to frame entanglement risk as a series of probabilities that an animal transitions through successive stages of entanglement. Gear properties influence the probability of transitioning from one stage to the next, along with environmental and species-specific factors. Characteristics like the profile, visual appearance, and acoustic properties of gear influence the likelihood that animals can detect and avoid contact with gear. By attracting protected species to gear, some visual and acoustic properties might increase the likelihood of contact. Once an animal comes in contact with gear, a set of physical properties influences the likelihood that the gear becomes affixed to the animal, whether by lodging in its mouth, looping around its body, or wrapping a tail or appendage. That set of properties includes stiffness or rigidity, tension, diameter, mesh size, and the presence or absence of knots. Another set of properties, including breaking strength, influences the likelihood that the animal can break free of gear once it is entangled and, thus, also influences the duration of entanglement. Finally, another overlapping set of characteristics influence the degree of harm resulting from the entanglement (i.e. entanglement severity) and the likelihood of mortality.

The likelihood of transitioning through each stage of entanglement also depends on species-specific differences, like differences in morphology, behavior, and the forces animals are capable of exerting. For example, differences in the sensory capabilities of odontocetes (i.e. toothed whales) and mysticetes (i.e. baleen whales) may influence the likelihood of gear detection and avoidance. Unlike toothed whales, baleen whales do not use sound to detect underwater objects. Additionally, some species of mysticetes, like gray whales, are thought to have poor visual acuity (Kropp 2013). Thus, we expect that there are differences in the abilities of mysticetes and odontocetes to respond to visual and acoustic cues and avoid contact with gear.

To continue with the example, morphological differences between the two groups of whales may also influence the likelihood of entanglement once they make contact with gear. Knotted ropes pose more entanglement risk to mysticete whales as they can become lodged in baleen (FAO 2018). As Knowlton et al (2016) demonstrate, larger whale species are either more likely to escape low breaking strength gear or less likely to die and go undetected in high breaking strength gear. Species-specific behaviors, like foraging methods or responses to gear, can also influence entanglement risk. In their simulation of right whale entanglements in lobster trap gear, Howle et al (2018) found that entanglement was most easily generated by initiating a rolling behavior characteristic of right whales. Given that the risk of entanglement is species-specific, identification of species overlap with aquaculture systems is essential for assessing risk.

Comparing Fisheries and Aquaculture Gears

Gears employed in commercial fisheries are rarely directly comparable to aquaculture gears. For example, the research presented above on whale behavioral responses to rope color has emerged from the need to reduce entanglement in trap and pot fisheries. However, gear fields in those fisheries are remarkably different from those of most aquaculture operations. For lobster fisheries in the Northeast U.S., for example, gear may be difficult to avoid even if it is easily detected due to the high density of lines in the water column. In contrast, aquaculture configurations tend to be more consolidated with larger, presumably more visible structures and lines on their periphery, although this varies from system to system. Aquaculture mooring lines are generally larger in diameter and under higher tension than the ropes used for trap fisheries, but other ropes, like farm marker buoy lines, may be comparable (Price et al. 2017). Similarly, the research on using illumination to reduce sea turtle bycatch is not directly comparable to aquaculture, particularly because gillnets use small diameter twines that are difficult to detect. This review of the literature on fisheries bycatch is useful for identifying important characteristics for assessing entanglement risk in aquaculture systems and for generating hypotheses. However, in using this approach we remain limited in our ability to recommend specific aquaculture gear modifications to reduce risk. The challenge is that doing so would typically require extrapolating findings from the fisheries research to values of gear metrics outside the range of those observed in fisheries. Using the fisheries literature to generate recommendations might also require assumptions about the generalizability of risk across species and sites.

Relationships and Interactions between Characteristics

One finding from this review of gear characteristics is that many characteristics are related to each other. For example, breaking strength, rigidity, and visibility all increase with diameter, other factors held constant. At farm sites, gear characteristics are constrained by operational requirements. Weakening gear components increases the risk of breakage, which is not only costly to operators but may generate entanglement hazards by creating ghost gear (Gilman 2015). The expected forces on gear, influenced by wind, tides, currents, and the weight of gear components, determine the lower bound of viable breaking strengths. In turn, breaking strength requirements dictate acceptable material types and diameters. The relationships between characteristics are summarized in the upper right (light blue) panel of Table 2.

Table 2 – Gear Relationships and Interactions

Entanglement Interaction\ Relationship	Diameter	Tension	Stiffness/ Rigidity	Material type	Mesh size	Breaking strength	Visual appearance	Acoustic Reflectivity	Line buoyancy
Diameter		Diameter increases weight, which increases tension	Stiffness increases with diameter	Material type and diameter determine breaking strength	Diameter and mesh size relate to size of opening and flexibility of netting	Breaking strength increases with diameter	Visibility increases with diameter	Acoustic reflectivity increases with diameter	Line buoyancy increases with diameter
Tension	Higher tension, smaller diameter increases laceration severity		Stiffness increases with tension	Type and tension affect rigidity	Higher tension and smaller mesh size increase rigidity	Breaking strength limits max tension	See diameter and material type	See diameter and material type	See diameter and material type
Stiffness/ Rigidity	As diameter increases and stiffness increases, bending diameter increases, reducing entanglement risk	Higher tension and higher stiffness reduce likelihood of looping and lower entanglement risk		Type determines stiffness	Smaller mesh size increases rigidity	Not necessarily related	N/A	Higher rigidity may increase reflectivity	N/A
Material type	See breaking strength	Material type influences friction forces, which interact with tension to influence whether rope slides or becomes affixed. Also, see rigidity and tension	Stiffer materials pose less entanglement risk		Affect rigidity of netting	Type determines breaking strength	Type influences visual appearance	Type determines reflectivity	Type determines buoyancy
Mesh size	Both influence net visibility. Amount of open area influences likelihood of entangled appendages	Higher rigidity reduces entanglement risk	Smaller mesh size and stiffer mesh reduce entanglement risk	See mesh size and rigidity		Higher breaking strength and smaller mesh size increase overall stability of net	Smaller mesh size increases visibility	Smaller mesh size increases reflectivity	Smaller mesh size increases buoyancy of netting, which affects profile
Breaking strength	Larger diameters decrease entanglement risk and injury severity. Higher breaking strength increases entanglement sustainment and injury severity	Jointly influence likelihood that animal can rupture line. Higher tension reduces entanglement risk. Higher breaking strengths increase entanglement sustainment	Higher rigidity reduces entanglement risk. Higher breaking strengths increase entanglement sustainment	Type influences rigidity, breaking strength, and diameter. Higher rigidity and larger diameters decrease entanglement risk. Higher breaking strengths increase entanglement sustainment	Smaller mesh size and higher breaking strength increases net rigidity and reduces entanglement risk		Diameter typically increases with breaking strength. See diameter and visual appearance	Diameter typically increases with breaking strength. See diameter and acoustic reflectivity	Diameter and material type influence line buoyancy
Visual appearance	May interact to influence detectability	May interact to influence detectability. Taught stationary lines may be more visible	May interact to influence detectability. Rigid stationary lines with potential biofouling may be more visible	Color, pattern, and acoustic properties of materials impact detection	Smaller mesh size increases visibility and could reduce entanglement risk	Diameter may increase with breaking strength. See diameter and visual appearance		N/A	N/A
Acoustic Reflectivity	Larger diameters increase acoustic reflectivity and may reduce entanglement risk for species like harbor porpoise	Higher tension increases acoustic reflectivity and may reduce entanglement risk for species like harbor porpoise	Higher rigidity increases acoustic reflectivity and may reduce entanglement risk for species like harbor porpoise	Color, patterns, and acoustic properties impact detection	Smaller mesh size increases acoustic reflectivity and may reduce entanglement risk for species like harbor porpoise	Diameter may increase with breaking strength. Larger diameters increase acoustic reflectivity and may reduce entanglement risk for species like harbor porpoise. Increased breaking strength increases entanglement sustainment especially for large whales	Color, patterns, and acoustic properties impact detection		N/A
Line buoyancy	Small diameter, low rigidity floating (i.e, buoyant) lines pose high entanglement risk	Jointly influence arcing- - greater arcing in water column increases entanglement risk	Floating (i.e, buoyant) lines with low rigidity pose greater entanglement risk	Material type determines buoyancy and influences rigidity. See rigidity and line buoyancy	N/A	Floating (i.e, buoyant) lines with small diameters/low rigidity pose high entanglement risk. Breaking strength tends to increase with diameter and can lead to entanglement sustainment especially for large whales	Buoyancy and visual appearance jointly the influence likelihood that an animal makes contact with gear	Buoyancy and acoustic reflectivity jointly the influence likelihood that an animal makes contact with gear	

Table 2: The upper right panel describes how characteristics relate to each other. The lower left panel describes how characteristics interact in their effect on entanglement risk.

Additionally, many characteristics seem to interact in their influence on entanglement risk. As an example, tension and breaking strength interact to influence the likelihood that an entangled animal can rupture gear. If gear is not pre-tensioned (i.e. it is slack in the water column), it is unlikely that an animal will be able to create enough tensile force on the gear component to rupture it. Separately, tension and diameter interact with each other to influence the severity of injuries sustained by animals that make contact with or become entangled in gear. Hypotheses about how characteristics interact in their influence on entanglement risk are summarized in the lower left (light gray) panel of Table 2.

Furthermore, changes to some characteristics involve trading off risk at different stages of entanglement. For example, increasing tension may decrease entanglement risk by increasing the rigidity of gear and by better enabling animals to rupture the gear component. However, higher tensions also relate to more severe lacerations. Increasing diameters may reduce risk by improving the visibility of gear, by increasing stiffness properties, and by reducing the likelihood of severe lacerations. However, larger diameters also correspond to higher breaking strengths, which can increase the probability that entanglement is sustained. Further research is needed to better characterize the risk tradeoffs of gear properties in species- and site-specific contexts.

Based on a review of the literature, there is fairly strong evidence that diameter, breaking strength, and tension can influence entanglement risk. Moreover, those characteristics also relate to and interact with a relatively high number of other identified characteristics. Accordingly, diameter, breaking strength, and tension may be of particular interest to environmental managers in future evaluations of entanglement risk.

Conclusion

A major challenge in the research on aquaculture and entanglement risk is the lack of empirical data on protected species-aquaculture interactions, particularly negative data (i.e. data on the absence of interactions). Without negative data, it is difficult to parse out whether reported aquaculture entanglement events are uncommon because a) aquaculture poses relatively little entanglement risk or because b) events are undetected or underreported (Price et al. 2017). With better data on interactions, researchers may be able to relate the type and characteristics of aquaculture systems to the frequency of protected species interactions with those systems. Improved data on interactions might also allow managers to predict where entanglements are likely to occur and direct research efforts accordingly.

The lack of data on interactions points to a need for better monitoring of farm sites, particularly in regions where aquaculture is newly introduced to determine the species at risk of entanglement. Monitoring could take the form of on-site observers, or it could involve electronic monitoring through video surveillance or acoustic monitoring. Monitoring might also entail gear instrumentation like tension sensors or accelerometers that provide real-time information on the movement of gear or the forces on particular components. Different monitoring goals for different projects will determine which method is appropriate. Observer coverage, which may produce higher-quality data at a higher cost (Bartholomew et al. 2018), may be most appropriate for monitoring trial or demo projects where the value of information is high.

Another avenue for improved information on protected species-aquaculture interactions is through gear marking. Often when an animal is found entangled, the origin of the entangling gear is unknown (Gilman 2015). Marking gears, especially rope, with distinct signatures that can be traced to particular activities (e.g. mussel longline culture, lobster fisheries) or even individual farm sites would create accountability for operators and provide better information on sources of entanglement risk.

There also is a need to centralize information on reported entanglements in aquaculture gear through shared databases. Currently, it can prove difficult to find detailed descriptions or pictures of entanglements, both of which are useful in reconstructing how entanglements occurred. Local news reports were often the only sources of information on specific entanglement events, but the reports tend to lack technical information relevant to managers. In the United States, there are protocols for reporting marine mammal stranding events, and all data collected through standardized Level A Stranding Report forms are added to the National Stranding Database (NOAA Fisheries 2021). A similar system for reporting entanglements is needed to improve data quality and ease of access. Reports on entanglement events should include a description of the entangling gear along with photographic evidence of how the animal was entangled and any injuries. Gear descriptions should include specifications like diameter, material type, condition, color, and the presence/absence of knots along with details on how the gear was configured with other components.

The limitations of relating the fisheries entanglement literature to aquaculture point to a need for a more system-specific approach to researching entanglement risk. However, there may be obstacles to researching aquaculture entanglement using the methods common to fisheries research. For fisheries, bycatch mitigation techniques are often tested using field trials in which researchers deploy modified gears along with standard gears to compare their rates of bycatch. These types of experiments require a large enough number of observed entanglements to power statistical models. Given the infrequency of aquaculture entanglements, it seems unlikely that researchers could obtain enough observations to replicate that approach.

One avenue for future field research on aquaculture interactions is studying how visual properties affect animal behavioral responses. As described above, multiple studies have investigated how large whale species respond to different rope colors and patterns (Kot et al. 2011; Kraus & Hagbloom 2016), but the ropes used in those field trials were not representative of gears used in aquaculture systems. Ropes used for aquaculture tend to have larger diameters than the ones tested, and they are configured in systems comprising much larger profiles. Knowledge gaps remain concerning how animals respond to different colored gears in different environmental conditions, like turbid or low-light settings. Monitoring the behavioral responses of animals as they encounter farm sites could enable researchers to relate the visual properties of farm sites (i.e. colors, patterns, and/or illumination) to avoidance behaviors.

In the absence of sufficient empirical evidence on interactions, models or simulation tools can be used to improve our understanding of entanglement mechanics. Howle et al. 2018 developed a simulation tool to model North Atlantic Right whale entanglements in buoy lines associated with trap and gillnet fisheries. The tool was constructed to help researchers "in understanding entanglement dynamics and testing potential new gear configurations" (Howle et al. 2018). Tools for simulating animal interactions with aquaculture systems could similarly improve our understanding of how animals become enwrapped, the expected severity of injuries and integrity of gear following collisions, and how altering configurations might impact entanglement risk. Importantly, this approach accommodates species- and system-specific research. The simulation tools could be tailored to model the behavior and morphologies of particular species (Howle et al. 2018) and would enable researchers to study entanglement risk using gear parameters characteristic of aquaculture systems.

While it is not in the scope of this research to provide recommendations on modifications to aquaculture gear to mitigate entanglement risk, a few best management practices are to avoid loose ropes, repair holes in netting, avoid the use of knots, and use stiff materials for ropes and netting (Price & Beck-Stimpert 2014; Clement 2013; FAO 2018). In reviewing the entanglement risk posed by potential farm sites, permitting agencies would be wise to identify and collect metrics on the following gear characteristics: breaking strength, diameter, tension, material stiffness, mesh size, and visual appearance. Characteristics like material type, line buoyancy, scope, profile, buoy volume, acoustic reflectivity, and anchor type are of secondary interest in weighing entanglement risk. This literature review supports future research on aquaculture gear characteristics and entanglement, which may yield specific guidelines on configuring gear to reduce entanglement risk. As the aquaculture industry grows, so does the urgency of finding ways to mitigating entanglement risk for protected species, whether through marine spatial planning, special devices like pingers, or modifications to gear.

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